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LBL-17072

APPLIED SCIENCE DIVISION ANNUAL REPORT

ENERGY EFFICIENT BUILDINGS PROGRAM

FY 1983

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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

Table 1 shows the importance of buildings in the U.S. economy. In 1983, our buildings sector used $150 billion worth of energy, mainly as electricity. In fact, of the total annual U.S. electricity sales of $130 billion, most ($90 billion) went to the equipment and appliances in buildings.

To get a better feeling for the cost of energy in buildings, we note that the U.S. 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 costing a little more.

Since 1973, rising energy prices and energy awareness have remarkably reduced our energy bills. Our real GNP is up 22%, yet our primary[3] energy use is down 5%, i.e., our ratio of E/GNP is down to 0.95/1.22 = 0.78. If our energy efficiency were still frozen at 1973 levels, we would today be paying $500 billion/0.78 = $640 billion annually, i.e., we are actually saving $140 billion each year, a very significant sum, comparable with our highly publicized national budget deficit.

In buildings, the percentage savings are comparable with those for our energy consumption as a whole. In the last 10 years we have built 27% more homes and added 32% to commercial floor space; yet primary energy use in buildings is up only 7%; so E/ft^2 is down to 0.83, and we are actually saving $30 billion/year.

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

Table 1. U.S. energy expenses in 1983.[1]

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

Our Energy Efficient Buildings program at LBL 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 report contributions to science and technology leading to actual advancements measured not in hours, but in months, and in many cases in years.

The Energy Efficient Buildings Program conducts theoretical and experimental research on various aspects of building technology that will permit such gains in energy efficiency without decreasing occupants' comfort or adversely affecting indoor air quality. To accomplish this goal, it has developed five major research groups whose findings and achievements are regularly reported in technical and scientific journals, presented at international conferences, and disseminated as Lawrence Berkeley Laboratory (LBL) reports.

A brief overview of the scope and objectives of each group follows.

ENERGY PERFORMANCE OF BUILDINGS (EPB)

The EPB Group studies the flow of energy through all elements of a building. It thus tests air infiltration rates, thermal characteristics of structural elements, and the behavior of the interface between dissimilar materials. From an analysis of overall performance, the group can recommend cost-effective solutions for reducing infiltration and thermal losses, either by retrofitting existing buildings or by improving design features for new construction. This research is conducted in the laboratory and in the field; EPB also regularly conducts field measurements in single- and multi-family buildings.

EPB has also developed a public-domain microcomputer program, CIRA (Computerized Instrumented Residential Audit), which is designed to speed up and improve the accuracy of residential audits of energy consumption. It automatically provides the homeowner with a tailored list of retrofit options, ordered by return on investment, and a corresponding set of energy labels for the house.

A recent activity has been the development of a prototype low-cost data acquisition system, the so-called "Energy Signature Monitor." EPB is developing this 16-channel, all-solid-state recorder, complete with sensors and user-friendly installation and analysis software, for residential, and possibly commercial, applications.

BUILDING VENTILATION AND INDOOR AIR QUALITY (BVIAQ)

An obvious means of improving the energy efficiency of a building is to lower air exchange rates by reducing air infiltration or forced infiltration. However, one of the factors affecting indoor concentrations of air pollutants is the exchange of air with the outdoors. 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. Ventilation with recuperation 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. However, it has become evident from the work of the BVIAQ group and others in the United States and around the world that the factor having the strongest influence on indoor concentrations is the pollutant emission rates rather than ventilation rates. Indoor concentrations exceeding outdoor levels (and exceeding outdoor standards) occur whether buildings have been tightened or not, and, throughout the building stock, there are houses with unacceptably high levels of radioactive radon gas, formaldehyde, and combustion products. Substantial attention needs to be given to indoor air quality, independently of the implementation of energy conservation measures, paying attention to limiting the sources of contamination. Such efforts can lead to a reduction in indoor pollutant concentrations (especially excessive levels), even with a modest reduction in air exchange rates. If we can learn to reduce safely the infiltration rate of U.S. houses by 1/4 air change per hour, our annual resource energy savings would be about 0.8×10^{15} Btu, worth $6 billion.

BUILDING ENERGY SIMULATION (BES)

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

The group is developing new techniques to calculate building loads and simulate heating, ventilating, and air-conditioning (HVAC) equipment. New techniques and algorithms have been developed to calculate the envelope element response to convective and radiative heat gains inside and outside of the building and to calculate the effect of using daylight. Calculation procedures for the analysis of passive solar designs, including direct gain, Trombe walls, and water walls, have been added, as have approaches to model more accurately the interactions between the thermal zones of multizone and multistory buildings. Finally, new control and equipment models in the HVAC section of the program simulate nighttime ventilation, plenum heating systems, controls for variable flow systems, and controls for cogeneration equipment.

WINDOWS AND DAYLIGHTING

The Windows and Daylighting Group focuses on developing the technical basis for understanding the energy-related performance of windows. If the flow of heat and light through windows and skylights can be properly filtered and controlled, these building elements not only can outperform any insulated wall or roof component, they can also provide net energy benefits to the building. The group's investigations are designed to develop the capability of accurately predicting fenestration performance. It develops analytical models and experimental procedures for determining the thermal and solar-optical properties of glazing materials; it also conducts materials-science studies to characterize a new generation of thin-film coatings and other advanced optical technologies that may someday enhance the performance of conventional glass and plastic glazings. The first generation of windows incorporating transparent heat mirrors (R-4.5 windows) is now reaching the market 6 years after their initial development in this program. If they capture the market, as expected, they will save consumers $5 billion annually in heating bills.

The DOE-2 building-energy analysis model has been modified to enable daylighting effects to be calculated; it is also being used for extensive parametric studies to determine total building energy use and peak loads as functions of climate, orientation, and window properties. LBL daylighting studies now use a recently completed 24-foot-diameter sky simulator for testing scale models under carefully controlled conditions. Data from outdoor model tests and daylighting resource studies are still being collected and analyzed. Computational procedures will be validated with the Mobile Window Thermal Test (MoWiTT) facility, now nearing completion. This unique facility combines the accuracy and control of laboratory testing with the realism and complexity of dynamic climatic effects. It should, for the first time, enable controlled measurement of the interaction between fenestration systems and the building HVAC system.

LIGHTING SYSTEMS RESEARCH

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

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

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

The Visibility Impacts Program focuses 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 the use of modern office equipment operating in an advanced lighting environment.

The Health Impacts Program extends electric lighting research to a wider class of human activities. Here, conditions can be varied, and nonsubjective responses to lighting can be measured by sensitive medical instruments.

Facilities for the Technical Program are located at LBL; the Visibility Impacts Program is located at the School of Optometry at Berkeley; and the Health Impacts Program is located at the Medical Center on the San Francisco Campus of the University of California.

The Lighting Group's successes include advancing the development of high-frequency solid-state "ballasts" for fluorescent lamps and several energy-efficient lamps to replace the familiar incandescent electric lamp. A 2-year test of solid-state ballasts in a large office building showed an electricity savings of 40%; scaled to the entire country, this would represent an annual savings of $5 billion. The energy-efficient lamps yield a factor-of-3 improvement in efficacy, and this could provide further annual savings of perhaps $5 billion.

BUILDINGS ENERGY DATA (BED)

The Buildings Energy Data Group compiles and evaluates data on end uses of energy, and on the costs and performance of energy-efficient technical measures. The BECA (Building Energy-use Compilation and Analysis) data base contains separate elements for each major subset of buildings (efficient new houses, retrofitted buildings, etc.).

Using these data, it 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, and industry groups. Individual conservation (or solar) measures are catalogued in order of increasing cost per unit of energy saved. The result is a supply curve (marginal cost curve) of

saved energy. These curves are comparable to the supply curves for other market commodities and show the expected levels of production as a function of unit price.

RELATED BUILDINGS RESEARCH IN OTHER PROGRAMS

Closely related research on energy-efficient buildings and appliances is carried on in other programs within the Energy and Environment Division and is reported in other chapters of this annual report. Specifically, the Energy Analysis chapter reviews building energy performance guidelines, appliance energy performance, and energy and peak-power modeling. The Solar Energy chapter summarizes the research of the Passive Solar Analysis and Design Group.

NOTES AND REFERENCES

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

Energy Performance of Buildings (EPB)*

R.C. Sonderegger, P. Brunello, P.G. Cleary, R.C. Diamond, D.J. Dickerhoff, J.B. Dickinson, V. Kendon, P. Levin, R.D. Lipschutz, M.P. Modera, C. Reinhold, M.H. Sherman, B.V. Smith, and R.F. Szydlowski

The Energy Performance of Buildings Group 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 help in the formulation of retrofit strategies for existing buildings. Our primary areas of research are air infiltration and thermal performance. We have also developed a microcomputer program to help in the design and retrofit of buildings. Most recently, our requirements for reliable data have lead to the design of a multipurpose data logger, the Energy Signature Monitor (ESM).

AIR INFILTRATION

Because of the strategic role infiltration plays in the total energy performance of conditioned spaces, studies of air infiltration have always formed the backbone of the EPB research program. Air infiltration is typically responsible for one-third of the energy load on residential buildings, and, in most envelope-dominated buildings, it is also the primary mechanism for the removal of pollutants and moisture. Furthermore, natural ventilation—primarily through open windows—can potentially displace large amounts of cooling in warm, humid climates.

Our work in this area includes measurement of the effects associated with air infiltration, as well as an effort to understand the theory and to model the physics behind infiltration processes. A major contribution has been the development of the LBL Infiltration Model. This simplified model is used to calculate air infiltration from weather data and easily measurable parameters, including the important one of whole-building effective leakage area. Our model has proved invaluable in the prediction of air infiltration.

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

Accomplishments During FY 1983

Infiltration Modeling

Investigations into understanding and extending the LBL infiltration model have continued. We made a detailed examination of the simplifying assumptions upon which the model is based and examined the effects of internal flow resistances on infiltration in multizone structures.

The LBL infiltration model contains four simplifying assumptions, as follows: (1) flow through the cracks in the building envelope can be represented by orifice flow; (2) wind-induced and stack-induced infiltration can be superimposed as the square root of the sum of the squares; (3) infiltration can be averaged over all wind directions; and (4) infiltration can be averaged over all building aspect ratios (the ratio of width to length). We examined the scatter and bias caused by each of these assumptions. Bias is a measure of how each assumption affects the average infiltration predictions, and scatter is a measure of the range of error for individual (e.g., hourly) infiltration predictions.

Our analysis provided several insights into the model. Although it did not cause significant scatter, the superposition assumption caused consistent overprediction of infiltration. The orifice flow and aspect ratio assumptions also biased the prediction, but the direction of the bias depended upon the weather and the building, respectively. The largest scatter was caused by the orifice flow and wind direction assumptions. The latter only biased the predictions when the local shielding was not uniform or the wind direction was not uniformly distributed. Overall, the model overestimated the infiltration by 10% (bias) and had a standard deviation (scatter) of 28%. These results define both the limitations of the model and the most efficient paths to its improvement.

Our investigations into adding the effects of internal resistances to the model (i.e., multizone infiltration) included an extensive literature search and development of a network model. Both efforts illustrated the need for classification of different building types to better define the modeling problem. A large building with a central ventilation system will not require the same modeling simplifications as a single-family residence. In the case of a wind-dominated building with large internal resistances (e.g., a small apartment building), the network model indicated that the effect of wind direction should be included in any simplified model.

Air Leakage Studies

Leakage is obviously an important factor in the energy calculations of architects and engineers, but they have not been able to estimate the leakage area of a building before it is built; instead, they have had to find the leakage area from pressurization measurements made after construction. A simple solution to this problem is to find the leakage area of each component of the building envelope and sum them to get a total value. This requires an extensive data base of measured leakages for the individual components. We have compiled such a data base for residential buildings, using published data from around the world. The summing technique was tested on 39 houses of various construction types. The predictions had an accuracy of about 20%, within the estimated error of the input data.

From the same data base of measured leakages, we have constructed pie charts of leakage sources for typical houses, both with and without fireplaces [Fig. 1(a) and (b)]. These pie charts show that doors and windows are not the dominant leakage sources, and that leaks such as wall outlets play almost no part. The largest leakage comes from windowsills and wall/ceiling joints and from air distribution systems.

The effective leakage area is normally measured by fan pressurization, using a blower door. We have continued to develop a promising alternative technique, AC pressurization, to measure air leakage. AC pressurization uses a mechanical device to sinusoidally increase and decrease the internal volume of the structure. By measuring the volume change and the pressure response, the air flow through the envelope can be determined, and the whole-building air leakage calculated. The AC pressurization equipment imposes a single-frequency volume change on the building. We use a computer program to extract the response that is in phase with the volume drive. This technique removes almost all of the noise from wind, which would otherwise make measurements impossible, and allows low pressures—around 4 pascals (Pa), typical of wind-induced infiltration—to be used. Since the blower-door method—DC pressurization—employs pressures on the order of 10 to 50 Pa and requires extrapolation to the 4 Pa region, AC pressurization is potentially more accurate than the blower door.

We have also looked at the possibility of using an audio system for these studies: speakers to change the volume and microphones to measure the pressure response. Initial work with a special low-frequency microphone has shown that it can easily make measurements in the frequency and pressure range required. Initial work with speakers, however, has shown that they cannot provide acceptable pressure signals at the frequencies required in AC pressurization. The speaker efficiency drops off significantly below 10 Hz, and the waveform is distorted by flexing of the speaker cone.

Thermal Comfort Modeling

In FY 1982, we began to study the problem of natural ventilation for cooling in hot, humid climates by measuring buildings on a Marine base on

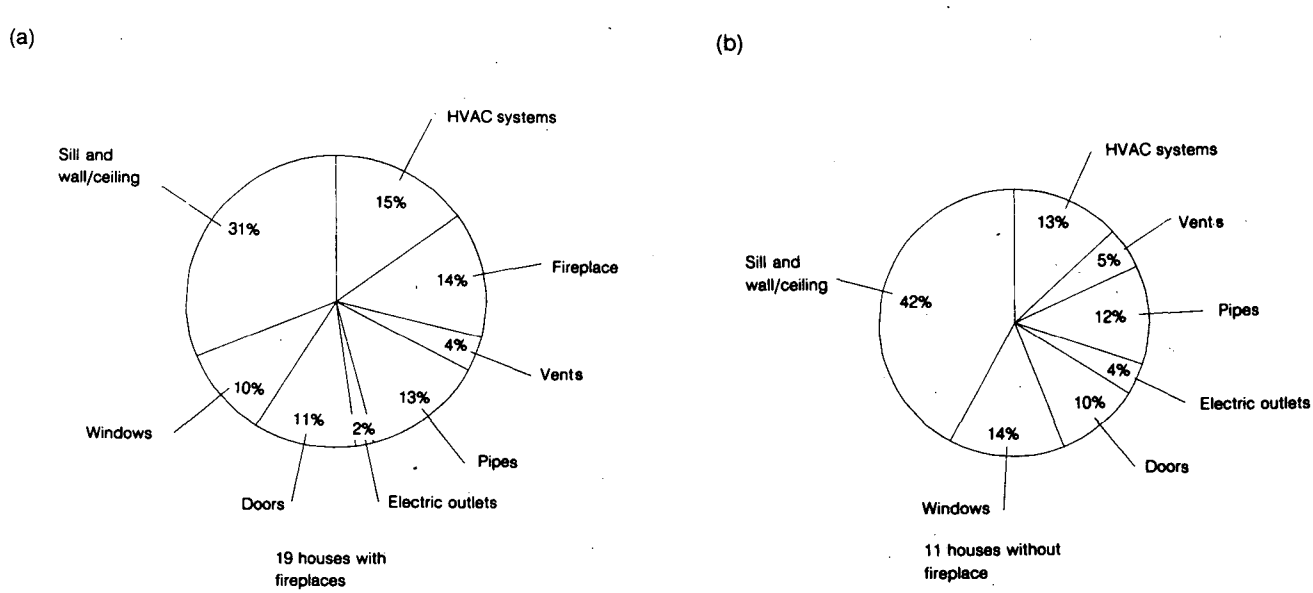

Figure 1. Calculated contribution of major house components to air leakage area: (a) for 19 houses with fireplaces; (b) for 11 houses without fireplaces. [(a) XBL 838-11275; (b) XBL 838-11276]

Oahu, Hawaii. We have continued that work by analyzing the collected data in some detail. In order to find the effect that increased natural ventilation (and, therefore, internal air speed) can have on cooling energy use, it was necessary to develop a simplified model of thermal comfort. Our model describes the effects of air temperature, humidity, air speed, and mean radiant temperature on a subject as a function of the subject's activity and clothing level. The physiological work has already been done elsewhere; our effort has been limited to making reasonable approximations and simplifying assumptions in order to derive the comfort formulae.

Output from the simplified model is shown in Fig. 2, which gives three comfort zones as a function of dry-bulb temperature and humidity. The lowest temperature zone is for low internal air speed, and the highest is for an internal air speed of 1 m/s. Typical indoor clothing and activity levels have been assumed. The plot shows that the comfort zone occurs at a dry-bulb temperature 2°C higher with an air speed of 1 m/s than with an air speed of less than 0.1 m/s. This would increase energy demand in a heating climate and decrease it in a cooling climate.

Modeling of Moisture Storage in Building Materials

A new area of research for the EPB group this year concerns moisture storage in materials. To assist the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) in giving recommendations for ventilation rates in attics, we have begun to study the moisture storage properties of wood and the heat/mass balance within attics. This effort is part of a project with the Forest Products Laboratory in Madison, Wisconsin, and the National Bureau of Standards. At present, there are no attic ventilation guidelines, and it is suspected that traditional rules of thumb do not apply to current well-insulated attics. We have developed a model that predicts the attic-air humidity ratio (kilograms of water per kilogram of dry air) and roof-sheathing (plywood) moisture levels as a function of the roof-sheathing temperature and the outside-air humidity ratio. The predictions of the model compare well with measurements, as shown in Fig. 3, which compares measurements by a group at Princeton University with the model's predictions. Wood moisture content can also be predicted over a heating season, for a given ventilation rate. In this way, a ventilation rate can be chosen that will keep wood moisture levels below the level at which damage may occur.

Contributions to Professional Societies

We have continued to make contributions to the professional societies and their work in the development of consensus standards and research agendas. We have actively assisted the American Society for Testing and Materials (ASTM) in the development of standards for the measurement of both air infiltra-

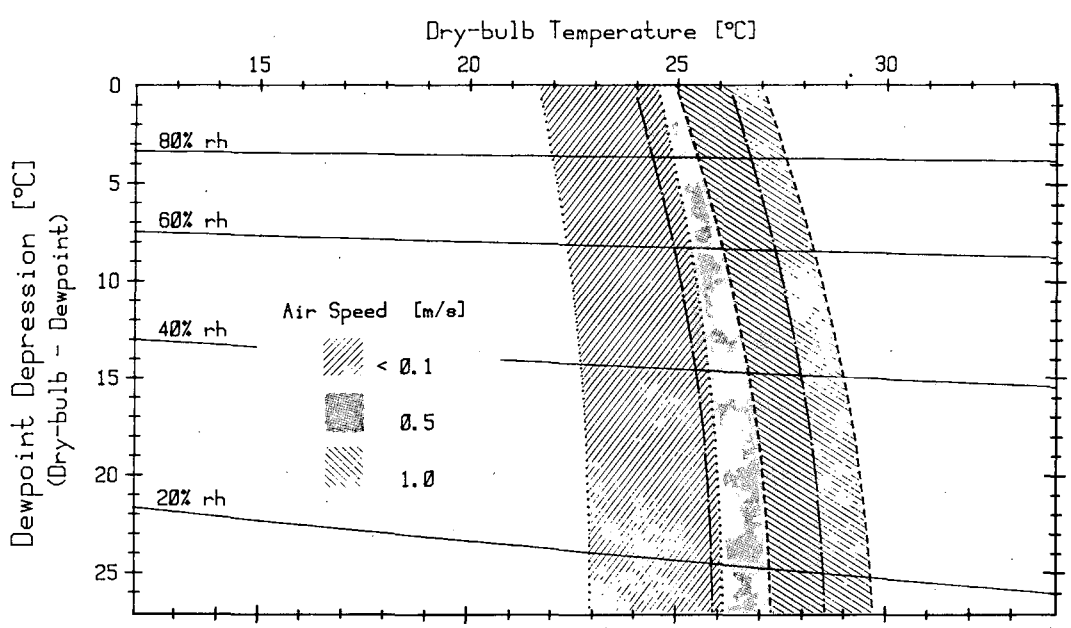

Figure 2. Human comfort zones as a function of air dry-bulb temperature and relative humidity (expressed as dew-point depression) for three air speeds. (XBL 841-159)

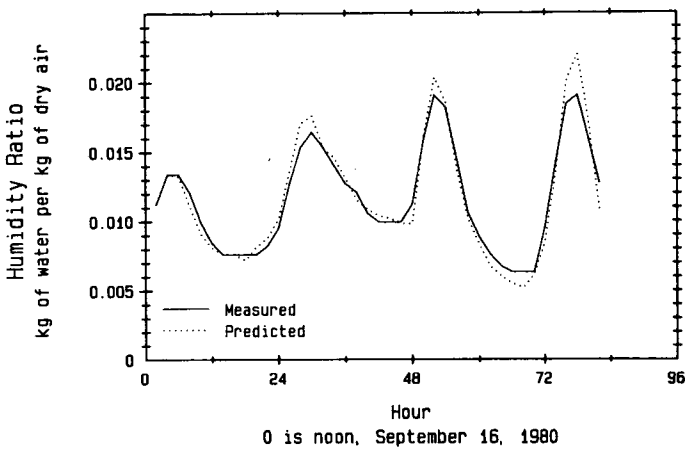

Figure 3. Comparison of the measured attic air humidity ratio and that predicted by theory for an attic in Pennington, New Jersey, for a period of four days. (XBL 842-603)

tion (ASTM E-741) and air leakage (ASTM E-779). We are also working on an ASHRAE draft standard (SPC-119P) for maximum acceptable air leakage in residential construction. Finally, we have been actively participating in Annex V of the International Energy Agency, which is responsible for the Air Infiltration Centre (AIC) in Britain. The AIC compiles data and bibliographies in all areas of air infiltration research; its work is freely available to any of the participating countries. The AIC also sponsors international conferences on air infiltration; the fifth AIC conference will be held in the United States during 1984.

Planned Activities for FY 1984

Work on the infiltration model will continue, based on the validation effort of FY 1983, and should lead to a more sophisticated version that includes techniques to compensate for the effects of the simplifying assumptions. The model will also be extended to take into account the interaction of HVAC (heating, ventilation, and air conditioning) systems with natural infiltration. Detailed experiments to measure the combined effects of natural infiltration and ventilation systems will be made in our Mobile Infiltration Test Unit, and comparisons of predicted and measured infiltration in actual buildings will be performed. A multizone infiltration model will be developed; the effect of HVAC systems will also be an important component of the multizone model.

The AC pressurization research will include detailed comparisons of AC pressurization measurements with fan pressurization tests, and a prototype field version of the AC system will be developed. The field version will be sized to provide a pressure signal of approximately 4 Pa, so as to measure leakage directly at our reference pressure. A number of different concepts for the volume driver are being considered. Possible pressure measurement schemes include low-cost microphones in enclosures designed for low-frequency measurements, and pressure transducers modified to measure alternating pressures.

We also plan to continue our work in natural ventilation and comfort. The simplified comfort equation will be used to make recommendations concerning design in hot, humid climates. The work will be expanded to include moisture and latent heat storage in building materials (see below).

Moisture studies in FY 1984 will include monitoring of an attic over the heating season, to validate the model. This will require the development of a continuous wood-moisture meter. Theoretical work will center on the prediction of roof-sheathing temperature from meteorological data and a physical description of the roof. From those predictions it will be possible to predict required ventilation rates for different parts of the country. The model will also be expanded to cover moisture storage in living spaces, to help in the thermal comfort research, where humidity levels are important. Some environmental chamber studies may be needed to determine the storage parameters of common building materials.

ENERGY SIGNATURE MONITOR

The Energy Signature Monitor (ESM), our multipurpose data logger, along with its attendant data-analysis software, will make possible the inexpensive gathering of large-scale, high-quality data on building energy use. It is being developed as a novel, cost-effective system that integrates measurement, data collection, and compilation and is designed to provide low-cost, sophisticated data in a standardized format. The electronically stored data will always contain full information as to the sensors used and the building and site identity to avoid time-consuming cross-referencing with logbooks and installation reports. Transformation of raw data to physical units and management of data from multiple sites will be done automatically by the data reduction software without further input by the user. ESM can monitor total energy consumption (broken down by end use), as well as related variables as diverse as temperature, lighting levels, indoor pollutant concentrations, office equipment loads, thermostat settings, and door openings.

Accomplishments During FY 1983

Based on laboratory tests and field experience with the original ESM, which was developed in FY 1982, the design was refined and six prototypes were built. The current ESM design, along with a standard computer terminal, is shown in Fig. 4. The computer terminal is used to communicate with the ESM during its setup at a test site and is not required during operation of the test, thus reducing site equipment requirements. Since the ESM was designed for long-term unattended operation, there is no need for a built-in data display (except for the the front panel's four status indicator lights), a printer, or a keyboard. A removable data module and two computer control switches are located behind the access door of the front panel. The rear panel has connectors for the sensors and power supplies, and a standard RS-232 connector for a computer terminal.

The ESM's data acquisition and communication is microprocessor-controlled (6502 CPU) with 8K byte of assembly language program memory contained in erasable programmable read-only memory (EPROM) and 4K byte of random-access memory (RAM) for intermediate data storage. Data is stored in 24K bytes of EPROM memory, which is contained on a removable 3.5 × 5 inch data module for convenient physical transfer to a central data analysis station. ESM has one pulse-count input channel and 16 analog voltage input channels. An analog channel's inputs can be read either as the sensor's voltage or as a digital signal where an "on" signal is defined as a voltage higher than a user-set threshold. The standard data acquisition program, written in assembly language, counts the pulses and scans the analog channels every 15 seconds. The total number of pulses, the digital channel's number of "on" scans, and the analog channels' average voltage level for an hourly record period is written to the EPROM data module. A data module can record 5 weeks' worth of data using the standard program and a full set of input channels. A laboratory modification of the data acquisition program can accommodate unusual scan intervals or data processing schemes.

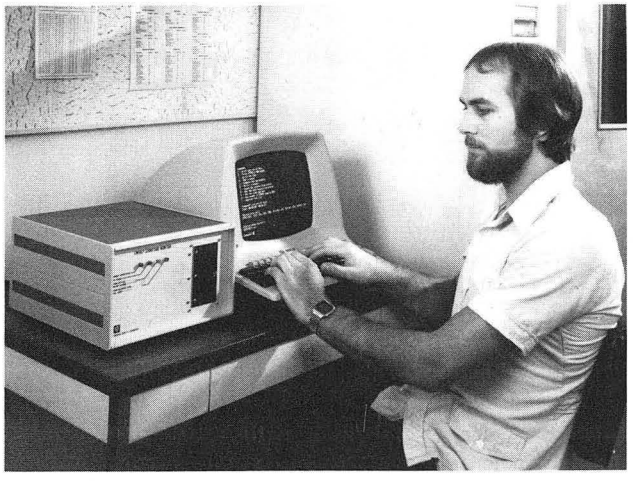

Figure 4. The Energy Signature Monitor (box on left). A computer scientist is setting up data files at the beginning of a field test of the ESM (the terminal is not required for data collection). (CBB 830-8721)

The ESM was designed to be as easy to use and as foolproof as possible during both installation and operation. All sensor electrical connectors use standard modular telephone jacks to assure quick, positive, and foolproof field connections, thus eliminating on-site wiring. A full data module is replaced with a new erased data module by simply unplugging the old and inserting the new data module. Modules cannot be installed incorrectly. A self-check feature shows immediately if the new data module is rejected due to incomplete erasure or incompatible information. The set-up program is menu-driven so that the operator does not need extensive knowledge of the options and input requirements. In case of a power outage, battery back-up power is supplied for memory, clock, and short-term data acquisition operation. ESM will go into a sleep mode if power is not restored within an hour, restarting automatically when line power is restored. The data modules are sent for analysis to a central station, where another ESM (identical to the field units) reads the recorded data into a microcomputer or mainframe, using its RS-232 serial interface. A preliminary code was written for the required user-friendly data management and analysis computer program to support the central processing station.

Although any sensor with a compatible output signal can be used with ESM, some low-cost sensor development was conducted to allow monitoring of electric power, temperature, thermostat (or similar switch), and burner (such as water heater, furnace, etc.). The electric power sensor monitors true power (including power factor); the temperature sensor is a standard current source transducer, with the appropriate signal conditioning built into its connector; and a thermostat status circuit is available to monitor the building's space conditioning thermostat, with provisions for a wide range of thermostat operating voltages. Of course, any other switch conforming to similar voltage ranges can be monitored. Burner status can be monitored by using a digital temperature sensor ("on" when the temperature is

high) or a photocell ("on" when the light level is high). The modular telephone plugs used to connect the sensors to ESM form a six-wire bus, with +5 and +15 volts available to any sensor that requires active signal conditioning.

A sample of reduced data from an ESM field test is given in Fig. 5. The operating ("on") time of a gas-burning hot water heater was monitored for one month using a digital temperature sensor, and an average weekday burner on-time profile was calculated from the recorded hourly values.

The six prototype ESMs were custom-built at a cost of $1500 per unit. With mass production, the cost should drop to under $500; this includes savings brought about by quantity buying of parts and refinements in assembly.

Through LBL's technology transfer office, the process of finding a private company to build ESMs was initiated.

Planned Activities for FY 1984

Special attention will be given to field testing required to assure long-term component reliability and ease of use. The computer terminal shown in Fig. 4 will be replaced with one of the new portable personal computers (such as the Radio Shack TRS-80 Model-100), which are smaller and lighter, making for easier field use. They can also be programmed to make the terminal perform automatically many of the checks currently done manually by a technician during ESM installation and checkout. Additional development of low-cost sensors will be conducted, with emphasis on a less expensive and more accurate electric power sensor and on non-intrusive heating-fuel monitors.

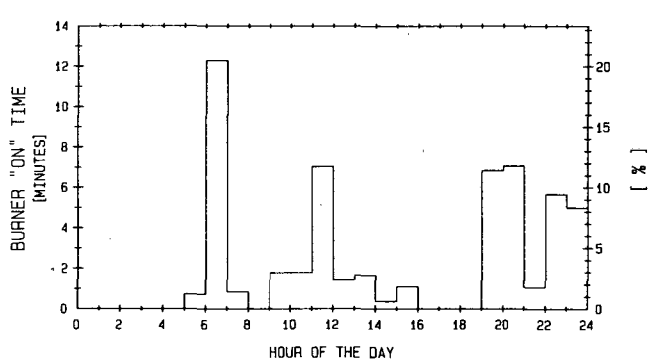

Figure 5. Data gathered by the Energy Signature Monitor during a 4-week field test, showing, on an hourly basis, the averaged "on" time of a gas-fired domestic hot-water heater. Site was a house in Martinez, California.

(XBL 842-602)

The data management and analysis software, to be used at the central data processing station, will be completed. This is a critical step in the development of an integrated system that will allow a user to monitor a large number of sites, perform automatic data management on the results, and process the aggregate data into a usable form with a minimum of time and expense. The hardware requirements of a large-scale data collection project are usually so overwhelming that data analysis is not given the attention it requires. As a result, much of the data acquired in such studies is not utilized.

Transfer of detailed ESM hardware and software specifications to the private sector will follow successful field demonstrations. The process of finding a manufacturer to produce the hardware and provide support for both hardware and software was begun in FY 1983, and will be completed during FY 1984.

THERMAL PERFORMANCE OF BUILDING SYSTEMS

The conduction of heat through walls represents a significant fraction of a building's energy load during the heating season. Although much information is available on the steady-state thermal performance of walls in a laboratory environment, very little exists on the performance of walls *in situ*. Existing field measurements do indicate that steady-state wall resistances can show significant degradation when compared with standard laboratory calculations. The goal of our walls research is to develop a complete methodology for determining the performance of walls. The methodology contains two relatively independent constituents: (a) a measurement apparatus (the Envelope Thermal Test Unit, ETTU) capable of both controlling and measuring instantaneous heat flows and surface temperatures on both sides of a wall and (b) a calculation procedure to extract static and dynamic wall parameters from measurements of heat flows and surface temperatures. Once complete, this system can be used in the field to determine the behavior of different wall constructions and placements and to assess their impact on overall energy consumption.

In addition to studying how heat enters or leaves a building through its envelope, we are also interested in the equipment used to maintain thermal comfort within the living space. For example, wood-burning equipment has seen an enormous jump in popularity over the past few years. With current analytical techniques, it is extremely difficult to balance the energy flows in a building that uses a wood stove. For this reason, we have begun to develop a system for monitoring the heat output of a

wood stove. To make it applicable to large statistical surveys, such as those that can be performed with the Energy Signature Monitor, it is constrained to use a single channel of a data acquisition system.

Accomplishments During FY 1983

Envelope Thermal Test Unit (ETTU)

For the past several years, the goal of our thermal measurement program has been to develop a methodology for determining the thermal performance of walls. The ETTU 1.3 prototype, which consists of two insulation blankets fitted with temperature sensors and computer-controlled electric heaters, was tested on walls in the laboratory and in the field. The laboratory work included tests of a well-defined insulating material (NBS Standard Reference Material 1450b), as well as tests of built-up specimens of typical residential walls. For the reference material tests, ETTU determined the thermal resistance to within 6% of the quoted value. For the wall specimen tests (insulated walls with and without studs), the results agreed with those obtained by simulating the walls with a response-factor computer program. The measured R-values and the time constants were within 10% of the values determined in the simulations.

In its first field tests, ETTU 1.3 proved to be a useful measurement tool. It was used to measure the static and dynamic characteristics of an insulated stud wall and an 8-inch-thick concrete wall. In both cases, field installation proved to be relatively quick, and the apparatus operated reliably for all tests.

The tests at the two sites confirmed our expectations for field operation. The stud wall results were quite good, but the concrete wall tests were plagued by problems with lateral heat losses. For the insulated stud wall, ETTU measured an R-value of 9.5 hr-ft^2°F/Btu, and a time constant of 12 minutes, compared with 10 hr-ft^2°F/Btu and 7 minutes, as determined by a response-factor computer program. Because of the large lateral heat losses in the concrete wall, the present analysis program was unable to determine the R-value and the time constant accurately. The results differed from those of the computer simulation by as much as 50%.

Because ETTU measures the thermal characteristics of a wall by actively imposing a series of surface heat fluxes, its operation should be independent of the weather. It was found, however, that this weather independence is limited, because lateral heat losses increase sharply whenever ETTU imposes fluxes very different from those naturally occurring in the wall. This was most apparent when measuring the thick, conductive, concrete wall under mild weather conditions. For both the concrete and insulated stud walls, the measurements improved when the ETTU-induced fluxes were in the direction of the weather-induced heat flux. These results indicate that, although ETTU's active heating system increases the useful frequency range of the measurements compared to a passive device, it is still somewhat dependent upon the weather to provide a steady heat flow through the wall. In late FY 1983, the ETTU 1.3 prototype was prepared for shipment to another National Laboratory, where it will be used to test walls in commercial buildings.

Single-Channel Monitor for Wood-Stove Heat Output

Our other thermal measurement project in FY 1983 was the development of a single-channel monitor whose output could be correlated with the heat output of a wood stove. To find such a sensor, we tested five typical wood stoves under controlled conditions. Each was monitored with surface temperature sensors and infrared radiometers while being operated in a calorimeter room. We could then attempt to correlate the output of the sensors with the measured heat output. By the end of FY 1983, all stove tests had been completed and preliminary correlations performed. The correlations indicated that both radiometers and surface temperature sensors are suitable wood stove monitors.

Planned Activities for FY 1984

Although experimentation with ETTU 1.3 was completed in FY 1983, the data analysis will continue in FY 1984. Using the data collected with ETTU 1.3 and wall data from outside sources, we will improve upon the analysis part of our wall measurement methodology. We plan to improve the present analysis program, which determines the Simplified Thermal Parameters (STPs) of a wall, so that it will incorporate the effects of lateral heat losses. The new program will also lead to recommendations for future field instruments.

We also plan to continue our analysis of the wood-stove data taken in FY 1983. By trying more sophisticated correlation techniques, we expect to be able to develop a general correlation based upon wood-stove size and geometry. These correlations will be applied in the Hood River Conservation Project in Portland, Oregon, and in various monitoring efforts being performed with the Energy Signature Monitor.

COMPUTERIZED, INSTRUMENTED RESIDENTIAL AUDIT (CIRA)

The aim of this continuing project is to develop a reasonably accurate, microprocessor-based energy audit and analysis tool that can be used by building energy professionals such as government officials, architects, engineers, energy auditors, and retrofit contractors. Existing methods for estimating energy use in buildings are based on either time-consuming paper-and-pencil procedures at one extreme or large-scale computer simulations that require a rigidly formatted input at the other extreme. The advent of many brands of low-cost microcomputers and easy-to-use programs has greatly reduced the amount of time required to analyze energy use in a residential building. These microcomputer programs ask multiple-choice questions in plain English; the user selects the appropriate answer. They expand the range of possible users of sophisticated energy analysis programs to include everyone from building contractors to energy policy planners. The CIRA program was developed in FY 1981 and FY 1982, and was released in March 1982.

Accomplishments During FY 1983

Since the public release of CIRA in FY 1982, the work carried out has been chiefly program consolidation and support. CIRA development was substantially completed with the release of the updated program in March 1983. The main changes include the addition of a new cooling load algorithm, an almost twentyfold expansion of the weather library to over 180 cities, and completion of a weather file editing program (CIRACTY) to allow users to enter their own data. Major revisions were made to the Engineering Methods, Economic Optimization, and Weather Library sections of the CIRA Reference Manual in order to reflect these changes in the algorithms and data bases. Minor revisions were also made to the Utility Programs, Question Library, and Retrofit Library sections. The new cooling algorithm is a major improvement, since it calculates exactly both the latent and the sensible loads; it can be used on pocket calculators as well as microcomputers. The cooling algorithm has shown excellent agreement with hour-by-hour calculations of energy use made by the DOE-2 program for a model house in both a hot, dry climate and a hot, humid climate.

The updated versions of the program and manual were sent to users responding to the announcement of the CIRA update. A survey of CIRA users was initiated at the same time. The results of the survey showed that the largest identifiable grouping of CIRA users consisted of government agencies and organizations conducting government-sponsored research, while the second largest was architects and engineers. Another interesting finding was that about 15% of CIRA users were from foreign countries, including Canada, France, Italy, Sweden, Switzerland, England, Denmark, Australia, and West Germany.

The source code of the program is available, and a number of engineers, researchers, and contractors have adapted it to suit their particular requirements. Some researchers have used the CIRA input and output format for their own energy programs, and others have made use of the original calculation methods and algorithms.

An important aspect of any energy-use model is how well its predictions compare to actual building energy use. A project begun this year was an effort to compare monthly and yearly energy-use predictions made using CIRA with measured energy consumption figures for a number of residential buildings in different climates. Submetered energy data and site-specific weather data were collected for 10 buildings in Warren, Arkansas; 8 in Birmingham, Alabama; 2 in Rio Linda, California; 12 in Eugene, Oregon; and 1 in Syracuse, New York. The initial comparisons shown in Fig. 6 are for CIRA-predicted use and measured annual space heating consumption for 24 buildings.

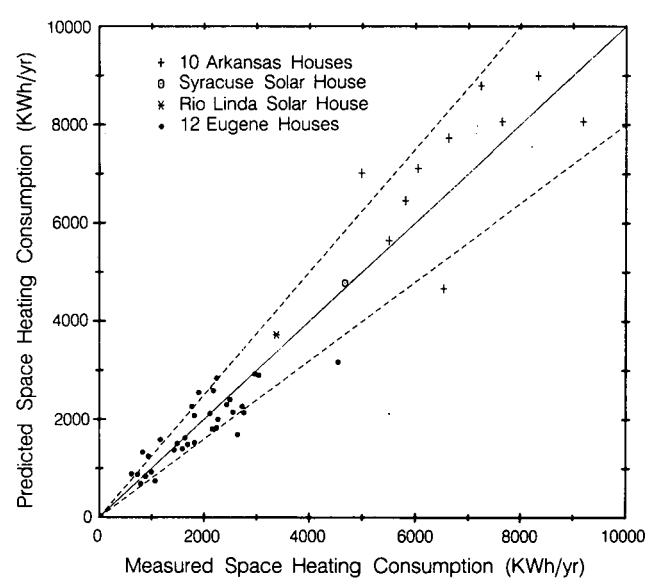

Figure 6. Initial results of a comparison between CIRA-predicted use and measured annual space heating consumption for 24 buildings; dots representing the Eugene, Oregon, houses reflect more than one year of data.
(XBL 842-601)

Planned Activities for FY 1984

The CIRA validation project will be completed, giving a comparison of measured and predicted energy consumption for a wide range of house types and locations. In the year ahead, we plan to continue support for and distribution of the CIRA program, although we hope to be able to hand this task over to the private sector by the end of FY 1984.

There have been an increasing number of requests for CIRA from companies that have IBM or IBM-compatible microcomputers. We expect that one or more companies in the private sector will modify CIRA to operate on these 16-bit microprocessors. This IBM-compatible version of CIRA will then be made available to the public through a company that is licensed to distribute it.

Figure 7. City Center Plaza, Oakland, California, viewed from the southwest. (CBB 833-2443)

MULTI-UNIT ENERGY MONITORING

The aim of this project, started in FY 1982, is twofold; first, to quantify variables in design and occupancy that affect energy use in multi-unit housing; second, to work with the private sector in exploring energy use in multi-unit buildings. About half the new dwelling units built in the U.S. are part of multi-family buildings. Although some results of work on single-family units are transferable to multi-unit buildings, there are problems unique to the larger buildings, e.g., metering and HVAC distribution systems, interunit air exchange, and heat stealing by adjacent units.

Accomplishments During FY 1983

We have continued our investigations of a high-rise apartment building in Oakland, California (Fig. 7). We have found a 20-to-1 range in the ratios of baseload electricity consumption and a 40-to-1 range for space heating in a sample of about 200 nominally identical units (Fig. 8). Technical explanations for these large variations, such as unit orientation, location, and exhaust ventilation flow rates, have been unable to account for the observed variations. We now suspect that behavioral effects such as temperature preference, use of gas stoves for space heating, and occupancy patterns are the important factors. The significance of these findings is that in a mild climate such as Oakland's, where the heating season is poorly defined, the absolute need for space heating will be determined largely by occupant preference. This may be contrary to the situation in more severe climates, where space heating is determined to a large extent by a building's physical features.

The second phase of multi-unit energy monitoring has involved a 60-unit housing project for the elderly, located in Oroville, California (Fig. 9). The focus here has been to look at the wide range of factors that affect comfort and energy use for the low-income elderly. A utility bill analysis for these units has shown a 5-to-1 variation in both winter heating and summer air conditioning for identical units. Blower-door pressurization tests of 57 units showed very little variation in the effective leakage areas

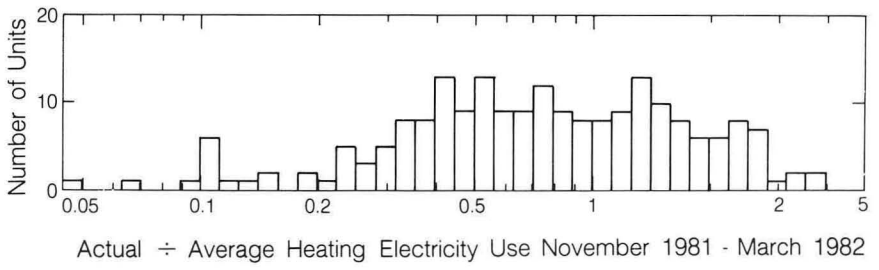

Figure 8. The distribution of actual space heating use divided by average use for 207 units at City Center Plaza, Oakland, California. (XBL 838-11231A)

Figure 9. Winston Gardens, housing for the elderly, Oroville, California. (CBB 839-7955)

(~18%), which suggests that construction quality is not a significant factor in the observed variation in energy use. Subsequent interviews of all the residents turned up several key behavioral factors involving issues of comfort and control. What we have seen so far is that conventional energy features, such as levels of insulation, window or building orientation, and construction details are only part of the picture, and that the residents' understanding and control over their environment are equally important considerations. In particular, the residents frequently complained of their inability to open and close the windows, and of their dissatisfaction with the heat pumps. Operation of the thermostat (a rather complicated affair with three control levers and two status lights) appears crucial to the whole pattern of energy use, and we will continue to study its use and misuse.

Planned Activities for FY 1984

We hope to monitor the energy use of another multi-unit building, although no new work is planned at this time for the Oakland apartment project. (An occupant survey may be undertaken in Oakland in the summer of FY 1984 to study behavioral effects in some detail if sufficient manpower and funding are available.) Work at the housing project for the elderly will continue with winter monitoring of indoor temperatures, heat pump performance, and energy use. We will continue to monitor weather conditions and analyze energy use by individual units. Changes in mechanical systems may be carried out, to analyze their impacts on energy use and comfort. The results will be written up as guidelines for the project architects, as operation and maintenance manuals for the Housing Authority, and as an illustrated booklet for the residents.

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 Building 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 formaldehyde and other organics, arising from a variety of materials and furnishings. In addition, other groups study techniques for controlling airborne concentrations, develop devices for monitoring pollutants in laboratories and buildings, and design or carry out field surveys of indoor air quality. Significant effort is also devoted to assessment of the health effects of indoor pollutant exposures.

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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.

POLLUTANT EMISSIONS FROM COMBUSTION APPLIANCES

Researchers in the Building Ventilation and Indoor Air Quality (BVIAQ) Program and elsewhere have demonstrated that operating unvented combustion appliances increases indoor pollutant concentrations: higher levels of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), nitric oxide (NO), formaldehyde (HCHO), and respirable particles have all been observed. In FY 1983, the BVIAQ Program completed the data analysis of its controlled field studies of pollutant emissions from unvented gas-fired space heaters[1,2] and conducted similar studies of unvented kerosene-fired space heaters and wood-burning stoves.

In general, our research efforts are devoted to: (1) characterizing the emission rates and pollutant concentrations of the many types of combustion devices used in buildings, (2) assessing the health implications of exposures to combustion-related pollutants, and (3) exploring techniques to reduce pollutant concentrations while maintaining energy efficiency in buildings.

Accomplishments During FY 1983

Data from our controlled field study of indoor air pollution from unvented gas-fired space heaters (UVGSH) were analyzed in detail to project steady-state CO_2, CO, NO_2, NO, and O_2 indoor concentrations resulting from the use of UVGSHs and to determine the time-dependent relationship of the CO, NO_2, and NO_x (NO + NO_2) emissions from the UVGSHs. Eighteen field tests were conducted on four UVGSHs, coded as 12A, 16B, 30A, and 30C. [The numbers, multiplied by 1000, are the manufacturers' heat input rating in units of Btu/h (1.054 kJ/h), and the letters stand for the manufacturers.] The tests were conducted at a research house maintained by LBL at Walnut Creek, CA.

"Projected" Steady-State Pollutant Concentrations

Since steady-state concentrations were not always reached before the UVGSH was turned off, the final pollutant concentration is a percentage of the steady-state concentration. This percentage was theoretically determined using the measured air exchange rate of the house, the pollutant reactivity rate, and the combustion time of the appliance. A "projected" steady-state value was then determined by correcting the final pollutant concentration. All concentrations reported here are averages of the kitchen, living-room and bedroom values. Except for two short 2-hour tests of the 12A and 30C heaters, all pollutant concentrations reached 78% to 98% of their steady-state concentration.

Graphs depicting the projected steady-state pollutant concentrations for CO_2, CO, and NO_2 versus the air exchange rate of our research house are given in Figs. 1–3. The curved lines in Fig. 1 represent

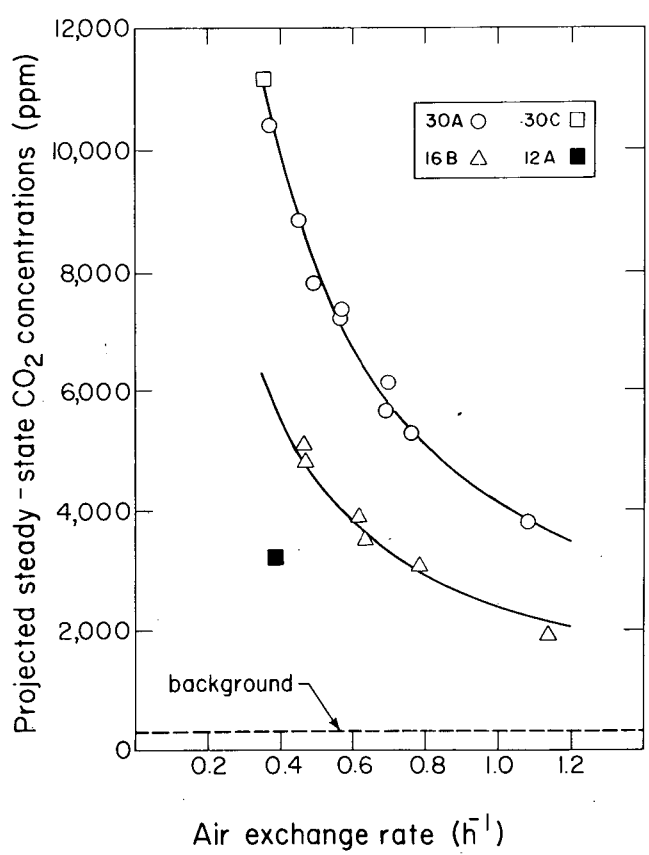

Figure 1. Projected steady-state CO_2 concentrations associated with the use of unvented gas-fired space heaters vs. the air exchange rate of the research house (a 240 m^3 unoccupied building). The solid lines are empirical fits of the data to the reciprocal of the air exchange rate for the 30A/30C and 16B heaters. (XBL 834-9040A)

empirical fits of the data to the reciprocal of the air exchange rate for the 30A/30C heaters and the 16B heater. These curves demonstrate that the steady-state concentrations of nonreactive gases whose source strength is constant follow the theoretical dependence on air exchange rate. Figure 1 shows that the CO_2 concentrations generated range from 2,000 ppm to 11,000 ppm; for comparison, the U.S. Occupational Safety and Health Administration (OSHA) 8-hour time-weighted workplace CO_2 standard is 5,000 ppm.[3] The steady-state CO_2 levels generated from the 30A/30C heaters exceeded the OSHA standard for all experiments where the air exchange rate was below 0.8 ach. The steady-state CO_2 levels generated by the 16B heater approached the OSHA standard at 0.46 ach.

Steady-state concentrations of oxygen were always above 19%. The lowest oxygen level measured was 19.5%; this occurred when a 31,600 kJ/h heater was operated for approximately 4 hours at an air exchange rate of 0.37 h^{-1}.

Our results show that the CO levels in a house with an UVGSH can exceed outdoor air quality standards (Fig. 2). Nine of the 18 tests resulted in projected steady-state CO levels exceeding the Environmental Protection Agency's 8-hour standard of 9 ppm.[4] Seven tests involved the 16B heater. The 30A heater was tested under an excess-air (maltuned) condition and exceeded the EPA's one-hour standard of 35 ppm.

Nitrogen dioxide concentrations were high relative to the only existing short-term standard for NO_2 that has been promulgated by a state or federal agency; this is the State of California standard of 0.25 ppm for a one-hour average exposure.[5] All projected NO_2 steady-state concentrations exceeded this one-hour standard (see Fig. 3).

Variable Emission Rates

An important observation was that the emission rates of CO, NO, NO_2, and N (of NO_x) varied throughout the operating period of the heater. A technique was developed to determine an emission rate every 24 minutes (the time to complete a set of bedroom, living room, kitchen, and outside measure-

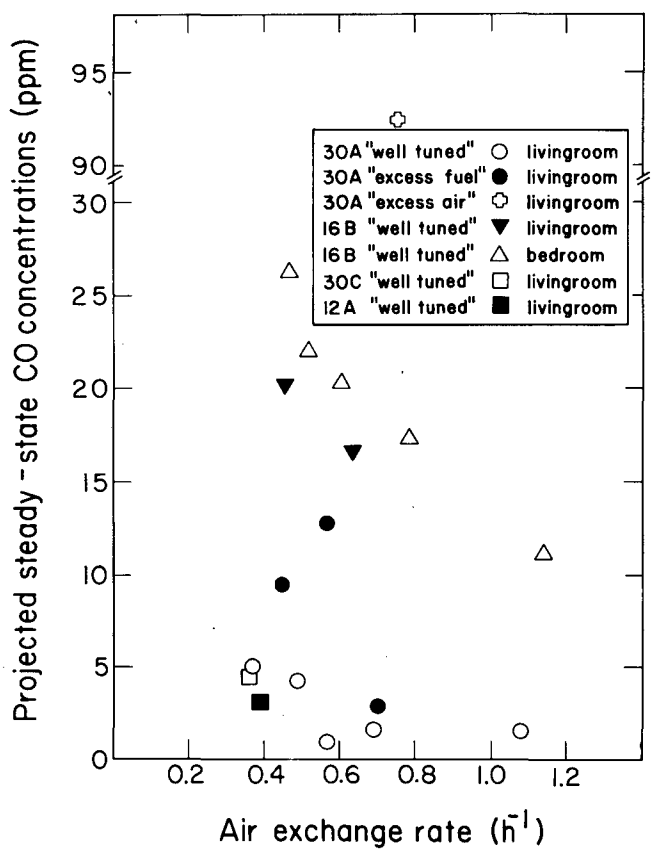

Figure 2. Projected steady-state CO concentrations associated with the use of unvented gas-fired space heaters vs. the air exchange rate of the research house.
(XBL 834-9042)

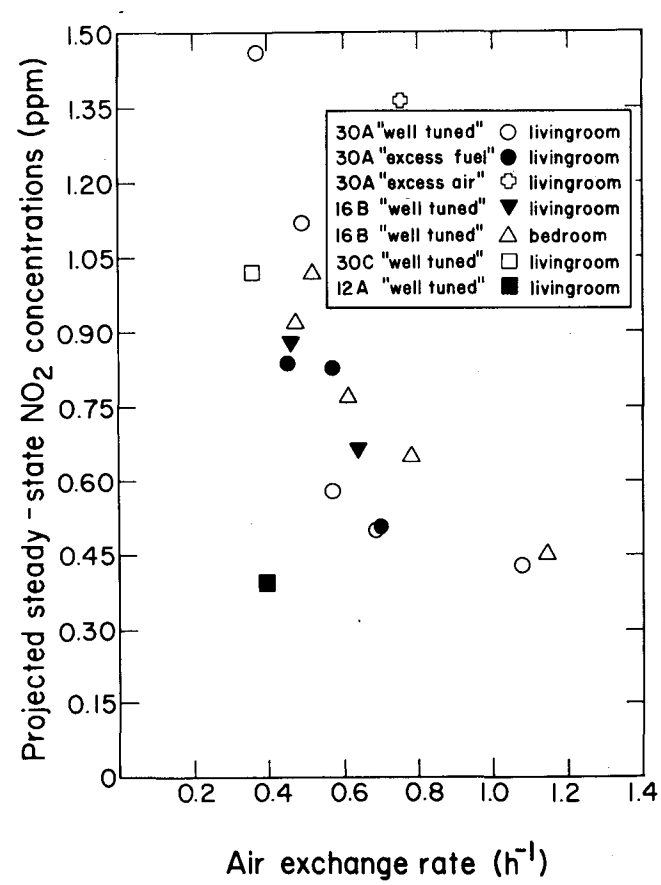

Figure 3. Projected steady-state NO_2 concentrations associated with the use of unvented gas-fired space heaters vs. the air exchange rate. (XBL 834-9043)

ments).[1,2] The results of this "semi-continuous" emission rate analysis of CO, N (of NO_x), and NO_2 are shown on Figs. 4–6 for representative tests.

The results show that the CO emission rate can change drastically with time. The initial emission rate of CO, determined within 5 to 15 minutes of ignition, can be very different from the final steady-state emission rate. Figure 4 shows this great variability in the CO emission rate for representative tests. The causes of this variability over time are not well understood. In some tests, the emission rate drops during an initial warm-up period (see tests 30A-2, 30A-6, 30C-1, and 12A-1 in Fig. 4). After warm-up, changing O_2, CO_2, and H_2O concentrations may affect the CO emission rate profile by slightly changing the flame temperature or other flame characteristics. This may explain the rise in the CO emission rate for the 30A-2, 30A-6, and 30C-1 tests between approximately 20 and 90 minutes.

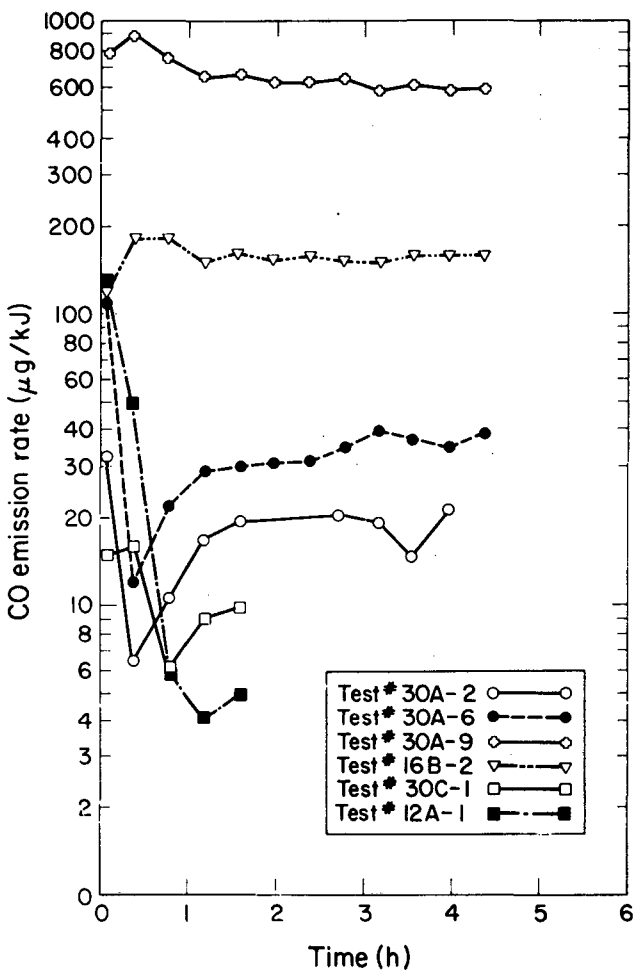

Figure 4. CO emission rates vs. time for representative controlled field tests. (XBL 835-9772)

Semi-continuous emission rate data for representative tests are shown graphically in Fig. 5 for N (of NO_x) and in Fig. 6 for NO_2. For N (of NO_x), there is a consistent trend in which the emission rate increases for an initial warm-up period, peaks between approximately 15 and 60 minutes of operation, then gradually decreases with time. Although not all factors that affect the temporal N (of NO_x) emission rate profile are known, it appears to be affected by the two phenomena that affect some of the CO emission rate profiles. First, the N (of NO_x) emission rate rapidly increases while the heater is warming up, when, presumably, the average and/or peak flame temperature is increasing as well. Second, the N (of NO_x) emission rate decreases as the O_2 level decreases and the CO_2, H_2O, and other combustion product concentrations increase. This change in supply air composition may cool the flame, thus accounting for the general decrease in the N (of NO_x) emission rate. Although consistent with some CO emission rate profiles, this explanation is speculative, and further research is needed to test it. The NO_2 profiles are more complicated than those of N (of NO_x), probably because the NO_2 emission

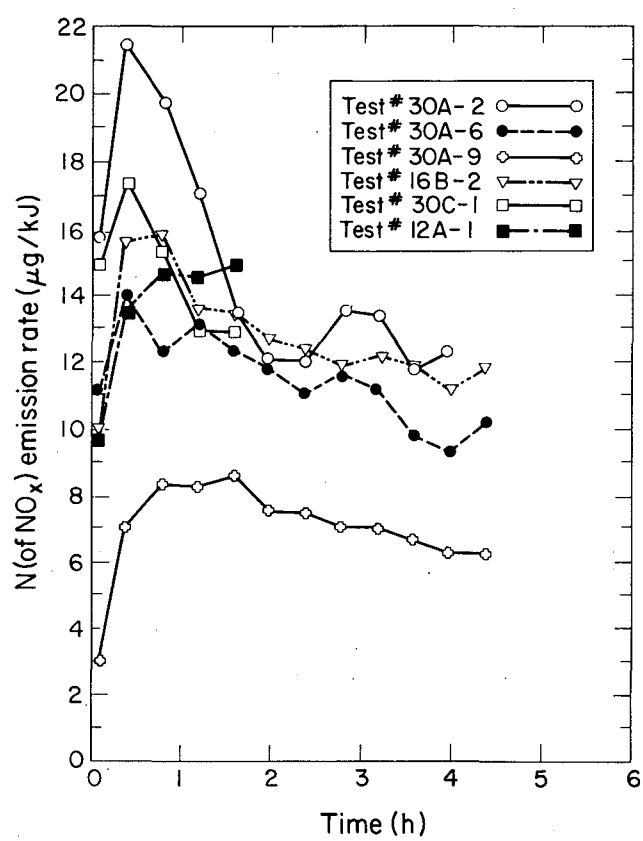

Figure 5. N (of NO_x) emission rates vs. time for representative controlled field tests. (XBL 835-9771)

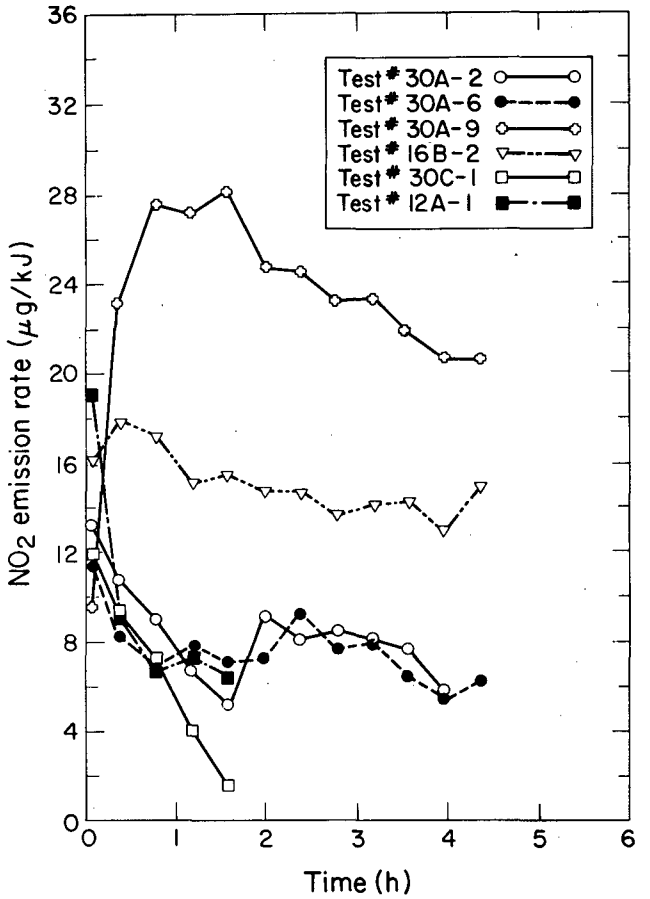

Figure 6. NO_2 emission rates vs. time for representative controlled field tests. (XBL 835-9770)

depends on factors other than flame temperature while the N (of NO_x) emission rate is driven primarily by the flame temperature.

Planned Activities for FY 1984

We plan to complete the data analysis of our field research on wood-burning stoves and portable kerosene-fired space heaters. For wood-burning stoves, data have been collected on CO, CO_2, NO_x, formaldehyde, and suspended-particle emissions. (Analysis for benzo (a) pyrene and other polycyclic organic compounds was conducted on the suspended particles.) Similar data have been collected on the field use of portable kerosene-fired space heaters, and analysis of these data will yield inter-room pollutant transport rates.

New work starting in FY 1984 includes laboratory tests on the new generation of unvented gas-fired space heaters that incorporate oxygen depletion sensors (ODS). In addition, protocols will be developed to study indoor air pollution from combustion appliances under actual field conditions. This research will complement our laboratory and field studies.

ORGANIC EMISSIONS FROM BUILDING MATERIALS

Because heating or cooling outdoor air as it enters an office building consumes a significant amount of energy, recent office construction practices have minimized the use of outdoor air for ventilation. These practices, along with the increased use of synthetic building materials and furnishings, have resulted in a large number of nonspecific health complaints by office workers that may be related to poor indoor air quality. The underlying causes of these complaints are unknown. Few studies of organic contaminants in indoor air in non-industrial buildings have been made; however, fragmentary evidence suggests that such contaminants can be major contributors to poor indoor air quality.[6,7] In the industrial indoor environment, elevated levels of organic contaminants have been shown to induce a variety of toxic, carcinogenic, and teratogenic effects. The possibility that chronic exposure to these same compounds may occur in non-industrial environments makes it imperative that these contaminants be identified and their levels and sources characterized.

Identification of contaminants will require studies of both organic emissions from building materials and organic concentrations in the air of office buildings. Only then can research begin into the health effects on occupants. These studies will also provide the range of organic concentrations that should be addressed and may also suggest which compounds are often associated with each other. The latter information will indicate whether synergistic effects should be examined. Finally, field studies of organic contaminants in office buildings under different conditions of ventilation, temperature, and humidity combined with similar studies of organic emissions from building materials will provide a data base for architects and builders so that materials with low potential for emissions can be used in new, energy-conserving buildings.

Accomplishments During FY 1983

Since the resumption of research in this project area, we have constructed and successfully used a system for the vacuum extraction of volatile organic compounds (VOC) from building materials. Depending on the material screened, there are two variations of the procedure. In the case of construc-

tion and interior finish materials, a sample of about 9 g is introduced into the vacuum system; in the case of adhesives, preweighed plates are coated with approximately 1 g of the material and dried for 9–14 days before introduction into the vacuum system. After cryogenic trapping, the VOC are taken up in solvent and injected into a gas chromatograph–mass spectrometer (GC-MS) for analysis. Compounds are identified by comparing unknown spectra with spectra contained in the EPA/NIH Mass Spectral Data Base.[8] This system allows quick screening of building material samples to determine which contain significant quantities of VOC of interest and thereby warrant further study. In addition, it has provided the basis for designing a more sophisticated system that includes temperature- and humidity-controlled flow of clean air and solid sorbent trapping.

Organic compounds emitted by 15 building construction and interior finish materials and 15 adhesives with indoor applications were identified by vacuum extraction and GC-MS analysis. These included representative samples of structural and insulating materials; interior finish materials used for floor, wall, and ceiling treatments; and adhesives. A total of 68 major compounds with molecular weights ranging from 94 to 458 were identified in the vacuum extracts of construction and interior finish materials; the 13 most frequently occurring compounds are listed in Table 1. The lowest molecular weight compounds were phenol, alkyl benzenes, naphthalenes, and terpenes. The most frequently occurring compounds were plasticizers: dibutyl phthalate and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate. The number of VOC varied greatly among the materials; for example, a carpet pad emitted only one compound, while a synthetic textile wall covering emitted more than 60.

Eight of the 15 adhesives studied continued to emit significant amounts of VOC after 1 week of drying. The major compounds identified in the vacuum extracts of the solvent-based adhesives are toluene (the most abundant), styrene, and a variety of cyclic, branched, and normal alkanes. A more complete listing of VOC emitted by adhesives is found in Table 2. Surprisingly, a large variety of alkanes were present in the extracts of three of the water-based adhesives; two of these, both from the same manufacturer, emitted an almost identical, complex mixture of normal and branched alkanes and cyclohexanes. Two other adhesives, S-6 and W-3, emitted a different mixture of higher-molecular-weight normal and branched alkanes. The similarity of the emissions from S-6 and W-3 is unexpected because one is a solvent-based asphalt adhesive and the other is a water-based natural rubber adhesive, the intended applications are very different, and they are supplied by different manufacturers.

Table 1. Most frequently occurring major compounds emitted by 15 representative building construction and interior finish materials.

Frequency (no. of samples)	Compound
10	Dibutyl phtalate
9	Di-isobutyrate (2,2,4-trimethyl-1,3-pentanediol)
7	n-Pentadecane
7	Diethyl phthalate
7	n-Heptadecane
7	n-Octadecane
7	Pristane
4	Dimethyl phthalate
4	n-Tetradecane
3	Benzophenone
3	n-Hexadecane
3	n-Nonadecane
3	Phytane

Adhesives have been suspected of causing widespread health complaints in office buildings[9]; for this reason, and because of the large variety and amount of VOC emitted by eight of the adhesives studied, we measured the VOC emission rates of these eight. A gas chromatograph equipped with a flame ionization detector was used with a flow-through exposure system to quantify VOC emissions. Humidified (40% relative humidity at 25°C), high-purity compressed air at room temperature and low pressure was passed over the adhesive samples, and the VOC emitted were trapped with a two-stage adsorption tube. After drying 9–14 days, only five of the adhesives had detectable solvent emission rates (Table 2). Three solvent-based adhesives had toluene emission rates between 0.6 and 62 mg g^{-1} h^{-1}. The two water-based adhesives, W-1 and W-2, emitted the same complex mixture of normal and branched alkanes and cyclohexanes in the emission rate tests as they had in the vacuum extraction screening tests. Because of the complexity of the mixture, emission rates were not determined for individual compounds. Instead, rates for total

Table 2. Volatile organic compounds emitted by adhesives with indoor applications. Emission rates are given for toluene or total alkanes for selected adhesives.

Adhesive chemical base	Application	Volatile organic compounds	Weight of adhesive (10^{-2}g cm^{-2})	Drying time (days)	Emission rate (μg g^{-1} h^{-1})
Solvent-based					*Toluene*
Synthetic rubber S-1	Rigid plastic foams for walls, ceilings	toluene; styrene	6.70	9	0.59
Unspecified polymer S-2	Styrene, polyurethane, cork, celotex, carpet	low-molecular-weight alcohol?; toluene			
Synthetic polymer S-3	Plasticized rubber, vinyl carpet	toluene	0.93 0.83	13 13	62 48
Asphalt S-6	Roof shingles, masonry cracks	*n*-decane, *n*-undecane, C_{10}–C_{11} branched alkanes(9+ compounds), C_{10} cyclohexanes (4 compounds)			
Unspecified polymer S-7	Subfloor bonding	methyl cyclopentane; cyclohexane; toluene	4.32 6.50	11 11	2.4 2.6
Water-based					*Total alkanes*
Synthetic rubber W-1	Foam-backed indoor and outdoor carpet	*n*-octane, *n*-nonane, C_8–C_9 branched alkanes (7+ compounds), methyl cyclohexane, C_8–C_9 cyclohexanes (10+ compounds)	2.54 2.85	14 14	740 760
Synthetic rubber W-2	Foam-backed indoor and outdoor carpet	same as compounds W-1	3.36 3.82	14 14	610 780
Natural rubber W-3	Foam-, sponge-backed indoor and outdoor carpet	toluene; *n*-nonane, *n*-decane, *n*-undecane, C_{10}–C_{11} branched alkanes (9+ compounds), C_{10} cyclohexane			

alkanes were calculated (Table 2). These emission rates ranged between 610 and 780 mg g^{-1} h^{-1}.

To assess the potential impacts of adhesives on indoor air quality, the emission rates determined in this study were used in a single-equation, mass-balance model that assumed well-mixed air. The model results demonstrated that the two water-based adhesives could produce significant concentrations of VOC in a hypothetical office space. However, these model results must be used with caution, since in an

office space the adhesives would be overlaid with carpet, and the carpet would undoubtedly moderate the VOC emissions. Thus the model results may represent an upper bound on VOC concentration. A more complete description of these studies can be found in a recent report.[10]

To assess occupant exposure to indoor pollutants in commercial and institutional buildings, we have developed an audit strategy for air quality and ventilation system performance.[11] As a first step, potential sources of pollutants (including radon, formaldehyde, carbon monoxide, carbon dioxide, suspended particles, and, perhaps most important, VOC) are recorded by the audit team on the basis of visual inspections and discussions with building managers. Then air sampling sites are selected to characterize the effect of different air handling systems, occupant activities, interior layouts, and proximity to potential pollutant sources. Air is sampled only during times of normal building occupancy. Mechanical ventilation systems are evaluated to determine the amount of outside air being delivered to the occupants.

Aspects of this audit strategy were tested in a building evaluation performed as a joint project with Public Works Canada. Various pollutants, including VOC collected on Tenax-GC, a solid sorbent, were sampled. After spiking with an internal standard, VOC samples were thermally desorbed into a GC-MS, where individual compounds were identified and quantified. Other pollutants were measured using standard sampling and analytical techniques. Ventilation system performance was evaluated using tracer gas, smoke sticks, detailed mapping, and thermography. Recommendations for actions required to improve air quality by both source removal and improved ventilation system performance are being developed.

Planned Activities for FY 1984

Studies of solid sorbent trapping materials exposed to an array of VOC and to thermal desorption will be conducted to optimize sampling conditions, not only when measuring emissions from building materials but also when measuring VOC concentrations in office buildings under field conditions. We plan to continue our studies of adhesives, with emphasis on determining emissions under a range of temperatures, humidities, and air flows while the adhesives are under simulated use, gluing appropriate materials such as carpets and tiles. We will also initiate a study determining the methylene chloride concentrations produced through the use of commercial paint strippers. Concentrations of major solvents other than methylene chloride will also be measured. The first phase of this study will be conducted in a large, recently constructed environmental chamber. In the second phase, we will attempt to scale down the test procedure to allow its use in small environmental chambers. Simple modeling will be an integral part of this study. Finally, concurrent with the activities outlined above, we will begin field sampling for VOC in a variety of commercial office buildings.

CHARACTERIZING THE SOURCES OF RADON IN BUILDINGS

Radon-222, a naturally occurring radioisotope and the heaviest noble gas, is produced by the decay of radium-226, a ubiquitous trace element in earth and earth-based materials. Concentrations of radon are often higher indoors than outside—commonly by an order of magnitude—because the house, acting like a leaky container, retards the transport of radon from radium-bearing materials to that part of the atmosphere that is higher than the breathing zone. Indoor radon is of concern because uranium miners developed a high incidence of lung cancer, an incidence associated with their inhalation of the radioactive progeny of radon. On the basis of studies of these miners, it has been suggested that exposure of the general population to the estimated mean indoor radon concentration of 1 picocurie per liter (pCi L^{-1}) (37 Bq m^{-3}) could account for 1000 to 20,000 lung cancers per year in the United States.[1] Because indoor radon concentrations vary by three orders of magnitude or more, a small fraction of the public is exposed to very high levels of radon progeny indoors: some exposures may even exceed the limit currently permitted for underground miners. For some individuals, the lifetime risk of lung cancer from indoor exposure to radon progeny may thus be as high as 10%.

Although ventilation rates affect indoor radon concentrations, the dominant cause of the wide range of concentrations is variability in the rate of entry from the sources, primarily the soil and rock under and near buildings.[6–13] Building materials, unless they contain unusually high concentrations of radium, contribute much less than 1 pCi L^{-1} to the indoor concentration. In some cases, domestic water from wells, especially those drilled in granitic areas, can account for high transport rates of radon from soil and rock into the house. Usually, however, radon from soil enters via pressure-driven flow through penetrations in the building substructure.

Our research efforts are directed toward providing a basis for (1) systematic identification of geo-

graphic areas where high indoor radon levels are endemic and (2) the identification or development of cost-effective construction techniques and control measures for preventing or reducing excessive entry rates. During the past year, our work has focused on three projects, two on the entry of radon into residences, and one on the use of aerial radiometric data for determining the geographic distribution of radon source potential. We have also continued some work on measurement of indoor radon concentrations and ventilation rates in the existing housing stock.[14] Studies of the behavior of radon decay products are described in a following section, "Particles and Radon Progeny."

Accomplishments During FY 1983

Radon Transport into a Detached One-Story House with a Basement[15]

During a 5-month period from late winter through early summer 1982, radon concentration and ventilation rate, as well as meteorological and radon-source parameters, were monitored continuously in a house near Chicago (which was known to have a higher-than-average indoor radon concentration), using an automated instrumentation system based on one previously described.[16] The mean radon concentration and mean ventilation rate were 2.6 pCi L^{-1} (96 Bq m^{-3}) and 0.22 h^{-1}, respectively; however, they both varied over a wide range. Radon activity measured at the cover of the basement sump varied bimodally (perhaps due to variations in the water level in the peripheral drain-tile system), and corresponding changes in indoor concentration were observed: in the higher mode, which persisted for 22% of the time, the sump activity ranged between 300 and 700 pCi L^{-1} (11,000–26,000 Bq m^{-3}), and the mean indoor radon concentration was 6.5 pCi L^{-1} (240 Bq m^{-3}); in the lower mode, the sump activity was less than 10 pCi L^{-1} (370 Bq m^{-3}), and the mean indoor radon concentration was 1.5 pCi L^{-1} (56 Bq m^{-3}).

As shown in Fig. 7, the indoor radon concentration in either mode shows little dependence on ventilation rate. The points were obtained as follows: Three-hour averages corresponding to periods of high and low sump activity were sorted according to ventilation rate. The data were then grouped into bins of 19–21 measurements. For each bin, the geometric means (GM) of the radon concentration and of the air-exchange rate were plotted; for some bins, error bars indicate the geometric standard error of the radon concentration. Two models of radon entry, as represented by the curves in Fig. 7, were then fit to the data.

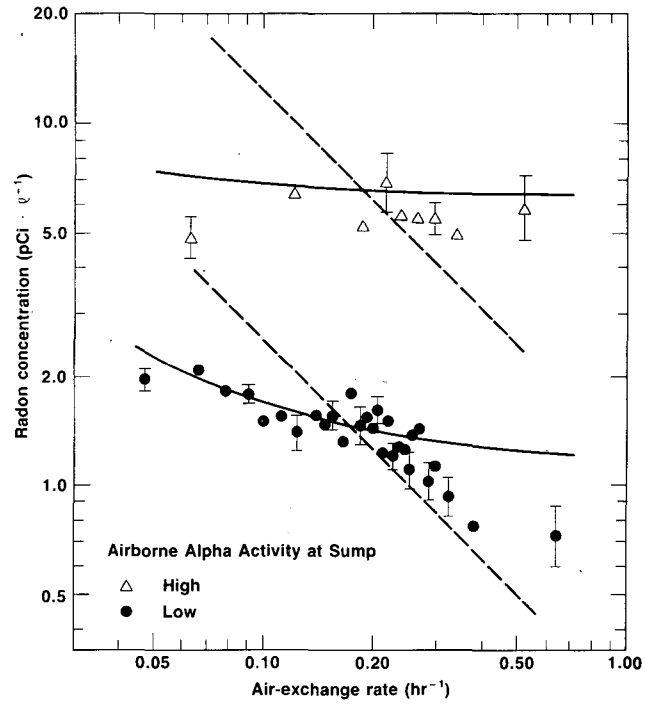

Figure 7. Scatter plot of radon concentration (in pCi/L) vs. air-exchange (ventilation) rate averaged over 3-hour periods. The triangles and circles represent periods of high and low airborne alpha activity at the sump, respectively. Each point reflects the geometric mean of 19–21 measurements, sorted according to ventilation rate. Error bars represent one geometric standard deviation of the mean; for clarity, only some are given. Dashed and solid lines reflect two models of radon entry, as discussed in the text. (XBL 836-2680)

In the first model (dashed lines), the radon entry rate is assumed to be independent of the ventilation rate so that the radon concentration and ventilation rate vary in inverse proportion. (The outdoor radon concentration, being much smaller, is ignored.) This model applies when radon entry is primarily via molecular diffusion or tap water. In the second model (solid lines), the entry rate has two components: a diffusive component that is independent of ventilation and a flow component that is proportional to the ventilation rate. The flow component models the entry of air from the soil; such air bears a high concentration of radon and is driven by the same mechanisms—temperature differences and wind—that cause infiltration. With the exception of a few points having high ventilation rates for periods of low sump activity, the second model fits the data far better than does the first.

For low sump activity, a least-squares fit to the 3-hour data determined that the flow and diffusive components were 1.15 pCi L^{-1} (43 Bq m^{-3}) and

0.06 pCi L^{-1} h^{-1} (2 Bq m^{-3} h^{-1}). For the high sump activity data, the diffusive component was assumed to be the same and the flow component was determined by a fit to be 6.3 pCi L^{-1} (230 Bq m^{-3}). On average, for low sump activity periods, the diffusive component accounts for only 20% of the radon entry rate, while for high sump activity periods, it accounts for only 3% of the total entry rate.

The diffusive component agrees well with the expected contributions from concrete and soil. To account for the flow component, a pressure difference of about 3.5 Pa must be able to drive a flow of 0.5 L/s through the soil and into the house. This appears possible if the soil permeability is relatively high. Alternatively, a comparable flow of air along the outside of the basement wall may sweep radon that has diffused through the soil into the house.

Radon Entry in Houses Having a Crawl Space[17]

Many single-family houses in the United States, particularly in areas with temperate climates, have a wooden floor over a vented crawl space. Radon, entering the crawl space from the soil, will pass either through the vents or through penetrations in the floor; in the latter case, it enters the living space. The fraction transmitted into the house depends not only on the size and location of vents and floor penetrations, but also on meteorological conditions: a large indoor-outdoor temperature difference will increase the convective flow of air into the living space through the floor, while high wind speeds will increase the cross-ventilation of the crawl space through the vents.

As part of a study investigating the transport of radon from soil into crawl spaces and its subsequent transmission into living spaces, detailed monitoring in two crawl-space houses was carried out in a manner similar to that in the basement house, except that ventilation rates were determined from an infiltration model rather than from tracer-gas decay measurements. The results from one house, located in Portland, Oregon, are displayed in Fig. 8. During the first 2 weeks of monitoring, the crawl-space vents were sealed with polyethylene sheets and tape. The average indoor radon concentration during this period was 2.2 pCi L^{-1} (81 Bq m^{-3}). This was significantly higher than the 1.2 pCi L^{-1} (44 Bq m^{-3}) average during the following 3 weeks when the vents were open, indicating that cross-ventilation of the crawl space is reduced when the vents are sealed.

Considerable evidence suggests that, for this house, radon transport from the soil into the crawl space does not result entirely from molecular diffusion, and that the presence of the house influences the spatial distribution of radon flux from the soil beneath it and nearby. Consider, for example, the results of March 29 and 30 (Fig. 8). Here, coincident with a day of heavy rainfall and a modest drop in barometric pressure, the radon concentrations in the living space and in the crawl space rise to the highest levels of the entire monitoring period; the radon entry rate is several times greater than can be accounted for by the diffusion of radon from the soil under the house. Apparently, the heavy rainfall reduces the permeability of the soil surrounding the house, so that the flow of air carrying a high concentration of radon out of the soil in response to the drop in barometric pressure or to the gravity-drawn flow of rainwater through the soil is focused into the crawl space.

In another house, a tracer gas was used to study air-flow rates from the crawl space into the living

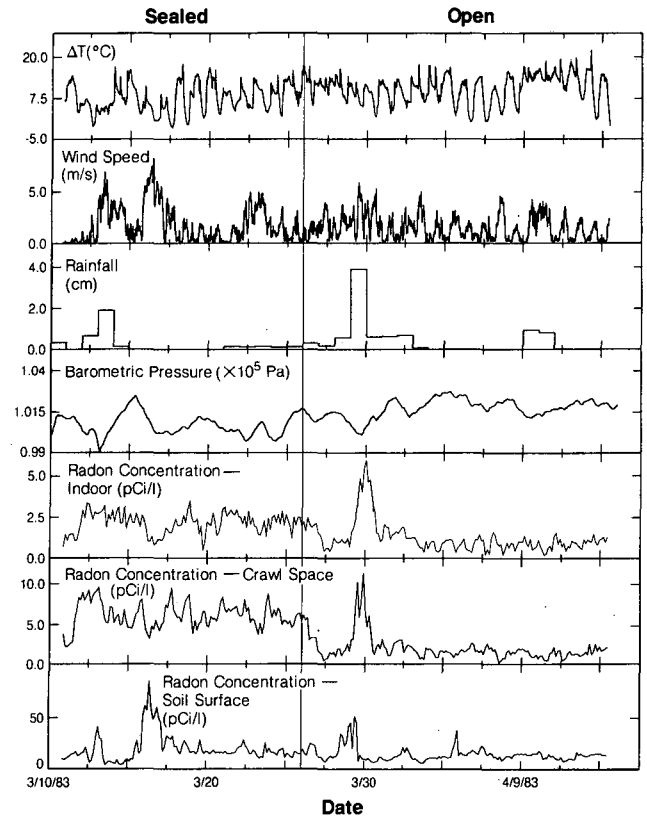

Figure 8. Measurements made over a 5-week period at a house in Portland, Oregon. Crawl-space vents were sealed during the first 2 weeks and open during the final 3. A positive temperature difference indicates the temperature is higher indoors than outside. Radon concentration at the soil surface was measured by sampling air from an accumulator that covered 0.95 m^2 of soil at a rate of 15 cm^3 s^{-1}. (XBL 837-457)

space. Over a range of vent and floor-leakage areas, 30% to 65% of the tracer gas released in the crawl space appeared in the living space. (The mean wind speed and indoor-outdoor temperature difference were 2.3 m s^{-1} and 9.1°C, respectively.) A two-person-day "house-doctoring" effort against floor leakage led to a 15% reduction in the leakage area of the entire house, but no increase in the indoor concentration of the tracer gas was subsequently observed. Thus, contrary to the common idea that lower ventilation rates lead to higher indoor pollutant concentrations, weatherization measures directed at tightening the floor may reduce infiltration in houses with crawl spaces without increasing indoor radon concentrations.

Radon Source Assessment Based on Aerial Radiometric Data[18]

From 1974 to 1981, the U.S. Department of Energy funded the National Uranium Resource Evaluation Program to improve estimates of potential uranium resources and uranium reserves. A major part of the program was the aerial measurement of gamma radiation from the earth's surface. One of the three radioisotopes measured directly in this manner was bismuth-214, a decay product of radium-226, the progenitor of radon. By itself, the radium content of the soil is not sufficient to determine radon entry rates, but it can, in principle, be used to locate some areas with high potential for elevated radon entry. In addition, by combining data on radium content with information relating to transport properties of air in soil, it may be possible to characterize, on a geographic basis, the potential entry rate of radon from the soil into buildings.

During the past year, the aerial data for the Pacific Northwest (Washington, Oregon, Idaho, and parts of Montana, Nevada, and Utah) and for California have been studied. Equivalent uranium (or radium) concentrations in soil have been characterized by calculating the mean and standard deviation for each of 92 quadrangles. Each quadrangle is delineated by one degree of latitude (approximately 72 miles north to south) and two degrees of longitude (120–140 miles east to west). Figure 9 shows the spatial distribution of these mean equivalent uranium concentrations. Generally, for the Pacific Northwest, radium concentrations in near-surface soil increase from west to east. In California, the San Francisco Bay Area and regions to the south appear to have higher radium concentrations than regions to the north of the Bay Area.

In two areas near Spokane, Washington, for which the aerial data exhibited great spatial variability, field measurements were also performed. Along one flight-line segment of 1.5 km, measurements at 20 sites were made of bismuth-214 gamma activity, radon flux from the soil surface, and emanating and total radium-226 content in the soil. Good agreement was seen between the aerial and ground-based determinations of bismuth, with somewhat greater spatial variation observed on the ground because measurements there integrate over a much smaller area of soil. The other parameters varied in rough correspondence to the ground-based bismuth measurements.

Planned Activities for FY 1984

Our experimental investigations of radon entry into residences will be expanded with a study of a house having a high indoor radon concentration. In this case, the objectives are to account for the source materials and transport processes, and to test the effectiveness of inexpensive control measures. Examination of the aerial radiometric data will continue; the local variability, which affects the extent to which the data should be aggregated to identify geographic areas with high source potential, will be investigated in more detail. In addition, strategies for using the data set covering the entire United States will be examined.

A third research direction that supports these two major efforts is a study of soil characteristics: some effort will be devoted to developing and applying techniques for measuring radon production and transport properties in soil.

PARTICLES AND RADON PROGENY

Sources of particles in the indoor environment include combustion processes such as tobacco smoke, unvented gas ranges or heaters, kerosene heaters, and wood stoves and fireplaces. The health effects of inhaling such particles depend on the physical and chemical characteristics of the particles and on the regions of the lung where deposition occurs. Particles less than 3 microns in diameter are likely to be deposited in the lower lung—the tracheobronchial and pulmonary regions.[19] Inhalation of fine particles may also have long-term health effects because these particles transport adsorbed toxic materials such as benzo(a)pyrene or radon progeny.

Alpha decay of radon gas produces radioactive isotopes of polonium, bismuth, and lead. These decay products (progeny) can be deposited in the lung, where subsequent alpha decays can cause lung cancer. The decay products may be deposited as *unattached* atoms or small molecules, or they may be

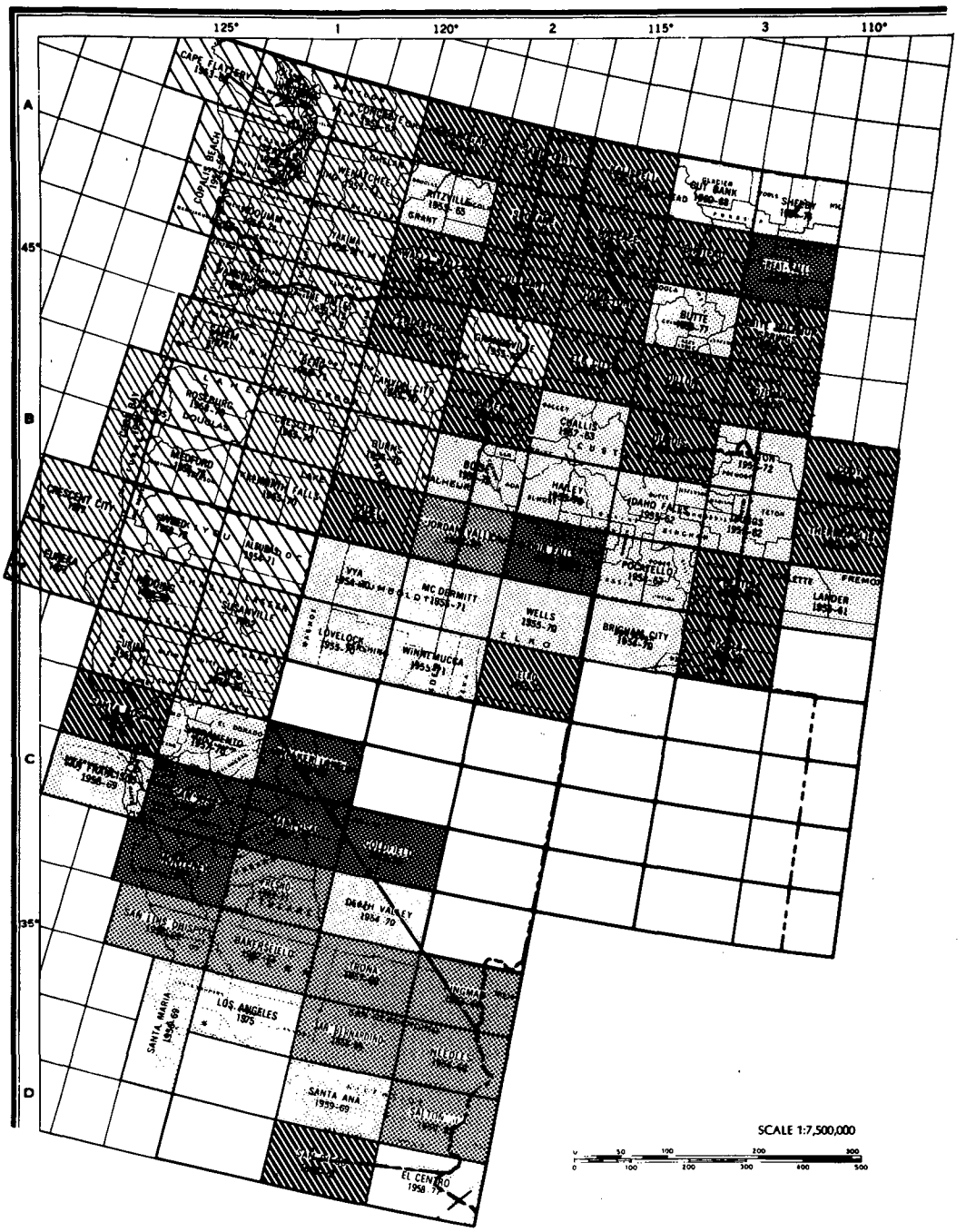

Figure 9. Mean near-surface radium-226 concentrations by quadrangle for the Pacific Northwest and California. The average for the entire region is 0.73 pCi g^{-1} (27 Bq kg^{-1}).

(XBL 841-9469C)

deposited *attached* to airborne particles. Estimates of the health effects of the decay products indicate that the alpha decay of unattached progeny produces a larger lung dose than does the decay of attached progeny.[20]

Our present research efforts have several objectives:

(1) to characterize the particle size and concentration profiles of aerosols from typical indoor sources;

(2) to study the interactions among particles and other chemical species, in this case, radon decay progeny;

(3) to investigate particle removal processes and the concomitant effects on radon progeny concentrations; and

(4) to develop an empirically based model for the behavior of radon progeny.

Accomplishments During FY 1983

Control of Particles and Radon Progeny[21,22]

There is growing interest in air cleaning for removal of airborne particles. Air cleaning devices, such as filters, electrostatic precipitators, or negative-ion generators, are available as stand-alone units or as part of a forced-air (ducted) furnace system. Experiments using both ducted and unducted control devices were performed at the Indoor Air Quality Research House to evaluate the effectiveness of different types and models of air cleaners and to investigate the effect of particle removal on the behavior of radon progeny. Results using the unducted devices are reported here.

The instrumentation employed in these experiments comprises a highly automated data acquisition, monitoring, and control system installed in the Research House. This system provides real-time data on particle sizes and concentrations and on radon and radon progeny concentrations, and allows programmable control over operation of the experiment. A more detailed description is provided below in the "Instrumentation" section.

Particles were generated by a cigarette-smoking machine. A typical 6-minute smoking cycle burned ~600 mg of tobacco and produced a peak concentration of up to 2×10^5 particles/cc. Radon was injected by passing air through a volume containing 200 μCi of ^{226}Ra stearate, resulting in initial radon concentrations of 150 to 400 pCi/liter. After the initial injection of pollutants, a 4-hour mixing and decay period established radioactive equilibrium among the radon and radon progeny and a constant decay rate for the particles. The control device was then turned on, usually for 3 to 5 hours.

Control device performance was measured by the difference in the rate of decay of particle concentrations (both total and by size fraction), with and without the control device operating. This net decay rate, multiplied by the volume of the test space, yielded an Effective Cleaning Rate (ECR). Dividing the ECR by the measured volume flow rate through the air cleaner provides a measure of overall system efficiency in removing particles. The results of these experiments are summarized in Fig. 10. As can be seen, the most effective devices were the extended surface filters and the electrostatic precipitators. Least effective were the panel filters and one of the negative-ion generators. A second negative-ion generator that operated at a higher voltage was moderately effective. In addition, two oscillating fans were operated as a test of the effect of rapid air circulation; no measurable reduction in particle concentrations was observed.

The effects of particle removal on radon progeny concentrations were determined by measurements of the concentrations before and at the end of device operation, when radioactive equilibrium was established. The particle concentrations and equilibrium factor, F, are tabulated in Table 3 for each pair of before-and-after measurements. F is the ratio of the potential alpha energy concentration (multiplied by 100) to the radon concentration. The table also lists the total removal rate Λ, measured for the first progeny, ^{218}Po. This rate consists of all removal

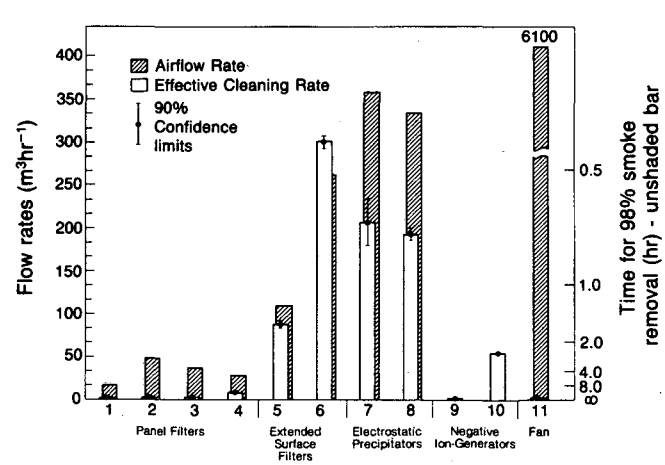

Figure 10. Performance measurements of unducted particle control devices. Measured air-flow rates through the device are shown by shaded bars, while unshaded bars give the effective air cleaning rate in cubic feet per minute (cfm). Superposition of the bars gives an indication of overall device efficiency. (XBL 8310-3343A)

Table 3. Effect of air cleaner operation on radon progeny equilibrium factors.

Air cleaner	Before operation		After operation		
	Particle concentration[a]	F[b]	Particle concentration[a]	F[b]	Λ_1[c]
Panel filters					
1	32,000	0.83	18,000	0.83	2.1
2	31,000	0.92	8,100	0.77	3.1
3	38,000	0.87	7,800	0.65	3.8
4	31,000	0.88	13,000	0.76	3.1
Extended surface filters					
5	28,000	0.81	120	0.068	25.
6	60,000	0.92	17	0.066	23.
Electrostatic precipitators					
7	30,000	0.86	<500	0.07	23.
8	24,000	0.82	230	0.076	20.
Negative-ion generator					
10	31,000	0.88	60	0.103	14.4
Fan					
11	33,000	0.81	15,000	0.58	6.1

[a]Concentration in particles/cm^3

[b]Ratio of potential alpha energy concentration ($\times 100$) to radon concentration.

[c]Total removal rate for ^{218}Po, the first progeny.

mechanisms, including deposition of radon progeny on walls or other room surfaces. Based on these total removal rates, the deposition rates for unattached and attached ^{218}Po can be estimated as a function of particle concentration. Similar estimates for the succeeding radon progeny, ^{214}Pb and ^{214}Bi, can also be made, and the results are illustrated in Fig. 11. At typical indoor particle concentrations (5000 to 10,000 particles/cm^3) progeny deposition rates range from 1 to 6 hr^{-1}; as particle concentrations decrease, the deposition rates increase rapidly, approaching 15 hr^{-1}. Thus, while operation of an air cleaner can remove radon progeny by direct filtration, a more substantial effect is produced by reducing the particle concentration so that deposition of progeny on surfaces is the predominant removal mechanism.

Instrumentation

Instrumentation for the measurement of particle concentrations and size distributions has been installed at the Indoor Air Quality Research House. Total aerosol concentration is measured with a condensation nucleus counter (CNC). The CNC also samples the output concentration of an electrostatic classifier (EC), which provides particle size and concentration data for particles between 0.01 and 0.3 μm in diameter. Information on larger particles is provided by an optical particle counter (OPC), which has been adapted to measure the size and concentration of particles between 0.1 and 3 μm diameter.

Instrumentation control and data logging are done by a microcomputer system designed and assembled at LBL. This computer also controls the

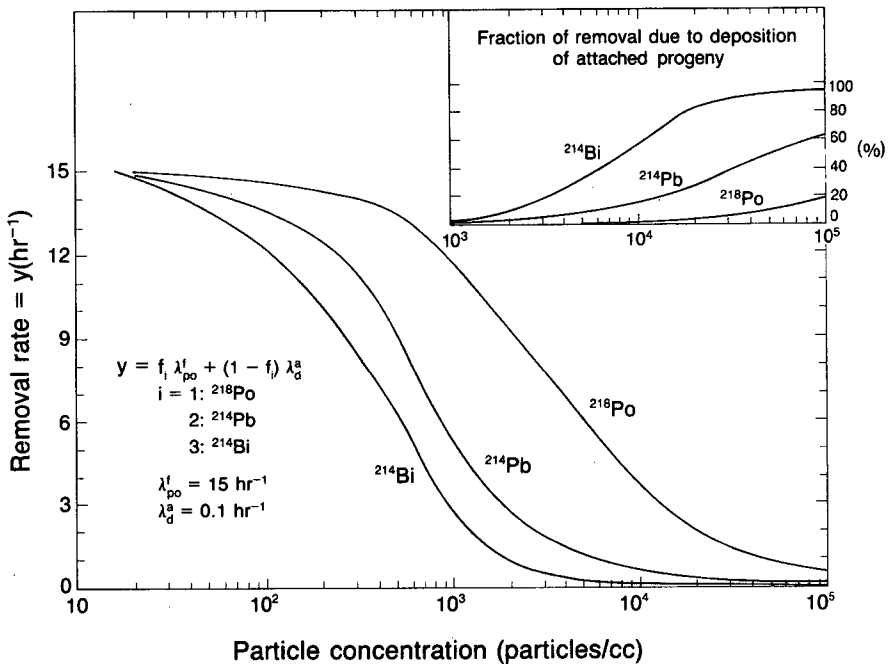

Figure 11. Removal of radon decay products due to plateout of unattached progeny and deposition of progeny attached to the environmental aerosol, as a function of particle concentration. Inset shows the fraction of removal rate due to deposition only. At particle concentrations below 1000 particles/cc, plateout of unattached progeny is dominant.

(XBL 8312-6708A)

sampling protocol and the timing for each sampling point. Data from the CNC and EC are stored in the computer, then written on a cartridge tape at the end of the sampling sequence. Data from an internal buffer in the OPC are written directly to tape after each sampling sequence.

An automated instrument for measuring indoor concentrations of radon progeny has been designed and built at LBL.[23] This instrument—the radon daughter carousel (RDC)—is microprocessor-controlled, using a filter sampler and a solid-state alpha particle detector to collect radon progeny and to subsequently analyze their alpha decays. Alpha spectroscopic data are stored internally, then transmitted at the end of each measurement sequence to the research house computer for storage on magnetic tape. Following data transmission, progeny collection on a new filter surface begins (total sampling time is typically 5 minutes). Total measurement times can be selected to optimize the operation of the device to the required precision. Concentrations as low as 0.5 pCi/L can be measured for individual progeny with a measurement time of 45 minutes.

A device to measure concentrations of unattached progeny has been constructed, using a 100- to 250-mesh wire screen backed by a filter sampler. Alpha decays from progeny collected on the screen and the backup filter are analyzed using a scintillator and photomultiplier package fabricated at LBL. This sampler is currently being checked out and will be used in future experiments on radon progeny behavior.

Modeling[24]

In order to examine the effects of air motion on the behavior of radon decay products in the indoor environment, a numerical model has been developed to simulate the generation, convective and diffusive transport, and removal mechanisms of radon and radon progeny. A number of basic flow configurations have been investigated, including flow over a flat plate, stagnation flow, and free convective flow on a vertical surface. The model is currently being used to examine the mechanisms by which radon progeny, both attached and unattached, are deposited on surfaces.

Planned Activities for FY 1984

Further evaluation of particle control and the resulting effect on radon progeny concentrations will

be performed. Of particular interest are measurements of unattached progeny as a function of particle concentration. Also of interest is the direct measurement of radon progeny plateout. Detailed characterization of particle concentrations and size distributions from a variety of combustion sources are also planned, with the possibility of using these results for indoor source apportionment.

Additional development of a model for progeny behavior will be undertaken, to include turbulent flow conditions. Since the model provides a theoretical framework for considering the general behavior and interactions of indoor pollutants, its extension to other indoor pollutants will be initiated.

PASSIVE SAMPLERS

Field studies of indoor air quality and the effects of reduced ventilation have been limited by the high cost of employing continuous monitors. Passive samplers capable of measuring daily or weekly integrated contaminant concentrations on site, without external power, accessories such as pumps and chart recorders, or the attendance of trained technicians offer a promising solution. Large-scale audits could be conducted with these samplers to insure that energy-conservation programs are implemented without an adverse effect upon occupant health and safety. In addition, passive samplers would make possible large-scale studies of the indoor air quality of existing buildings and facilitate epidemiological studies, which have typically had to rely upon exposures derived from distant, fixed-site monitors. With lightweight, inexpensive, and unobtrusive passive samplers, personal monitoring would be possible and a major uncertainty in epidemiological studies would be removed. The development and validation of passive samplers to meet these needs is the focus of this project.

Accomplishments During FY 1983

Nitrogen Dioxide Passive Sampler

The nitrogen dioxide (NO_2) passive sampler,[25] which was developed for industrial hygiene applications, is the most widely used sampler in studies of indoor air quality. Yet even this sampler has been used under conditions for which it has been inadequately tested. Because diffusion theory predicts only a 1.7% change in the sampling rate with a 10°C change in temperature at 21°C, temperature corrections have generally been ignored. However, the NO_2 absorbent employed in the sampler, triethanolamine, has a liquid-solid phase transition at 21°C.[26] Because this phase change occurs at a typical ambient temperature, the effect of temperature upon the performance of the sampler was investigated.[27]

In this study, the NO_2 concentration, exposure time, and face velocity were held constant while the temperature of the sampled air was varied from 7°C to 38°C. The collection efficiency of the sampler was found to decrease by 15% with a temperature decrease from 27°C to 15°C.

During this study, it became evident that face velocity effects produced by the low flow conditions in our exposure system could also be significant. Therefore, we conducted a preliminary study on the effect of low face velocity on the NO_2 passive sampler. The results supported a previously published theoretical treatment of sampler starvation.[28] After a correction for sampler starvation caused by low face velocity was applied, we obtained the temperature dependence for the NO_2 passive sampler illustrated in Fig. 12.

Carbon Monoxide Passive Sampler

We have continued the laboratory development of a carbon monoxide (CO) passive sampler based on a diffusion tube and a class of compounds sensitive to CO. These compounds, all containing palladium, are reduced upon exposure to CO, producing metallic palladium. The analytical technique employed is based upon detecting the amount of palladium present after exposure. Because the palladium compounds require water vapor as a reactant or catalyst, a major difficulty to overcome was the stabilization of the samplers' response to CO atmospheres over a wide range of humidities. Figure 13

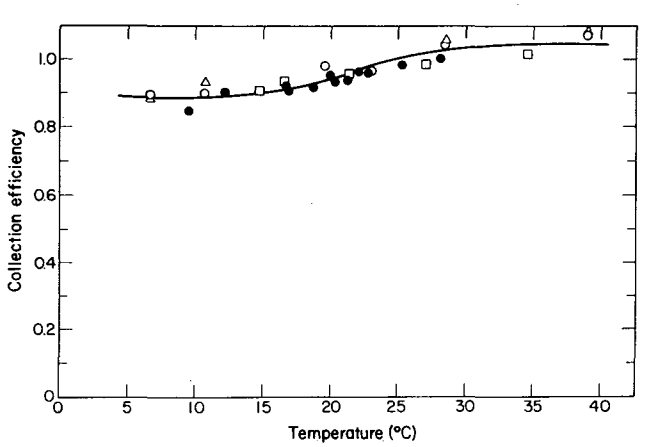

Figure 12. Collection efficiencies of the Palmes NO_2 passive sampler vs. temperature after correction for face velocity effects. Efficiencies are also corrected for the theoretical temperature dependence (see text). Symbols correspond to different sampler lots. (XBL 834-1570)

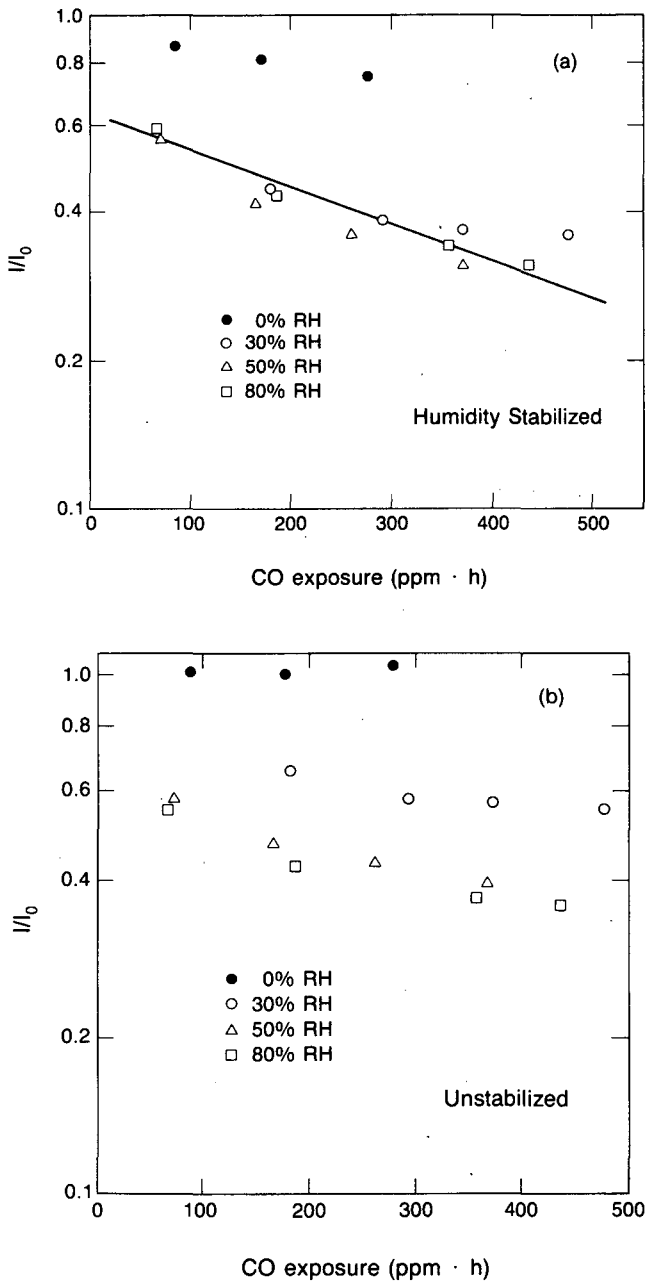

Figure 13. Comparison of the responses of carbon monoxide passive samplers (a) with and (b) without humidity stabilization; test atmospheres were at indicated relative humidities (RH) and near 5 ppm carbon monoxide.
[(a) XBL 8312-7402A; (b) XBL 8312-7401A]

depicts representative results for samplers with and without this stabilization. The samplers in both cases were exposed to controlled atmospheres near 5 ppm of CO for different lengths of time. Four lots of samplers were exposed to atmospheres differing only in relative humidity. The response of the stabilized samplers is uniform for all atmospheres with relative humidities of 30% or greater. While linearity within a lot of stabilized samplers is good, variation with respect to lot is evident and must be improved.

Water Vapor Passive Sampler

We have improved the design and performance and nearly completed the field validation of a water vapor passive sampler first described by Palmes.[25] This sampler uses molecular sieve contained in the closed end of a diffusion tube to trap water vapor. After exposure, the weight gain of the sampler and the duration of sampling can be related to the time-weighted average humidity of the sampled atmosphere. The sampler is shown schematically in Fig. 14. Improvements include the addition of cloth backing to prevent leakage of molecular sieve during handling and sampling and the substitution of aluminum diffusion tubes for the acrylic tubes initially used. (Acrylic tubes adsorbed water nonreproducibly, so that stable blanks and adequate shelf life weren't obtained.) As illustrated in Fig. 15, which compares the results of 1- to 9-day exposures to relative humidities near 50% at room temperature with the theoretically expected results, linearity and accuracy are excellent. Average precision is better than 3%. Tests have demonstrated that sensitivity is adequate for sampling times as low as 1 day, yet capacity is still sufficient for over 7 days of sampling near 100% RH.

Planned Activities for FY 1984

The field validation of the water vapor passive sampler will be completed in the early part of the year, as will tests of pre- and post-exposure storage

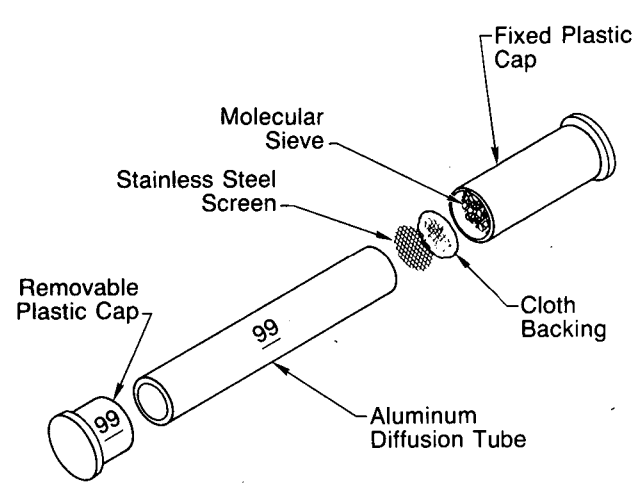

Figure 14. Exploded schematic of the water vapor passive sampler. Note that cap and tube are numbered to maintain a matched set. (XBL 8312-7408)

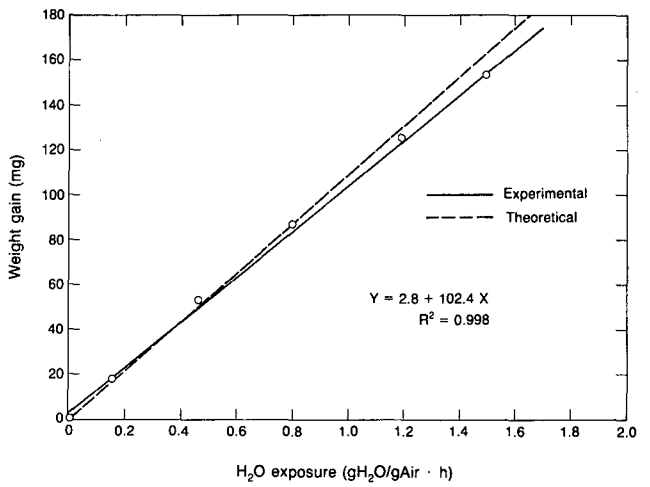

Figure 15. Comparison of experimental and theoretical weight gain of water vapor passive sampler after 1, 3, 5, 7, and 9 days of exposure to an atmosphere near 50% relative humidity. (XBL 8312-7400)

stability. We will begin the field validation of the carbon monoxide passive sampler, comparing its performance with that of a continuous analyzer in a variety of residential environments. The remaining laboratory tests of this sampler will also be completed with the goal of improving precision, sensitivity, and range.

A major uncertainty in the use of passive samplers is the air speed at the sampler face in various environments. While the air speed at which starvation occurs for a given sampler can be calculated from theory, no instrument at present can measure the low air speeds typical of non-industrial settings. To address this uncertainty, we will begin the development of a low-air-speed sampler to determine appropriate conditions for the deployment of passive samplers. Air speeds as determined by such a sampler would also be useful in validating models of pollutant transport.

INDOOR AIR QUALITY CONTROL TECHNIQUES

Control of the indoor concentrations of indoor-generated air pollutants can be accomplished by exclusion or suppression of pollutant sources, by air cleaning, and by ventilation. Residential mechanical ventilation with heat recovery in air-to-air heat exchangers has been the focus of a major effort by the Control Techniques Project. In earlier work, the energy performance, impact on indoor air quality, ventilation efficiency, and economics of this technique were investigated in laboratory and field studies and with computer models. During FY 1983, an experimental study of the freezing problem in residential air-to-air heat exchangers was completed. In addition, a method of removing formaldehyde from indoor air by absorption in water was tested, and the use of tracer gases to evaluate the performance of ventilation systems in removing pollutants was investigated.

Accomplishments During FY 1983

Freezing in Air-to-Air Heat Exchangers

An increasingly common and energy-efficient technique of ventilating residences is to mechanically supply and exhaust approximately equal amounts of air to and from the residence and to transfer heat between the incoming and outgoing airstreams in an air-to-air heat exchanger. Because of the transfer of heat, the incoming air is preheated or precooled before entering the residence. Thus, the energy loads imposed on the heating or cooling systems are less than for ventilation without heat recovery. Previous studies have shown that this technique of mechanical ventilation is most economically attractive in cold climates. However, when it is sufficiently cold outdoors, moisture in the exhaust airstream can freeze within the core of the heat exchanger, and the accumulated ice or frost can substantially reduce the flow rate of the exhaust airstream and the amount of heat recovery. A laboratory investigation[29] was therefore conducted with the following objectives: (1) to determine the environmental conditions (indoor and outdoor) that lead to freezing; (2) to determine the impact of freezing on heat exchanger performance; and (3) to evaluate a freeze protection strategy based on periodic defrosts.

Figure 16 shows some of the results of these experiments. The inlet temperature of the cold airstream, at which freezing was initiated in both a cross-flow and a counterflow sensible heat exchanger, is plotted versus the inlet relative humidity of the warm airstream. (A sensible heat exchanger transfers only heat between airstreams, while an enthalpy exchanger transfers both heat and moisture.) In our tests of the sensible heat exchangers and an enthalpy cross-flow exchanger (data for the latter are not shown), the temperature at the onset of freezing ranged from −3° to −12°C. The results for the counterflow exchanger are in fair agreement with our predictions based on a simple theoretical model and with observations of freezing in earlier field studies. Experimental studies with a sensible counterflow heat exchanger at the University of Missouri-Rolla[30]

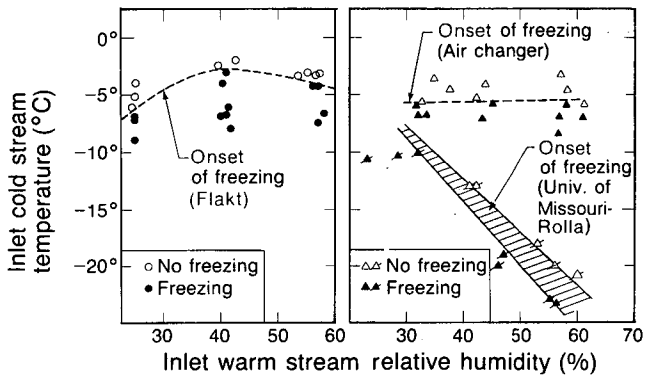

Figure 16. Results of tests to determine the onset of freezing for the cross-flow (Flakt) and counterflow (air changer) heat exchangers and previous results from tests of a counterflow heat exchanger at the University of Missouri at Rolla. (XBL 839-3294)

(Fig. 16) and data tabulated by the American Society of Heating, Refrigerating, and Air Conditioning Engineers,[31] however, indicate that freezing is initiated at significantly lower temperatures. We suspect that the major reasons for the discrepancies are differences between the heat exchangers used in the experiments and the different criteria used for the onset of freezing. For future studies, we have proposed new criteria for the onset of freezing that are based on a decrease in heat recovery performance.

The experimental studies of freezing included an evaluation of heat exchanger performance when periods with freezing were periodically interrupted by a defrost. The defrosts were accomplished by stopping the flow of cold air through the exchanger long enough to melt the accumulated ice or frost. The tests were conducted with two sensible exchangers (one cross-flow, the other counterflow), a variety of airstream humidities and temperatures, and a variable length of time between defrosts. Two parameters calculated from the data are based on the temperature efficiency E_T of the exchangers; this is a measure of the heat recovery performance and is defined by the equation:

$$E_T = (T_{s,o} - T_{s,i})/(T_{e,i} - T_{s,i}) \qquad (1)$$

Where T is an airstream temperature; subscripts s and e refer to the supply and exhaust airstreams, while subscripts i and o refer to flow into and out of the heat exchanger. In tests of a cross-flow exchanger, freezing caused the temperature efficiency to decrease at a rate from 1.5 to 13.2 percentage points per hour (Fig. 17). More rapid decreases in efficiency were associated with lower cold-airstream temperatures, higher warm-airstream humidities, and shorter periods of freezing. Temperature efficiency decreased at a slower rate (0.6 to 2.0%/h) in tests of a counterflow exchanger. It appeared that the performance of the counterflow exchanger decreased at a slower rate because the core contained larger air flow passages that are not easily obstructed by ice and because much of the water that condensed in the core drained to its warm end, where it did not freeze.

The "defrost time fraction"—the amount of time required to defrost these heat exchangers divided by the total operating time—ranged from 0.06 to 0.26 and did not differ greatly between the cross-flow and counterflow exchangers when corresponding tests were compared. This ratio was smaller after long periods of freezing, which indicates that the defrosting periods were used more efficiently after significant ice or frost had accumulated. The optimal amount of time between defrosts appeared to be in the range of 1 to 6 hours for the cross-flow exchanger and 6 to 13 hours for the counterflow exchanger. When the frequency of defrost was in the optimal range, the average temperature efficiency was approximately 62% for the cross-flow exchanger and 75% for the counterflow exchanger. It was estimated that the freezing and periodic defrosts reduced the time-averaged temperature efficiency of the cross-flow and counterflow exchangers by 15% and 10%, respectively, under nearly optimal operating conditions. Larger reductions in time-averaged performance are likely with currently available freeze protection systems. Heat exchanger designs that minimize the effects of freezing and improved controls for freeze-protection systems were recommended.

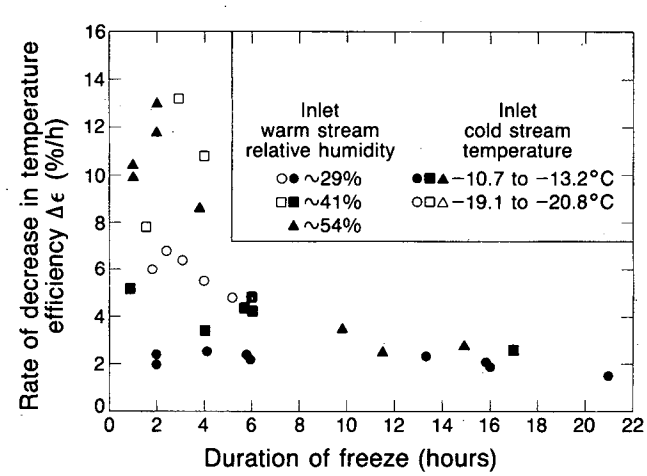

Figure 17. Rate of decrease in temperature efficiency of cross-flow (Flakt) heat exchanger versus duration of the freeze. (XBL 839-3288)

Air Washing for Formaldehyde Control

A potential control technique for indoor formaldehyde that had not been evaluated previously is removal by absorption in water; this is also referred to as air washing. Formaldehyde reacts rapidly with liquid water to form methylene glycol and polyoxymethylene glycol polymers; its effective solubility in water is therefore high. Air washing is accomplished by forcing air through an air-water contact system. To prevent saturation of the washing water with formaldehyde, a small amount of the water is continuously replaced with fresh water. Humidification of the air can be prevented by using a refrigeration system to cool the air or the water prior to the air-water contact. In some situations, the air washer can simultaneously remove formaldehyde and provide dehumidification. Energy consumed by the refrigeration system can be delivered to indoors, thus reducing the heating load, or can be rejected to outdoors, so that the air washer acts as an air conditioner.

Theoretical calculations indicated the feasibility of air washing for indoor formaldehyde control. Two air washers were therefore fabricated and tested in the laboratory under controlled conditions.[32] A semi-theoretical model of air washer performance was developed and used to correct experimental data from tests that were not conducted under steady-state conditions (i.e., when there was a net storage of formaldehyde within the water in the air washer). The model was also used to illustrate the relationship between various operational parameters and air washer performance.

Tests were first conducted with wetted porous mats as the air-water contact system. The mats were maintained wet by rotation with their lower ends suspended in the sump of the air washer. The measured formaldehyde removal efficiency (Table 4, tests 1–4 through 1–9) ranged from 38% to 49%. Small corrections to the measured efficiency were required to account for the storage of formaldehyde in the air washer. Another series of tests was conducted with a nonporous mass transfer medium used as the air-water contact system. This medium provided considerably more surface area for air-water contact. Water was continuously pumped from the sump to a distribution system above the medium. The measured formaldehyde removal efficiency of this system (Table 4, tests 2–1 through 2–7) ranged from 63% to 77%. For some tests, however, the corrected efficiency was substantially lower than the measured efficiency.

An overall measure of the formaldehyde removal performance of these air washers is the product of the actual air flow rate and the corrected efficiency (last column of Table 4). An air washer with an efficiency/flow-rate product equal to the largest value reported in Table 4 (74 L/s) would have approximately the same impact on indoor formaldehyde concentration as one air change per hour of ventilation (assuming an average house volume). Thus, the air washers removed formaldehyde at a significant rate, maintained their effectiveness with low inlet formaldehyde concentrations, and consumed a relatively small amount of water.

The air washer's refrigeration system, however, will require a significant amount of power. The requirement for a residential-sized unit with a 140 L/s flow rate was estimated to be 1500 to 1800 W. Also, the initial cost of the air washer would probably be fairly high, even if it is mass-produced. If the air washing process can be implemented without substantial increases in energy consumption, it may be an attractive formaldehyde control technique. Such situations may occur if the air washing process is integrated into an air conditioning system (such as that of a commercial building) or if most of the energy consumed provides usable heat.

Ventilation Efficiency Studies

A primary objective of ventilation is the control of indoor air pollutants. The performance of a ventilation system will depend on the patterns of air flow throughout the structure and on the location and emission characteristics (e.g., velocity and temperature) of pollutant sources. Air flow patterns will be a function of the locations of air supply and exhaust, the temperature and velocity of the supply airstream, and the various factors that affect indoor air movement.

Ventilation performance is often studied by using tracer gases. Either the air within the structure is labeled by injecting a tracer gas and mixing the air to obtain a uniform concentration or the incoming (supply) air is labeled. Measurements of tracer gas concentration versus time in the exhaust airstream and within the structure provide information on the distribution of the ventilation air and on the overall nature of air flow from supply to exhaust (i.e., the degree to which the flow pattern resembles short-circuiting of air or a displacement-type flow of air).

Recently, age distribution concepts have been applied in ventilation system studies. The age of a parcel of air is defined as the amount of time elapsed since the air entered the structure.[33] The average age of air within the ventilated space and the local age of air at various indoor locations can be calculated from the measured tracer gas data and compared to the ages that would result if the indoor air were per-

Table 4. Results from tests of air washers no. 1 and 2.

Test No.	Air flow rate (L/s)	Inlet HCHO conc. (ng/L)	Water repl. rate (L/h)	Water circ. rate (L/m)	HCHO removal efficiency		Product of efficiency × flow (L/s)
					Measured	Corrected	
1-4	119	116	7.6	-	0.42	0.41	49
1-5	119	106	4.5	-	0.40	0.40	48
1-6	118	218	7.4	-	0.42	0.42	50
1-7	119	222	5.7	-	0.49	0.47	56
1-8	120	250	4.1	-	0.38	0.36	43
1-9	157	360	4.1	-	0.38	0.36	56
2-1	117	269	2.3	57	0.77	0.63	74
2-2	117	252	2.3	23	0.68	0.56	66
2-3	160	85	1.7	38	0.65	0.46	74
2-4	116	80	1.4	38	0.70	0.51	59
2-5	116	161	2.3	38	0.72	0.60	70
2-6	116	102	0.7	38	0.74	0.35	41
2-7	116	136	0.5	38	0.63	0.30	35

fectly mixed. The resulting ventilation efficiencies (i.e., age with perfect mixing divided by measured age) are indicators of ventilation system performance. However, these ventilation efficiencies only provide information on the flow pattern of the ventilation air; they do not characterize the performance of the ventilation system in removing pollutants emitted from a nonuniform source.

Tracer gases can also be used to simulate indoor pollutant sources. The measured tracer concentrations can then be used to calculate the mean and local ages of the tracer within the ventilated space as well as the corresponding ventilation efficiencies. Only limited data are available from studies with concentrated pollutant (or tracer gas) sources. In addition, the usefulness and practicality of this method of characterizing ventilation system performance have not been determined. Two experimental studies were therefore conducted with tracer gases released in a manner to simulate the emission of pollutants.

The first study was conducted in a single chamber. The neutral-density tracer gases simulated pollutant emissions from either a single point or the surface of a wall. Three different mechanical ventilation systems were employed, and factors that have an impact on indoor air movement (e.g., operation of heating equipment within the chamber) were also varied between experiments. A total of 26 experiments were conducted. The data were analyzed to determine mean and local tracer ages, plus the corresponding ventilation efficiencies. This technique of data analysis did not yield satisfactory information on ventilation system performance, however, because of unstable patterns in tracer-gas transport. Therefore, other techniques of analyzing

the data are being considered.

In the second study,[34] the effectiveness of a range hood and a window fan in removing pollutants emitted from a point source was considered. Experiments were conducted in a two-room test space. The range-hood experiments were carried out with both a heated and unheated tracer gas introduced at the location of the burner. The air flow rate through the range hood (a commercially available model) was varied from 37 to 216 m^3/hr. With a heated tracer gas, the ventilation efficiency of the hood increased linearly with flow rate from 16% to 77%. (The ventilation efficiency was defined as $(C_o - C_m)/C_o$, where C_o is the concentration that would result in the test space if the indoor air had been perfectly mixed and C_m is the measured average tracer concentration in the test space.) With an unheated tracer gas, the ventilation efficiency depended highly on environmental conditions.

Window fan experiments were conducted with the fan's location fixed and the source of tracer gas in each of the two rooms. When the source and fan were in different rooms, the measured data agreed fairly well with predictions from a two-zone model in which mixing factors ranged from unity to 17.5. When the source and fan were in the same room, however, agreement with the model was poor. A measure of ventilation efficiency was the ratio of the steady-state concentration in the exhaust duct to that in the room with the fan. This ratio reached approximately four, with a flow rate of 163 m^3/hr.

Planned Activities for FY 1984

An experimental study will be conducted to determine the rates of formaldehyde transfer between airstreams of enthalpy-type air-to-air heat exchangers. These enthalpy exchangers are frequently employed in U.S. residences when ventilation with heat recovery is desired. A modest effort will also be devoted to identifying an air washing process for formaldehyde that does not require a refrigeration system. A significant effort will be devoted toward the development and validation of a practical tracer-gas-based system for studying the performance of ventilation systems in large buildings. Finally, work will begin on a computer model of residential exhaust ventilation with heat recovery.

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Lighting Systems Research*

S.M. Berman, R.R. Verderber, R.D. Clear, O.C. Morse, F.M. Rubinstein, and R.K. Sun

We estimate that approximately 50% of the electrical energy consumed by lighting, or about 12% of total national electrical energy sales, could be saved by a gradual replacement of existing lighting with energy-efficient lighting. This would amount to an annual savings of some 220 billion kilowatt-hours of electricity.

The National Lighting Program is managed by the Lawrence Berkeley Laboratory (LBL) for the U.S. Department of Energy. Its objective is to work in concert with the lighting community (manufacturers, designers, and users) to achieve a more efficient lighting economy. The program at LBL exemplifies a new kind of partnership between a national laboratory/university complex and the lighting community, accelerating both technical advances and industry implementation.

As the Lighting Program grew, it was divided into three sections: a Technical Program to study the fundamental properties of light sources, and the engineering science involved, in order to improve their efficacies; a Building Applications Program to study advanced, energy-efficient lighting designs and their relationship to overall building energy performance; and an Impacts Program to study the effects of energy-efficient lighting systems on visibility, and on the performance and health of those who work with them. The engineering science component undertakes research and development projects in lamp technology that are both long range and high risk—projects in which the lighting industry has an interest but is unable to 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 Program is concerned with developing a full technical understanding of the electromagnetic compatibility of high-frequency lighting in relation to the internal functions of a building, including machinery, computers, and other electrical and electronic systems. The Impacts component examines relationships between occupants and the physical lighting environment to assure that new energy-efficient technologies relate positively to human productivity and health.

Since its inception in 1976, the LBL Lighting Program has produced more than 75 reports and publications. These reports are all 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. The results are directed toward enhancing the capabilities and long-term viability of the lighting industry and providing the design profession and the general public with needed information; as such, the program is unique in the United States.

Described below are the highlights of the accomplishments realized in FY 1983 by our three major efforts—the technical, building applications, and impacts programs—and activities planned for 1984. Publications and conference presentations of the past year are also listed.[1-8]

TECHNICAL PROGRAM

Energy-Efficient Light Bulbs (EELBs)

Accomplishments During FY 1983

Six types of energy-efficient light bulbs that could replace incandescent bulbs were assessed. Three of the lamps were developed by LBL under subcontract to the Department of Energy (DOE), and the other three were submitted to LBL by their developers. Table 1 shows the results of the measurements, comparing important parameters for these lamps with those for a standard 75-watt incandescent lamp. The table also includes the targeted performance goals for EELBs for incandescent and gas-discharge lamps; these goals were developed by the LBL staff and an industrial advisory group. The first three lamps listed in the table were developed within the LBL program. The efficacies of the EELBs are all two to four times as great as those of the incandescent lamp. Although the retail cost of EELBs is 7

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Table 1. Technical and economic characteristics of energy-efficient replacements for incandescent lamps.

CHARACTERISTIC	Incandescent (75-watt)	LONG-TERM GOALS: ENERGY-EFFICIENT LAMPS: Filament	LONG-TERM GOALS: ENERGY-EFFICIENT LAMPS: Gas-Discharge	INITIAL PERFORMANCE: Coated Filament	INITIAL PERFORMANCE: Electrodeless Fluorescent	INITIAL PERFORMANCE: COMPACT FLUORESCENT: High Light	INITIAL PERFORMANCE: COMPACT FLUORESCENT: Medium Light	INITIAL PERFORMANCE: COMPACT FLUORESCENT: Low Light	INITIAL PERFORMANCE: High-Intensity Discharge
Input Voltage (volts)	0-120	0-120	120	0-120	120	120	120	120	120
Frequency (hertz)	60	60	60	60	60	60	60	60	60
Power Factor (%)	100	100	50	71.1	59±0.5	75±1	62±0.3	61±0.2	59±0.6
Initial Light (lumens—lm)	1210	1000-2200	1000-2200	1550±68	1665±110	1700±60	1020±10	490±70	2410±160
Power (watts—W)	75	---	---	54±1	32±1	34±0.5	18±0.2	16±0.5	51±2
System Efficacy (lm/W)	16	34	50	29±1	53±3	50±2	56±1	32±5	43±2
Burning Position	any	any	any	any	any	any	any	any	base down
Life (hr)	750	2500	10,000	2500*	10,000*	8000*	6500*	10,000*	6500*
Weight (oz)	1	6	16	4.1	9.6	22.7	7.4	5.9	4.5
Size (length × diameter)	4.5×2.38	5×2.5	7.5×4	5.1×3.3	7.2×3.1	9.7×3.4	7.2×2.8	8.3×2.4	5.7×2.5
Retail Cost ($)	0.70	5.00	15.00	5*	15*	17*	15*	10*	10*
Total Cost/10^6 lm-hr ($) @ $0.07/kWh	5.27	<5.27	<5.27	3.71*	2.23*	2.64*	3.52*	4.26*	2.27*
Number of Units Tested				9	10	10	6	5	19
Color Rendering Index	93	90	70	90±3	16±2	82±2	81±0.4	39±6	65±2
Color Temperature (°K)	2800	3000±200	3000±200	2940±50	4815±111	2620±70	2790±70	4507±240	3020±150

to 20 times as great as the cost of incandescents, the total cost of the light is less than one-half. Figure 1 shows another important attribute of these lamps, their long lifetimes. Some of these lamps have lives ten times as long as standard incandescents.

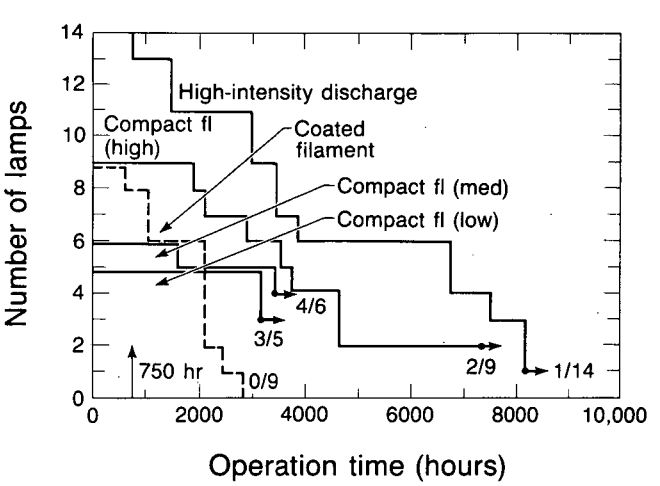

Figure 1. Lifetimes of energy-efficient replacements for the incandescent lamp. (XBL 839-3155)

Planned Activities for FY 1984

This program has largely accomplished its goals. The final life test data will be collected and the program phased out. Industry is now producing various forms of the compact fluorescent lamp with standard core-coil ballasts and solid-state ballasts.

Solid-State Ballasts

Accomplishments During FY 1983

Efficient solid-state ballasts that operate fluorescent lamps at high frequency have been developed. We have been investigating the influence of the ballasts' high-frequency operation on the lamps, including starting characteristics and the nature of the improvement in lamp efficacy. We have found that the peak voltage required to start an F-40 (40-watt) fluorescent lamp at high frequency is about half as great as with a standard ballast. We have confirmed that the improved efficacy of operating the lamp at high frequency is due to reducing the anode fall from 20 to 5 volts.

In this area of endeavor, we contracted with the U.S. Navy to reduce the power (energy) used for lighting on its ships. Several lamps and ballasts were submitted by industry; a system was selected that provided the same light output and reduced the wattage of each system by 7 to 8 watts, i.e., from 25 to 17 watts.

Planned Activities for FY 1984

One important question about solid-state ballasts remains unexamined—their ability to withstand voltage surges. We know that these ballasts are likely to fail during such surges unless suitably protected. The tests involved will be completed in FY 1984, at which point the formal LBL solid-state ballast program will be over.

The Navy contract will continue; LBL will assess the new system to verify its quality assurance. The Navy will then adopt this system as a retrofit by August 1984.

Electromagnetic Compatibility

Accomplishments During FY 1983

The new high-frequency lighting systems emit electromagnetic radiation (EMI) at their fundamental frequency (~20 kHz) and harmonics. The effects of this EMI on other electrical equipment (e.g., computers, medical instruments) are unknown. LBL is attempting to measure the EMI from lighting systems and to assess its impacts. Radiated and conducted electromagnetic energy was measured for several types of solid-state ballasts in our office environment, in an open field, and in a screen room (a facility that shields the units from stray external fields), in order to compare the values. Measurements of the near fields indicated little variation according to environment. The tests employed several field instruments to determine whether a simple, low-cost system for field measurements is commercially available. To calibrate the near-field antenna, an electromagnetic-field source for the 20-kHz region is being built and is near completion. LBL also replied to a Notice of Inquiry issued by the Federal Communications Commission regarding the need for federal regulations for EMI. Our recommendations were to permit industry to set up its own standards through the National Electrical Manufacturers Association.

Planned Activities for FY 1984

Measurements on single and multiple fixtures will be made to determine the distribution of the radiated fields. This will serve as the basis for developing a model to assess the intensities of the fields in a building and surrounding areas.

Fundamental Plasma Studies (Gas-Discharge Lamps)

Accomplishments During FY 1983

To increase the efficacy of the low-pressure gas discharge in fluorescent lamps, LBL continued efforts to reduce radiation entrapment in mercury vapor (Hg) lamps that emanate from the $6P^3{}_1$ level to the ground state (2537 Å).

Initial studies on reducing entrapment by applying a magnetic field, resulting in a splitting of the energy levels (Zeeman effect), were in agreement with the Berman-Richardson (B-R) model.[7] Figure 2 shows the increase in emitted ultraviolet resonant radiation (254 nm) as a function of applied field. A near 25% improvement is observed, as well as the maxima predicted by the B-R model.

The effect of using different isotopes of mercury has also been studied, with and without the Zeeman effect. Figure 3 compares the improved emittance of a ^{202}Hg isotope lamp and a natural Hg lamp as a function of lamp-wall (cold-spot) temperature. Notice that the peak emittance of the natural Hg lamp occurs at a higher cold-spot temperature.

Under subcontract, General Telephone and Electronics (GTE) has been working on the ^{196}Hg isotope photochemical process; 30-fold yields have been observed. Increasing ^{196}Hg concentrations to 5% has increased lamp efficacy 3% to 5%.

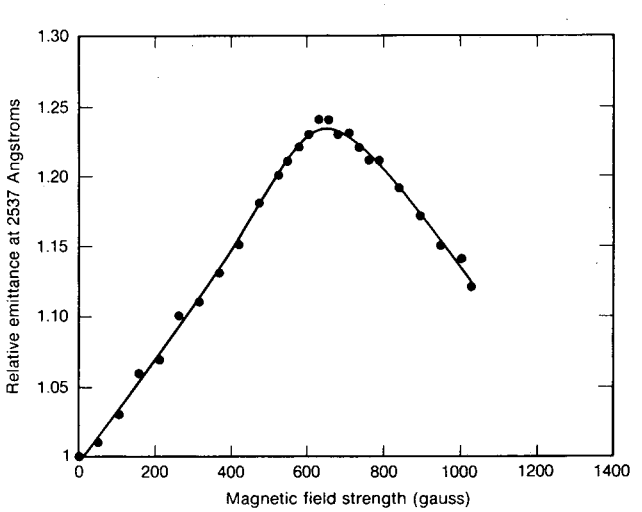

Figure 2. Change in the UV resonant radiation intensity of a low-pressure Hg plasma as a function of magnetic field. (XBL 8311-4543)

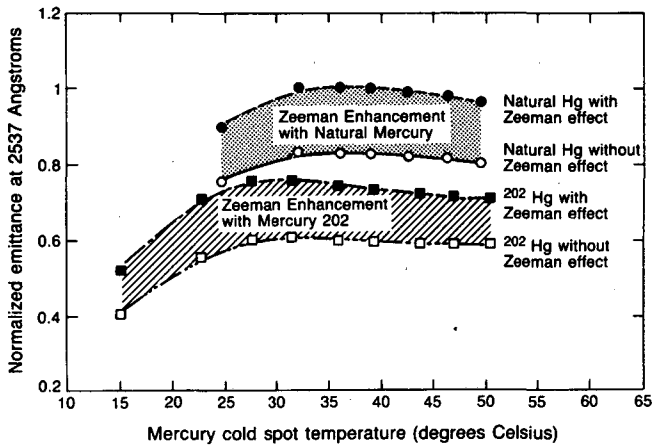

Figure 3. Relative resonance radiation production of natural mercury (Hg) and natural mercury enriched with ^{202}Hg isotope as augmented by the Zeeman effect.
(XBL 842-9411)

Planned Activities for FY 1984

Current work will continue, with a focus at LBL on improving the efficacy of the fluorescent lamp by adding the more abundant mercury isotopes to the natural mix. These isotopes will be easier to extract than ^{196}Hg. The commercial potential will therefore be greater if the more abundant isotopes can be used in place of ^{196}Hg.

A new initiative is the investigation of an electrodeless high-intensity discharge lamp that promises a 30% increase in efficacy for the lower-wattage lamps as well as improved color through the use of new gases.

The gigahertz lamp system, in which the plasma distribution is altered so that plasma density is increased toward the plasma-glass interface, is being studied. This arrangement should reduce the entrapment effect, yielding higher efficacies and permitting new lamp configurations to be employed, e.g., two concentric cylinders.

LBL will also initiate studies exploring the possibility of a two-photon phosphor. In existing phosphors, for every ultraviolet (UV) photon striking the phosphor, at most one visible photon is created. However, it is theoretically possible for the UV photon to create two visible photons. If such a phosphor can be found, lamp efficacy can be doubled. This effort will examine samarian-type ferrites. In addition, magnetic phosphors (ferrite systems) that can be used to create a suitable magnetic field within the plasma will be explored. Together, these programs are expected to develop a 200-lumen-per-watt fluorescent lamp and improve the present efficacy of small high-intensity discharge lamps by a factor of two.

BUILDING APPLICATIONS

Accomplishments During FY 1983

The CONTROLITE computer program, which predicts the economics and energy performance of lighting management systems and techniques, has been integrated into the QUICKLITE program. QUICKLITE inputs daylighting conditions and was selected for its simplicity. The combined program is in its final debugging stage.

A project to design futuristic energy-efficient lighting layouts and assess them for quantity and quality of illumination is under way. Eventually, a variety of design approaches will be compared to partial-task and task-ambient systems. The energy-efficient components have been selected, and laboratory tests will be conducted to determine the thermal performance of lighting appliances (luminaires). A standard Illuminating Engineering Society isothermal chamber has been designed for this study.

A photocell placement experiment—to discover, for example, the optimum position for sensing ambient light for daylighting—is being prepared. A scale-model space has been constructed and will be placed on the roof of LBL's Building 90, which houses offices of the Applied Science Division. The scale model is one-third size and is illuminated with F-40 lamps and a standard dimming system. Figure 4 shows the model with photocells placed at desk level to measure the distribution of illumination.

Planned Activities for FY 1984

We plan to complete the CONTROLITE program and to conduct a two-day workshop on its use in the summer of 1984. The goal of the seminar is to transfer this program to the private sector.

The advanced lighting design project will measure several types of luminaire systems and use the data to design lighting layouts. Each system will be assessed with regard to initial and operating costs, illumination levels, visual comfort probability, and equivalent-sphere illumination. We plan to complete the scale-model space for the photocell placement studies and initiate measurements.

A new initiative will be started, in concert with the National Bureau of Standards, to study the influence of lighting systems on the thermal performance of buildings.

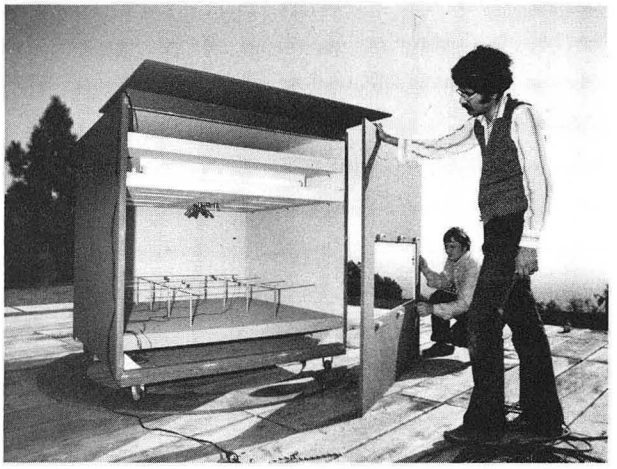

Figure 4. Scale model for measuring the effect of photocell placement on the performance of dimming systems. (The photocells control the dimmers by sensing available daylight.) The model is being installed on the roof of Building 90 at LBL. (CBB 8310-9419)

IMPACTS PROGRAM

Visibility and Performance

Accomplishments During FY 1983

Much of the existing visibility data base has been reviewed. These data are being examined to assess existing visibility models and to determine future experiments required to validate or improve the present models or to decide whether a new approach is needed.

Planned Activities for FY 1984

We plan to complete the review of existing visibility data and Reá's check-reading experiment, and to develop a series of visibility experiments.

Video Display/Fatigue

Accomplishments During FY 1983

We have been studying eye responses to video display terminals under various ambient lighting conditions. With the newly acquired pupillometer, pupil oscillation has been found to be influenced by the beat frequency (~1 Hz) resulting from the different frequencies of the refresher rate on the screen and the ambient fluorescent lamps. The stimulation of pupil oscillation has been suggested as a cause of eye fatigue.

Planned Activities for FY 1984

We will continue to explore all ramifications of the beat frequency. We will continue studying the effects of intensities of the screen, the effects of altering the ambient frequency, and modulation.

New studies will be initiated to examine the influence of the color of the display and ambient lighting on the subject's susceptibility to fatigue.

Health and Environment

Accomplishments During FY 1983

The chamber for testing subjects' physiological responses to lighting and lighting systems has been completed, and several modifications were made to control light intensities over a greater range. Sequences of tests have been run on two sets of subjects; heart rate and muscle responses were measured.

Figure 5 shows the change in the heartbeat of a subject over a period of 320 seconds after the ambient illumination was changed from a 100-W incandescent to a 1000-W cool-white fluorescent and a 50-W incandescent. There appears to be an initial response. The initial heart rate is less for the cool-white fluorescent lamp than for the incandescent lamps, but appears to slightly exceed the incandescent at 240 seconds.

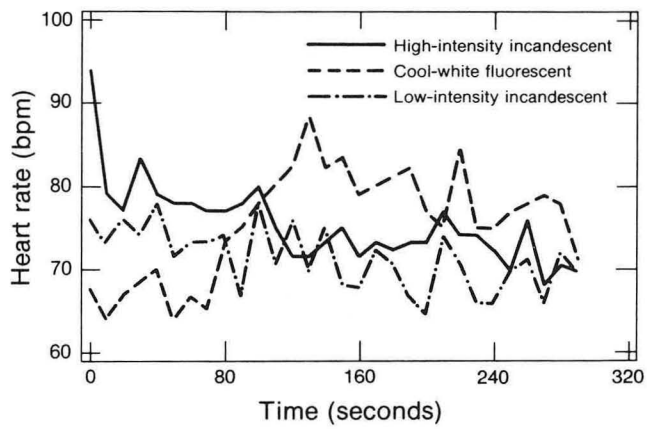

Figure 5. Changes in heart rate under exposure to three different light sources. (XBL 8311-4555)

Planned Activities for FY 1984

We plan to continue examining physiological functions in response to various lighting conditions. Such functions include those of muscles and muscle fatigue and those influenced by autonomic nervous system activation—heart rate, respiratory rates, skin resistance, skin temperature, and changes in pupil diameter.

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Buildings Energy Data*

J.P. Harris, A.K. Meier, J.F. Busch, B.L. Gardiner, C.A. Goldman, S.E. Greenberg, W. Luhrsen, V. Magnus, M.A. Meal, T.S. Nagpal, B.C. O'Regan, M.A. Piette, A.H. Rosenfeld, A. Usibelli, B.S. Wagner, and L.W. Wall

The Buildings Energy Data Group (BED) compiles and analyzes data on the monitored energy performance of buildings and equipment. Building designers, facility managers, researchers, utilities, and government policy-makers have all experienced difficulty in obtaining good-quality measured data on savings and cost-effectiveness of conservation in occupied buildings. The group was established to respond to the need for better, more accessible data.

In spite of the enormous amount of research, program activity, and private investment directed towards improved energy efficiency, there have been—until now—only scattered attempts to monitor field performance. Nor has there been any sustained effort to compile data, critically review them using a common analytical framework, or regularly update and publish results.

BED maintains six data compilations that together make up the Buildings Energy Use Compilation and Analysis (BECA) series. Each one focuses on energy performance and cost-effectiveness in one subsector, as follows:

BECA–A: *new*, low-energy *residential* buildings

BECA–B: *retrofits* of *residential* buildings

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BECA–CN: *new commercial* buildings

BECA–CR: *retrofits* of *existing commercial* buildings

BECA–D: efficient *appliances* and building-related *equipment*

BECA–V: comparisons of *monitored* performance to *predictions* using computer simulations or simplified methods

We regularly update each compilation, incorporating both published and unpublished data from the United States and abroad. We publish detailed results in the refereed technical literature. To help make the information available to industry and professional audiences, summaries are presented at conferences and in trade journals.

We believe that the BECA series is now the largest compilation of monitored building performance data in the world. We have developed, and continue to refine, the necessary data base management procedures to sort and analyze large amounts of data. We are constantly devising and testing new indicators of energy and economic performance.

The BECA compilations involve analyses that cut across traditional research and program boundaries. For example, improvements in building shells and systems can be evaluated within a common framework. Solar energy and other alternative resources can be systematically compared with improved efficiency in the use of electricity and conventional fuels. Other concerns are peak power requirements, durability of conservation measures, and overall trends in energy conservation activities.

The attempt to make consistent, unbiased performance comparisons across building types, climate zones, and varying usage patterns has raised a number of challenging issues for buildings research, as well as for the general endeavor of data compilation:

- What is the minimum amount of data that must be continuously measured on-site to characterize the performance of various building types? What are the trade-offs between detailed on-site data for a few buildings and less intensive monitoring of larger numbers of buildings?
- What are appropriate "baseline" buildings for comparison with the energy-efficient BECA buildings? Are the data on these baseline buildings sufficiently detailed to compare their performance with energy-efficient buildings?
- How much information is needed to confidently attribute changes in building energy use to the effects of conservation measures, as opposed to changes in weather, interior comfort conditions, occupancy patterns, or other factors?
- What methods of weather normalization are required for medium and large commercial buildings—and practical, given limited data on physical and operating characteristics? What variables (other than floor space) should be considered when deciding whether to climate-normalize building performance data?

BED also maintains a modest capability to monitor buildings and equipment and to assist others to improve the quality of their data. As we identify gaps in primary data, we attempt to fill them either by encouraging utilities or industry groups to undertake field measurements, or on occasion by initiating pilot-scale studies directly. In addition, as the BECA data bases have gained recognition, we have begun to receive inquiries from researchers just beginning monitoring. This allows us to offer suggestions at an early stage of the research design. Over time, we will be developing and testing recommended standard protocols for field measurement, to assist researchers and others involved in data collection.

Complementing the BECA data bases is the analysis of the technical potential for conservation in buildings. An estimate of conservation potential identifies the technical and economic "envelope of opportunities" for saving energy; the BECA data indicate how much progress we have made so far.

We have estimated the conservation potential for residences in California, the Pacific Northwest, and the United States, and in 1984 we will complete an initial study of conservation potential in California commercial buildings. In the past, we relied heavily on engineering calculations to estimate conservation potentials, but now, as our data bases mature, we are beginning to draw upon measured performance data from the BECA series.

The following sections describe results from the past year and outline work planned for the future.

BUILDINGS ENERGY-USE COMPILATION AND ANALYSIS (BECA)

Accomplishments During FY 1983

Major results in FY 1983 for each BECA project are summarized by sector: Residential, Commercial, and Appliances and Equipment. During the past

year we began two new data compilations, covering appliances and new commercial buildings. A major accomplishment was the installation of an improved computerized storage and retrieval system based on the DATATRIEVE data base system. This will greatly simplify data entry and analysis. In the future, provisions for remote access will allow other institutions to retrieve and sort information and (under our supervision) to enter new data.

Residential Sector

BECA-A: New residences. We have collected data on the heating performance and economics of new passive-solar, active-solar, and superinsulated homes throughout North America.[1] During the past year, we have concentrated on improving data quality and coverage and on developing more accurate baseline consumption data for "typical" new homes. To date, we have compiled submetered data for 215 residential buildings (208 single-family residences and 7 low-rise apartment buildings with a total of 68 units).

Some gaps in coverage arise from measurement problems; for instance, the use of wood stoves complicates performance analysis, because the burning wood represents a significant but unmetered energy flow into the house. Thus far, we have been forced to exclude new homes with unmonitored wood stoves from the data base. This has created a serious data gap, especially for new, passive-solar homes, which very often contain wood stoves. With support from the Bonneville Power Administration, LBL has developed a simple, low-cost method to reliably monitor the net heat output from a wood stove, using only one channel of a data logger.

In addition to seeking better quality data from intensively monitored individual houses, we have begun contacting builders of new, energy-efficient subdivisions. For each site, we plan to obtain utility billing data and basic household characteristics on a number of houses with identical designs. We are also expanding efforts to obtain data on new manufactured homes and multi-family buildings, sectors that are currently underrepresented in BECA but that represent almost 40% of new construction.

We have also been working on a more meaningful basis for comparing the performance of new, low-energy homes with that of "typical" new construction. Without a reasonably accurate baseline for new construction, both the energy savings and cost-effectiveness attributed to better designs could be greatly distorted. Often, energy-efficient houses involve design changes as well as specific conservation features, so they must be compared with a prototype house representing current local practice. In these cases, our approach involves defining "typical" new houses (disaggregated by structure type and heating fuel for 45 major metropolitan areas), using housing characteristics reported in the annual survey by the National Association of Home Builders (NAHB). We then model the energy consumption of these prototypes on the DOE-2.1A building simulation model. Finally, we are exploring the use of building characteristics and metered billing data from the Department of Energy's Residential Energy Consumption (RECS) survey to characterize the energy performance of new homes.

Conventional energy performance indicators become less reliable for low-energy buildings, but do give a quantitative clue to their success. When heating energy requirements are normalized for internal temperature settings and heat gains from appliances and occupants, we find that the average space heating load for a sub-sample of the 37 best-documented homes was 2.5 Btu/(ft^2-4°F-day) [50 kJ/(m^2-°C-day)], compared with the average of 8.9 [180] for the U.S. housing stock and about 5.0 [100] for all new single-family homes surveyed by the NAHB. In other words, space heating energy use in these houses has been reduced to less than one-third the level required in the average existing house, or about one-half the level estimated for typical new homes. Another way of interpreting these results is that many low-energy homes, even in the coldest U.S. climates, use roughly as much energy for space heating as that required for heating water.

Figure 1 is a scatter plot of "thermal intensity" (annual space heating load per unit of floor area) versus degree-days for 215 buildings. The loads have not been normalized for interior temperatures and appliance/occupant heat, because of insufficient data for many of the houses. The points are identified by category of conservation measure. (The numbers within these symbols represent individual houses.) For each data point, the slope of a line drawn to the origin represents the "thermal integrity" (or thermal intensity divided by heating degree-days). In this sample, the average thermal integrity values for each building type (in units of Btu/ft^2-DD$_F$) are as follows: superinsulated homes, 1.6; passive solar, 1.8; earth-sheltered, 2.4; superinsulated/passive homes, 2.5 and active solar, 3.8. Note that these averages are based on relatively small, nonrandom samples. This comparison should also be interpreted cautiously, since thermal integrity is a simplified measure of building performance. In addition, we have not included energy used for space cooling.

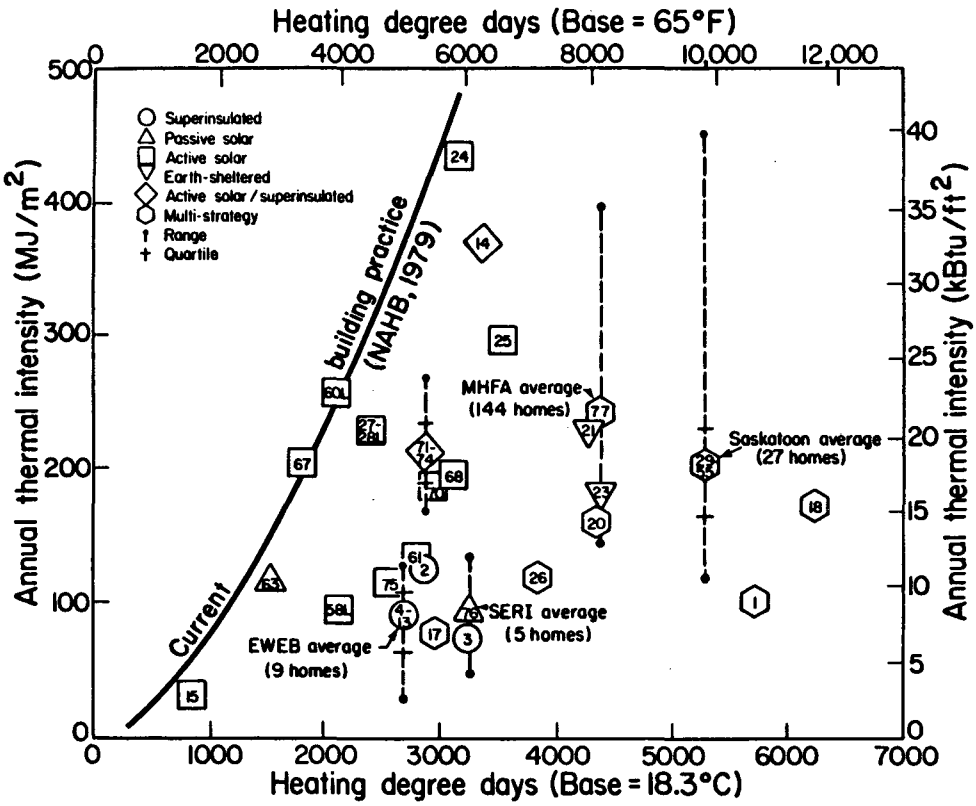

Figure 1. Scatter plot of annual heating loads vs. climate for 27 points representing 276 submetered energy-efficient new homes. The solid curve represents the simulated performance of houses built by respondents to the National Association of Home Builders' 1979 survey of U.S. building practice. The shape of the symbols identifies the conservation strategy; the enclosed numbers are the house I.D. numbers. (XBL 827-958)

BECA-B: Residential retrofits. The BECA-B data base addresses the technical performance and economics of energy-saving retrofits in existing homes.[2] The compilation includes approximately 115 retrofit projects, with sample sizes ranging from 1 to 33,000 homes. The data base has roughly doubled in size during the past year, and now includes data on 28 multi-family buildings and disaggregated results from 450 individual homes. Data come principally from four types of retrofit projects: utility-sponsored programs, low-income weatherization, research studies, and multi-family buildings. Average annual resource energy savings in the four categories range from 23 to 38 MBtu per household. Savings are typically 20 to 35% of pre-retrofit space heating energy use. Most of the retrofits involve insulation or other shell improvements, but some data are becoming available on measures that increase the efficiency of heating and hot water systems.

Figure 2 shows annual space-heat energy savings as a function of the contractor cost of the retrofit. The data points are either utility-sponsored programs or low-income weatherization programs. Participants in the 19 utility-sponsored conservation programs achieved average annual space-heat savings of 38.4 million Btu (MBtu), while low-income households reduced their annual consumption by an average of 35.9 MBtu. At any given investment level, there is substantial variation in savings (e.g., savings differ by a factor of 4 for an investment of $2400). Even for groups of houses where similar measures are installed, the range of savings can be ±70% of the median.

The sloping reference lines in Fig. 2 show the minimum energy savings that must be achieved by each level of investment for the retrofit to be cost-effective at national average residential prices for fuel and electricity. Seventy-four percent of the points lie above their respective price lines and thus are cost-effective compared to average national energy prices. There is a story behind each point. We summarize three as examples of the richness of information in the data base.

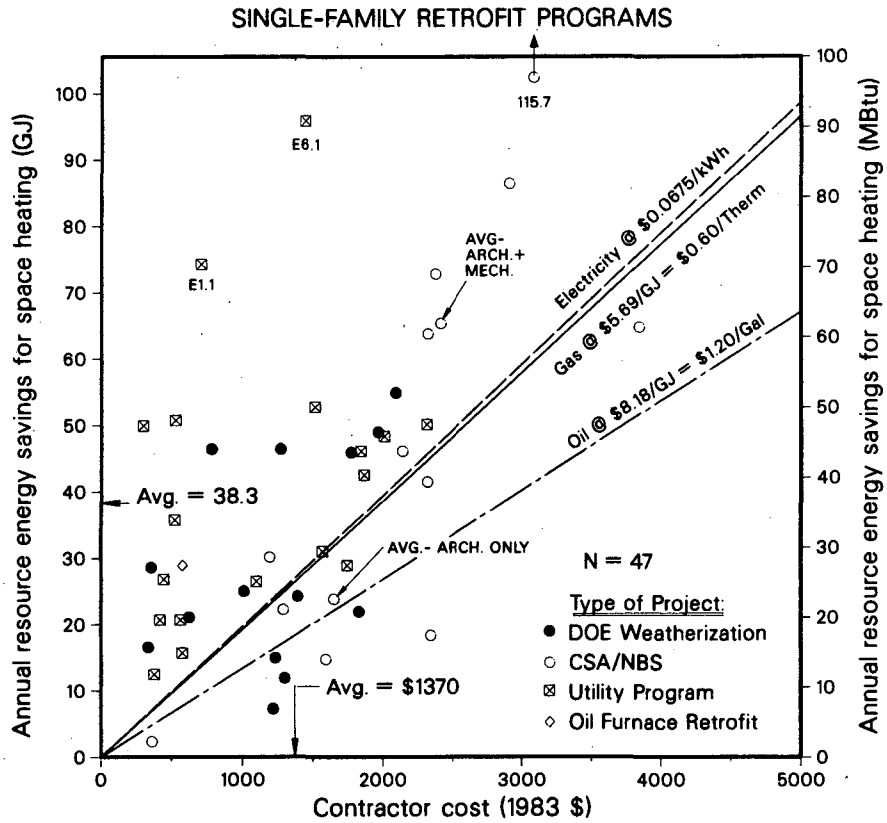

Figure 2. Annual space-heating energy savings vs. first cost of the retrofit investment for utility-sponsored or low-income weatherization programs. Average savings are 38.3 MBtu. The 47 data points represent results from over 50,000 homes. The sloping reference lines show the minimum energy savings that must be achieved, for each level of investment, if the retrofit is to be cost-effective compared to national average residential prices for fuel and electricity. In order to compare a 15-year future stream of energy purchases with the "one-time" conservation investment, the energy purchases are assumed to be constant and are converted to a single present value, using a 7% real discount rate. Roughly 75% of the data points lie above their respective reference line. Electricity is expressed in resource units of 11,500 Btu per kWh. (XCG 839-7233A)

Conservation programs initiated by Puget Power and the Tennessee Valley Authority (TVA) (data points E6.1 and E1.1) achieved high energy savings (91 and 70 MBtu) relative to costs ($1450 and $700). The TVA pilot program specifically targeted low-income, high-energy consumers; hence significant improvements in building thermal performance were obtained at low cost. Savings from the Puget Power program are also impressive, especially given the large sample (6289 homes). As the Pacific Northwest region has historically relied on cheap hydroelectric power, many homes built prior to the mid-1970s were uninsulated and "leaky." Straightforward building shell improvements (in addition to changes in occupant behavior spurred by dramatic increases in the price of electricity) contributed to substantial reductions in electricity consumption.

Our third example, the Community Service Agency/National Bureau of Standards Optimal Weatherization Demonstration Program (CSA/NBS open circles in Fig. 2) achieved average space-heating energy savings of 31% in 12 cities. Sixty-nine homes that received only architectural options (retrofits designed to reduce building-shell conduction and infiltration heat loss) saved an average of 23 MBtu per year for an average cost of $1650. Seventy-three homes that installed architectural plus mechanical options (retrofits applied to the heating system or hot water system) reduced their annual consumption by an average of 62 MBtu, at an average cost of $2400. Hence, for these homes, the combination of heating system and shell retrofits was roughly two times more cost-effective than shell measures alone.

Commercial Sector

BECA-CN: New commercial buildings. During the past year the commercial data base has been

expanded to include new, energy-efficient commercial buildings. The data base contains actual measured performance data for 74 buildings, and design energy predictions for an additional 47 buildings. Of these 121 buildings, 83 are offices, 18 are schools, and 20 are other commercial building types. The buildings are generally large (over 50,000 ft^2); about 40% are all-electric. Energy-saving features of the buildings include: low lighting loads (1–2 watts/ft^2), daylighting, envelope insulation, improved air handling, heat recovery, and thermal storage.

Figure 3 shows the range in performance for those office buildings with measured data, compared with past energy usage and proposed ASHRAE commercial building standards. There is considerable variation—partly because these data are not yet normalized for weather, operating hours, or other factors—but also because many of the buildings are achieving site energy consumption levels in the range of 30–70 kBtu/ft^2-year. This is in the range of the proposed ASHRAE 90-E and of the ASHRAE 90-E/daylighting standards, and significantly less than the energy required for the average existing office building.

BECA-CR: Commercial building retrofits. The commercial retrofit data base currently includes energy savings for over 200 nonresidential buildings (including a large number of schools in the eastern United States).[3] The data base is now being updated

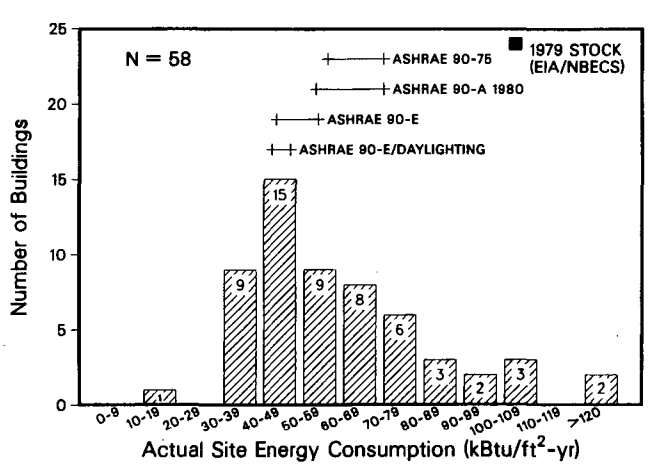

Figure 3. Histogram of the distribution of total site energy consumption for 58 new, energy-efficient office buildings. The ASHRAE ranges are based on applications to test buildings of the indicated voluntary and proposed standards. The 1979 stock number is from the Energy Information Administration's *Nonresidential Buildings Energy Consumption Survey: Part 1* (March, 1983) and covers only electricity and natural gas consumption.

(XCG 8312-4932)

and expanded from the original data compilation prepared by Ross and Whalen.

We are expanding the data base to include building types that were missing from the original compilation. Also, we are re-contacting the data sources for the Ross and Whalen study to collect more detailed information on the retrofit projects, and to obtain additional years of post-retrofit consumption data. This will permit us to better understand long-term changes in energy use, as well as to observe any degradation in performance of the retrofits themselves.

Analysis of commercial buildings is complicated not only by the diversity of physical and operating characteristics but by the frequent lack of fixed "pre" and "post" retrofit periods. There are instead several overlapping retrofit projects done over a period of years. In an effort to address these characteristics of retrofitted commercial buildings, we are expanding the scope of analysis as well as the data base.

Median fuel savings for nonresidential buildings in the BECA-CR data base were over 20% of pre-retrofit consumption; electricity savings were much less. This might be explained by the relatively low pre-retrofit electricity usage in the sample, the small number of all-electric buildings, and the predominance of schools, which may have been originally designed to use daylight rather than intensive artificial lighting in classrooms.

The buildings currently within the BECA-CR data base were generally retrofitted with low-cost operational and maintenance measures. This emphasis was reflected in the low level of retrofit investments (median under \$1.00/ft^2) and the short payback times (median less than 2 years).

From the building owner's perspective, this reluctance to invest more money in longer-payback measures may be explained not only in terms of capital cost and availability, but as a reasonable response to the perceived uncertainty of actually saving energy and money. In fact, 10% of the buildings used more energy after retrofit than before. These "negative results" may have been due to poor operation and maintenance, to product failure (in one case, for example, a window film failed to adhere), or to significant weather variations in the post-retrofit period. More data on "instructive failures" are needed to improve our understanding of such factors.

BECA-D: Appliances and equipment. There are currently four compilations within BECA-D: residential water heaters, residential refrigerators, commercial refrigerators, and refrigerated drinking fountains.

The residential water heating data base contains information on the monitored performance of over 10,000 new and retrofitted electric resistance, heat pump, natural gas, and solar water heaters (of these, 6900 are in one project). Its utility, however, is limited by a lack of data essential for calculating performance. These include water inlet and outlet temperatures, heated water consumption, temperatures around the storage tank, water-consuming appliances, and, in some cases, even submetered energy use. Nevertheless, we can begin to describe the performance of several water heating conservation measures: heat pumps, thermal traps (also called anti-convection valves), and insulating blankets (Fig. 4 and Table 1). Field performance of thermal traps proved surprisingly good, even better than the commonly accepted water heater blanket. Electricity savings for thermal traps were typically 9 to 14%, and blankets saved 5 to 8% of the average annual electricity consumption. A larger sample size is needed, however, before concluding that the thermal trap is superior to the blanket. Seasonal coefficients of performance for the heat pump field tests ranged from 1.8 to 2.2.

The difficulty in collecting data to perform an adequate analysis of water heating performance has prompted us to explore the availability of low-cost, non-intrusive instrumentation for water heaters, and to propose, along with the Energy Performance of Buildings group, development of a recommended standard protocol for field monitoring of residential water heaters.

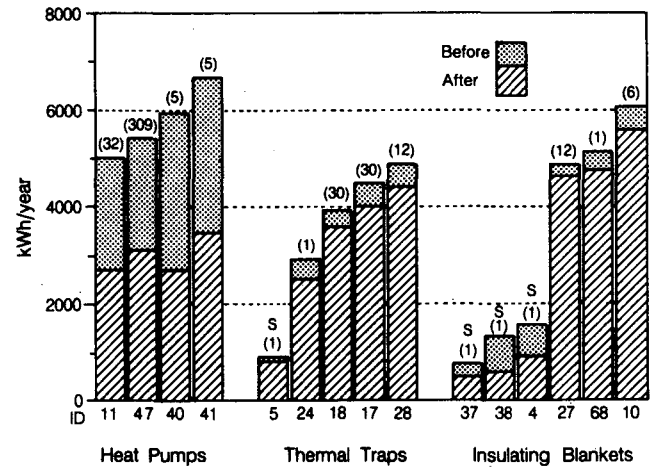

Figure 4. Measured savings from conversion to heat pumps, use of thermal traps (anti-convection valves), and insulating blankets for electric water heaters. The difference between the "before" and "after" areas represents the measured savings. Numbers in parentheses are number of units in a sample; bars headed by "S" are for standby losses only. Table 1 gives additional information on specific projects. (XBL 842-808A)

The residential refrigerator data base is still at an early stage. The quality of existing data is poor; we

Table 1. Selected electric water heater conservation measures (BECA-D).

I.D. code	Annual use Before	Annual use After	Number of units	Average number of occupants	Type of project[a]	Water temp. Inlet (°F)	Water temp. Outlet (°F)	Ambient temp. (°F)	City, State
0011	5034	2690	32	2.9	N				MD, VA, WV
0040	5950	2700	5	2.8	R		140		Russellville, AL
0041	6672	3468	5	3.4	N		140		Russellville, AL
0047	5440	3101	309	3.4	N				OR
0005	918	813	1		LR		140	60	Portland, OR
0017	4500	4018	30		R	47	150	64	Seattle, WA
0018	3930	3580	30		R	47	130	64	Seattle, WA
0024	2918	2515	1		LR				Arlington, VA
0028	4893	4410	12		LR		140	70	New York, NY
0004	1483	918	1		LR		133	64	Portland, OR
0010	6089	5607	6	3.3	R	59	150	59	Birmingham, AL
0027	4893	4643	12		LR		140	70	New York, NY
0037	760	480	1		L	70	130	70	Emeryville, CA
0038	1349	591	1		L	70	140	70	Emeryville, CA
0068	5157	4773	1	4.0	R	60	139		Chico, CA

[a]Type of retrofit: L—laboratory test; LR—laboratory retrofit; R—field retrofit; N—new field unit(s).

have considerable consumption data, but virtually no related information on appliance usage patterns. The remaining two data bases, those for commercial refrigerators and drinking fountains, were established as a result of primary data collection activities. There are essentially no published data on energy consumption of either appliance, but even with our limited data sets we can identify substantial opportunities for improved efficiency—on the order of 30% in each case. Electricity use by commercial refrigerators in the U.S. is equivalent to the output of about two 1000-MW power plants; drinking fountains may use as much as half the output of one power plant.

BECA-V: Predicted versus measured performance. In the BECA-V data base, we compile results of studies comparing predictions of building energy use to the measured use of actual buildings.[4] In addition, we prepare brief descriptions of metered data for use in conducting verifications of building energy use models, and a bibliography of related studies (e.g., comparisons between simplified modeling techniques and standard reference codes). The BECA-V compilation summarizes the predictive ability of both state-of-the-art, detailed computer models and simplified calculation procedures. BECA-V also emphasizes the importance of model users, data limitations, and other factors affecting performance predictions.

We classify comparisons according to the quality and detail of input data. This helps to separate sources of external error, such as faulty measurements, from user input error or inadequate data on occupant behavior. We are also interested in the success of performance predictions made in the field (e.g., methods used by building energy auditors) as well as in research applications.

The 20 studies examined to date include 100 data points, representing 500 (mostly residential) buildings.[4] Figures 5 and 6 compare results for research and field applications, respectively. Figure 5 shows measured versus predicted energy use for studies in which carefully measured data were entered in detailed computer models. In most cases, the error is within 10%. Monitoring periods varied from 24 hours to one month; longer monitoring periods resulted in better agreement between measured and predicted consumptions. Figure 6 compares energy savings predicted by various simple models versus actual savings. Many details of the buildings and their occupants are unknown. Each point in Fig. 6 represents results averaged for a group of houses; the variance for individual houses is considerably larger.

Regional compilations. The Cal-BECA project is an effort to identify and incorporate additional data on energy-saving features, costs, and performance of California buildings. The project is jointly sponsored by the University of California and the California Energy Commission, with the assistance of the California Building Industry Association. Currently data collection is focused on new homes and commercial buildings, and on energy management and retrofits of public buildings. We may undertake additional region-specific data compilations in the future as appropriate sponsors are identified.

Planned Activities for FY 1984

A major continuing goal for all BECA data bases is to increase the number of data points and to broaden coverage. However, each compilation also must address specific limitations or opportunities. In BECA-A, we need to concentrate on new houses in mild climates, cooling performance, multi-family buildings, and manufactured housing. We also plan to refine the procedures for weather-normalization, and to improve the baseline from which both incremental energy savings and costs are calculated.

In BECA-B, we also hope to identify more residential retrofit data from mild climates, and to address savings for cooling and water heating, as well as space heating. Through participation in a field research project involving several of the National Laboratories, we hope to collect data from buildings that have been "super-retrofitted," at a level approaching the identified technical potential for conservation.

We plan to expand the mix of building types and sizes in the BECA-CN data base, and to continue tracking the energy consumption of buildings currently in our data base so as to better observe the effects of management strategies and the fine-tuning of energy systems over time. We will also examine the effect of weather variations as functions of building size and features. Finally, we hope to include better data on the incremental costs of conservation features—both the initial and the annual operating maintenance costs.

Retrofits of privately-owned commercial buildings will be a major focus for the BECA-CR compilation, including cooperative efforts with industry groups and energy services companies to exchange data on savings and cost-effectiveness.

Proposed areas for expanding our water heating data base (BECA-D) include heat pumps, retrofits, heat-recovery devices, and conservation measures for large multi-family buildings. In addition, we hope to

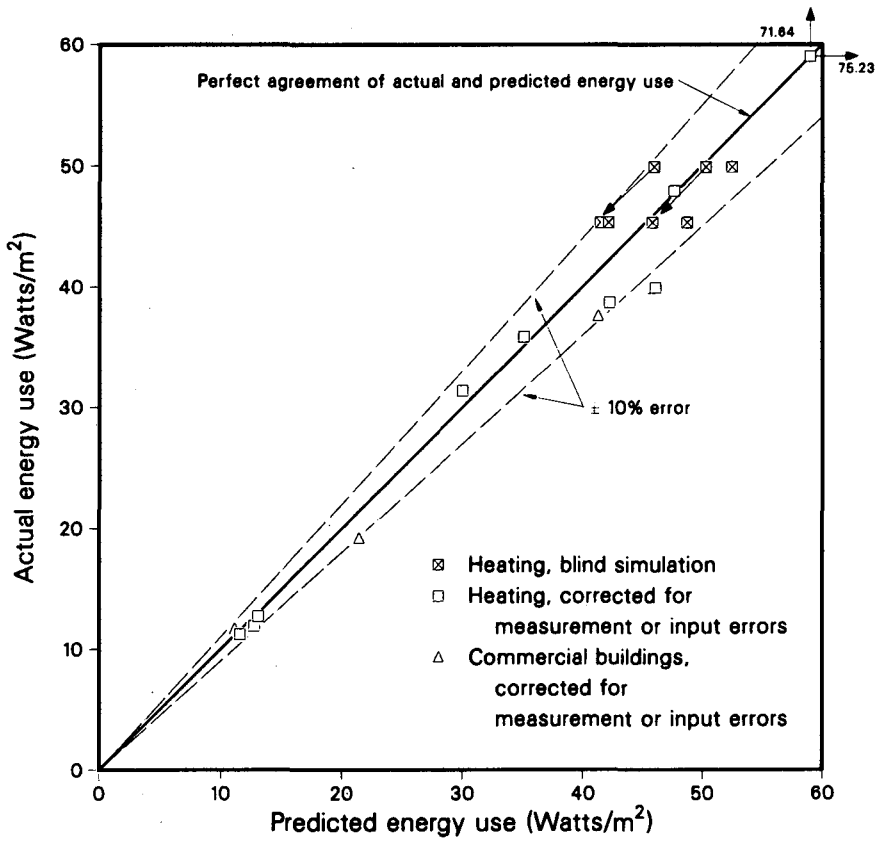

Figure 5. Predicted vs. actual building energy use in validation studies. Energy consumption is expressed in average W/m^2 because measurement times for the buildings varied widely. In the blind studies, the modelers did not have an opportunity to compare preliminary simulations and "fine tune" the models. In the other buildings both the modelers and the measurers revised their data (there were numerous measurement errors) following preliminary simulations. The results shown are the final simulations. Two buildings were both modeled and measured for one day and one week; the arrows connect the one-day to the one-week measurements. (XCG 841-13001)

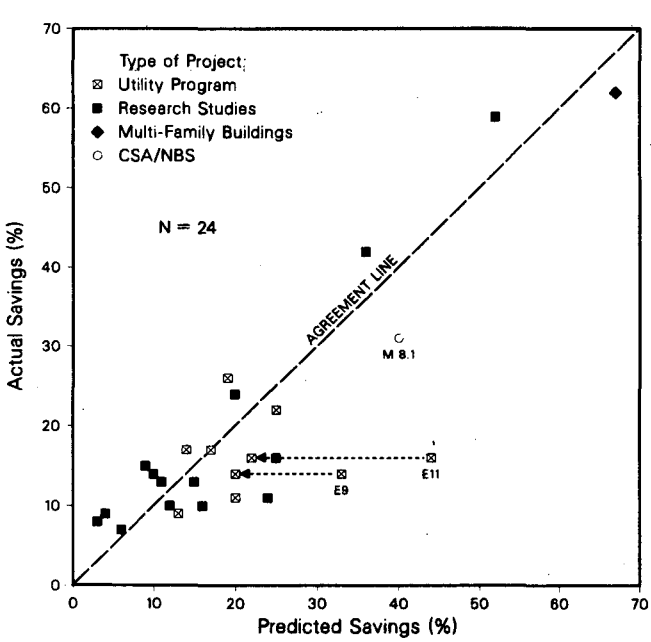

Figure 6. Predicted versus actual savings for 24 residential conservation studies. The predicted savings were made using a variety of computer programs and heat-loss calculations. Information feedback during the research studies generally permitted greater accuracy in predictions of energy savings than in the utility studies; however, in two utility studies, the predictive methods were revised after early predictions were compared to metered data (arrows show the relationship between initial and revised predictions). Note that the axes represent percentage savings; the absolute difference between predicted and actual savings may be quite large when the percentages are small. (XCG 839-7235)

incorporate more performance data on solar water-heating units.

In BECA-V (Validation), we will continue to explore the effect of external and internal errors on model predictions and to track the progress of model refinement. More work is also needed to suggest methods for reducing errors in measurement and user input, both in research and field applications.

CONSERVATION TECHNOLOGIES DATA AND POTENTIALS

Accomplishments During FY 1983

We prepared a data base and estimated the technical potential for electricity conservation for the residential sector in the Bonneville Power Administration (BPA) service area.[5] This is a continuation of earlier studies made for California and the United States.[6–8] We displayed these potentials in terms of "supply curves of conserved energy" (Fig. 7). We analyzed 336 residential conservation measures and gathered critical technical, economic, and existing-stock data on each. Each measure was ranked according to its "cost of conserved energy." We found that the technical potential for conservation achievable by the year 2000 was 42% more than that forecast in 1982 by BPA. We also developed a computer program, CPS 2.0, to store the data and calculate energy savings for interdependent conservation measures. The program and data base are currently being installed at BPA. In FY 1984, we expect to assist BPA staff in updating the data base and incorporating new conservation measures.

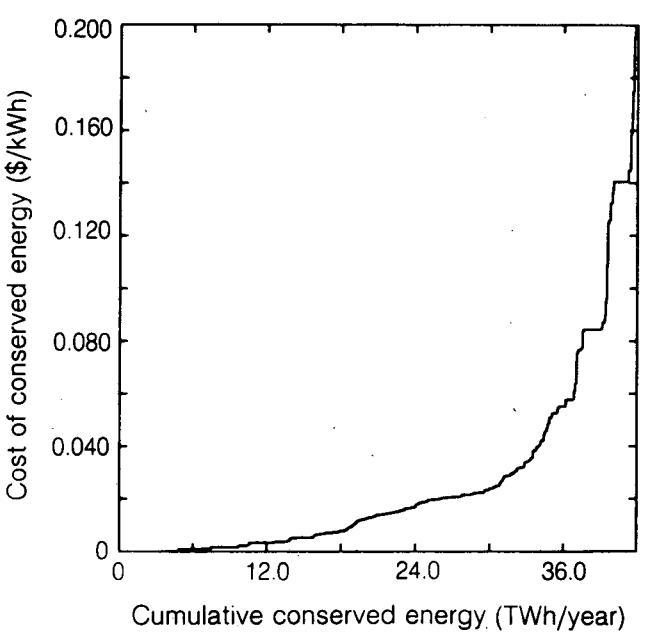

Figure 7. A supply curve of conserved electricity for the residential sector of the Pacific Northwest. Each step represents a conservation measure. The measure's height indicates its cost of conserved energy. A measure is cost-effective if its cost of conserved energy is less than the price of the energy it displaces. The width of each step represents the technical potential for savings through implementation of that measure in the region. The supply curve shows that 41.5 TWh/year can be conserved at less than 15 cents/kWh. (A terawatt-hour = 10^9 kWh.) These savings represent 42% of the forecasted residential electricity consumption in the year 2000. (XBL 842-897)

Planned Activites for FY 1984

In the coming year, we will be developing a commercial energy conservation technology data base under contract to Pacific Gas and Electric (PG&E) and Southern California Edison (SCE). The data base will be supported by a series of detailed technical reports on individual conservation technologies for both new buildings and retrofits of existing stock. Besides assisting utility conservation planners and demand forecasters, this work may be useful to conservation program staffs in the field.

Data for the project will be drawn from a large variety of sources, including published and unpublished research findings, product literature and test data, utility demonstration projects, and computer simulations of existing commercial buildings. As much as possible, we will use material in the BECA-CN and -CR data bases to incorporate measured performance data on conservation technologies. For each technology, the analysis will include energy and peak power savings, cost-effectiveness, and potential applicability to the building stock.

PRIMARY DATA COLLECTION

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

Accomplishments During FY 1983

Commercial Refrigerators

Virtually no energy performance data exist on commercial food service (e.g., restaurant) refrigerators. We completed a study of commercial refrigerators in order to better understand their contribution

to total energy consumption in small buildings. This included monitoring a few selected units in restaurants and cafeterias. In addition, we intensively monitored one typical unit in order to determine sensitivity of energy use to interior and exterior temperatures and changes in loads. We estimate that food service refrigerators in the U.S. use the equivalent output of two large baseload (1000 MW) power plants. Unlike the case of residential refrigerators, little effort has been made to improve energy efficiency, even though there exists considerable potential and economic incentive.

Drinking Fountains

The 5 million mechanically refrigerated drinking fountains in the United States consume about 2600 GWh/year, or half the output of a 1000 MW baseload power plant. Again, we began measuring these units when we discovered that they consume, in the aggregate, significant amounts of electricity, yet had no measured consumption data in the literature. We have also investigated simple conservation measures that could potentially reduce their use of electricity by 30%.

Warm-Room Retrofits

In FY 1983, BED staff assisted local agencies in Kansas City, Missouri, to select houses suitable for a pilot "warm-room" retrofit project, and began monitoring them prior to retrofit.

Planned Activities for FY 1984

In cooperation with the Urban Consortium and the Alliance to Save Energy, BED and the Energy Performance of Buildings Group at LBL are planning to measure the energy savings from "warm room" retrofits in zone-heated houses. Among the issues to be analyzed are optimal levels of interior and exterior insulation, combinations of furnace derating and supplemental zone heating, strategies to prevent pipes from freezing, and maintenance of occupant comfort within the heated areas (and in moving between heated and unheated areas).

SUMMER STUDY ON ENERGY-EFFICIENT BUILDINGS

Accomplishments During FY 1983

We edited proceedings from the 1982 Summer Study on Energy-Efficient Buildings and prepared summary material to be published as a book. The Summer Study, held in August 1982 at the University of California, Santa Cruz, was organized by the American Council for an Energy-Efficient Economy (ACEEE) and co-sponsored by several public and private organizations, as well as the U.S. Department of Energy and LBL. Its 240 participants represented a stimulating cross-section of researchers and practitioners in the field. Its theme, "What Works? Documenting Energy Conservation in Buildings," is closely related to the central concerns of the BED group; our participation offered excellent opportunities to develop contacts and identify new sources of data.

Planned Activities for FY 1984

A future Summer Study, continuing many of the same topics, is scheduled for August 1984. We plan to present updated BECA results and solicit further input from the participants.

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Windows and Daylighting*

S.E. Selkowitz, U.S. Choi, C. Conner, D.L. DiBartololomeo, R.L. Johnson, J.D. Kessel, J.H. Klems, C.M. Lampert, M. Navvab, E. Ne'eman, M.D. Rubin, J. Ryan, M. Spitzglas, B. Stearns, and G.M. Wilde

Approximately 20% of annual energy consumption in the United States is used 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.

The Windows and Daylighting Group aims 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. A multidisciplinary team of scientists, engineers, and architects conducts these studies, with assistance as required from industrial and academic consultants and subcontractors. 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.

It is also important that technical data developed by our program be communicated to design professionals, to industry, and to other public and private interest groups. We publish our results and participate in all appropriate professional and scientific societies, national and international, to ensure that our research results are widely disseminated.

Our work is organized into four major areas:

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

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 fenestration materials. Since the inception of our program in 1976, identification, characterization, and exploratory development of promising new fenestration materials have been major program activities. Research on new optical materials for glazing and on modifications of existing materials is intended to assist industry with development of the next generation of advanced fenestration systems. During the past 7 years, the Office of Buildings Energy Research and Development at DOE has supported research studies on low-emittance films, electrochromic coatings, and gradient-index materials that minimize reflection, as well as a number of smaller studies on other materials aspects of fenestration systems. In FY 1983, additional support for related exploratory studies was

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

obtained from the LBL Director's Office and from the Office of Energy Systems Research, Division of Energy Conversion and Utilization Technologies in DOE. We also initiated a major new research program on advanced optical and thermal technologies for aperture control, with support from the Office of Solar Heat Technologies, Passive and Hybrid Solar Energy Division. A multiyear research plan was prepared, circulated, and revised in accordance with reviewers' comments. An annual technical conference and industry forum is now held each year in August in conjunction with a meeting of the International Society for Optical Engineering (SPIE).

Glass and Plastic Substrates

Accomplishments During FY 1983

Accurate characterization of the optical properties of glazing substrates is essential to all parts of our research program. We therefore continued measurements of the optical properties of glass glazing materials. These properties have not been available in a complete and self-consistent form, even for the most common varieties of glass used in windows. This year, we completed measurements on standard clear glasses, glasses with absorbing additives, and high-purity glasses. Large variations in properties were sometimes observed among the products of different manufacturers. However, the most important extension over previously available data was the determination of a complete set of optical constants from the near ultraviolet through the little-studied far infrared. Figure 1 shows the components of the complex index of refraction for clear soda-lime silica glass as determined by the Kramers-Kronig analysis of reflectance measured with a Fourier-transform spectrometer.

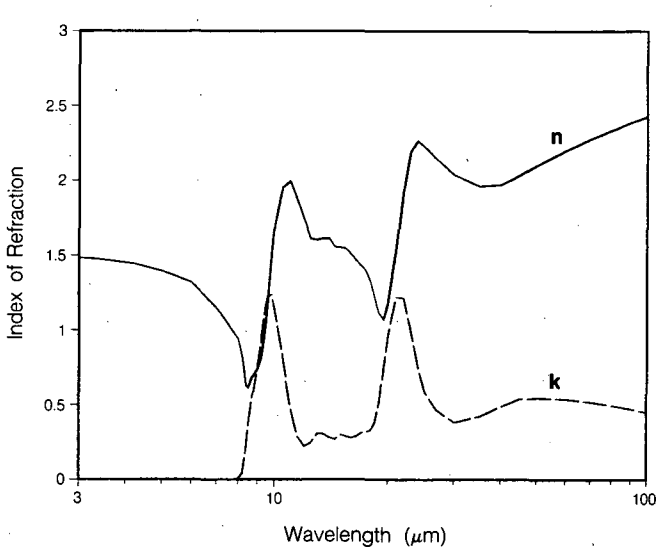


Figure 1. Real (n) and imaginary (k) parts of the complex index of refraction for soda-lime silica glass.
(XBL 8412-5271)

Planned Activities for FY 1984

We will complete measurements on glass substrates and publish results after circulating them for industry review. We will begin planning and data collection for the next phase of this work, which will examine common and experimental plastic films and sheets as well as glasses and plastics with a variety of thin-film coatings. A new spectrophotometer, covering the spectrum from UV through near infrared, will be added to our optical laboratory to extend our data collection and analysis capabilities.

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. Two specific promising research activities are under way to develop the technical basis for these advanced windows.

Low-Emittance, Gradient-Index Coatings

Accomplishments During FY 1983

Since 1976, we have contributed to the development and analysis of coatings that reflect infrared but transmit visible light and thereby suppress radiative heat transfer in windows. Commercially available coatings based on multilayer metal dielectric films have satisfactory optical properties but are not sufficiently durable to be used in nonsealed glazings. By producing a film with a continuously varying index of refraction to reduce reflection in the visible spectrum, we could use materials that are inherently more durable and less transparent than the metal and semiconductor films that have better optical properties. Initially, we are studying TiN_xO_y films made either by reactive sputtering or by chemical-vapor deposition. In FY 1983, we completed a detailed review of existing data on these oxy-nitride coatings and an initial analysis; this analysis suggested that substantial improvements in coating properties are possible. Samples were obtained from several sources, and measurements of optical properties confirmed our analytically derived predictions.

Figure 2 shows a broad region of induced low reflectance that would be possible with such films.

Planned Activities for FY 1984

We will continue to analyze and characterize coatings from several sources and will purchase a reactive magnetron sputtering system that will enable us to fabricate films to our own specifications.

Aerogels

An unusual material, silica aerogel, is being developed at LBL for application as a transparent, insulating window.[1,2] Aerogel is a microporous silica material containing a high fraction of voids (up to 97% by volume). It is transparent rather than translucent because the *pore size is much smaller than the wavelength of light;* therefore, it transmits rather than scatters light. Aerogel is an excellent thermal insulator because of its low density and extremely small pore size. A 1-inch-thick aerogel window would have an R value of about 7. The goals of this project are to improve the optical and thermal properties of aerogel, develop methods to protect it from the environment, and discover less expensive synthesis methods to accelerate its introduction to the commercial window market.

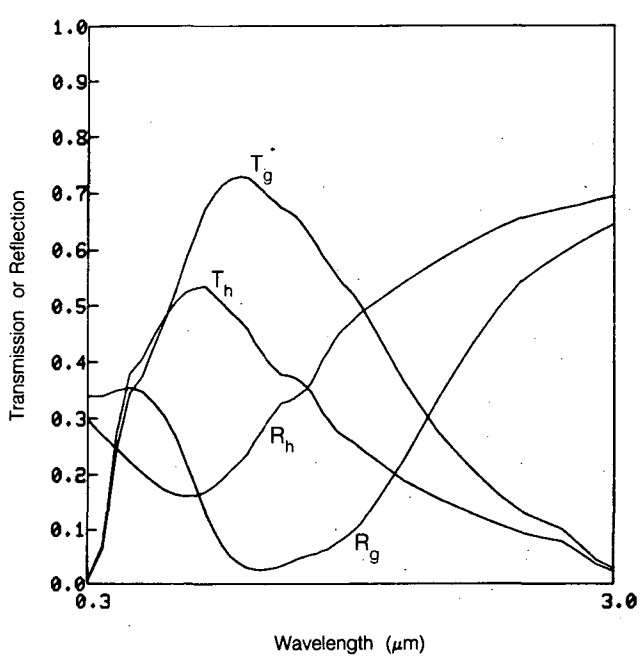


Figure 2. Increased transmission (T_g, T_h) and decreased reflection (R_g, R_h) of, respectively, gradient-index TiN coatings and homogeneous coatings. (XBL 8412-5270)

Accomplishments During FY 1983

A feasibility study was carried out to evaluate the potential of aerogel as an insulating glazing material.[1] Three primary areas were identified as requiring research. First, the optical properties of aerogel must be improved. Color effects arising from residual scattering of light that passes through aerogel reddens it and reduces its overall solar transmission. Therefore, an important goal of the research is to reduce this scattering by understanding its origin and modifying the preparation procedure to minimize the effect.

Second, aerogel is an open-pore, low-density material that must be sealed from the environment. Because of its low density, aerogel is also a relatively weak material that must be strengthened. Third, the preparation of aerogel requires a combination of time, temperature, and pressure that may pose problems for commercialization. Alternative methods of preparation that reduce these requirements are therefore under investigation.

During FY 1983, two major experimental tasks were undertaken. A supercritical drying system capable of producing temperatures up to 300°C and pressures to 3000 psi was constructed. The system was completed in mid–FY 1983, and the first aerogels were produced. To study the cause of light scattering and its relationship to the structure of aerogel, a polar nephelometer was designed and constructed (Fig. 3). The polarization state of the incoming light is fixed by the polarizer. The scattered light is collected by the slit, lens, and filter system and detected by a photomultiplier. The results are plotted as a function of angle on an x-y plotter.

Results of the differential light scattering measurements on several aerogel samples were similar to those produced by Rayleigh scattering theory, suggesting that the scattering may be interpreted as originating from small particles or dipoles. However, the material does not meet the requirements for independent scattering centers upon which the Rayleigh theory is based. Other samples produced results that differed significantly from these.

Such striking differences in the scattering behavior suggest that different microstructural properties are responsible for its causes. We have advanced the hypothesis that the scattering was due to structural inhomogeneities that are larger than typical pore sizes.[3] We plan to explore theoretical models of scattering to account for these data. A successful interpretation of the data may provide information on ways to vary aerogel preparation methods that will reduce the scattering and produce a clearer material.

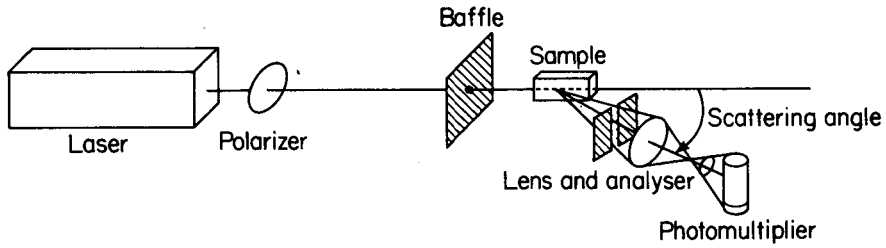


Figure 3. Diagram of the polar nephelometer used for the angular light scattering measurements. (XBL 832-1260)

Planned Activities for FY 1984

Initial production of aerogel is under way, but several problems remain. Some shrinkage and sample cracking occur during preparation. New production methods will be investigated to reduce shrinking. Techniques to reduce cracking by releasing the gels from the molds will be explored. Preparation methods using base-catalyzed tetramethyl ortho silicate (TMOS) give clearer samples than those using acid-catalyzed tetraethyl ortho silicate (TEOS). However, we have not used TMOS because of its toxicity. We plan to explore safe methods of TMOS-based aerogel production as well as new methods of using TEOS.

Light scattering appears to be an ideal tool to study the preparation process and characterize the final properties of aerogels. We plan to continue the study of light-scattering techniques to understand and improve the properties of aerogels, based on experimental and theoretical studies. Measurements of thermal conductivity will also be made. Based on these measurements, potential improvements using low-conductance gas-filled and evacuated aerogels will be analyzed.

Optical Switching Processes and Materials

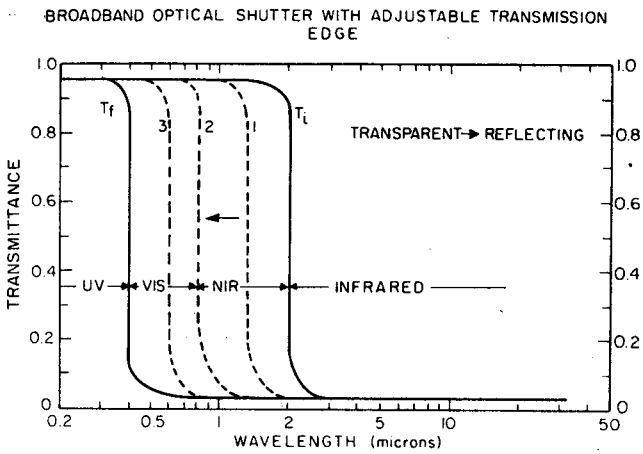
A variety of optical switching devices can be used to modulate solar heat gain and daylighting through building glazings. These functions are important to control glare and overheating, to reduce cooling energy consumption and size requirements of the heating, ventilation, and air-conditioning (HVAC) system, and to minimize peak electrical load. Our prior reviews of optical switching materials suggested that specialized solid- and liquid-state materials could be developed to perform dynamic optical switching functions that equal or exceed the performance of existing mechanical systems for sunlight control. Switching materials can provide optical control of the glazing by being automatically responsive to light intensity, spectral content, and/or temperature or can be controlled electrically in response to any specific set of interior and exterior conditions. An idealized spectral response of such a coating is shown in Fig. 4.

Optical switching phenomena can be categorized as chromogenic, electro-optic, or kineto-optic. For large-area window applications, chromogenic materials appear to be the most promising. Of the chromogenic materials, electrochromic, thermochromic, and photochromic types appear the most promising. Some compounds exhibit combined properties.

The overall DOE-supported effort to develop switching films includes the efforts of four major participants. In addition to our research role, we act as scientific coordinators for the entire effort.

Accomplishments During FY 1983

Our recent overview study indicates that a variety of chromogenic materials have promise as large-area switching films.[4] Initial emphasis in the DOE program is placed on electrochromic materials because there has been a major prior research and development investment in examining their role as display devices and because their controllable switching offers higher performance potentials. Certain transition-metal oxides and hydroxides exhibit electrochromism. These oxides are the most useful for window switching. A schematic of how these films might function in a multilayer device is shown in Fig. 5. Substoichometric tungsten oxide films based on WO_3 show considerable promise as visible and near-infrared switching materials. An example of results with a material synthesized by rf sputtering (investigated by another contractor in the DOE program)[5] is shown in Fig. 6. This film shows the enhanced infrared response necessary to control the near-infrared portion of the solar spectrum. Other materials, such as MoO_3, TiO_2, and NiO_2, have not



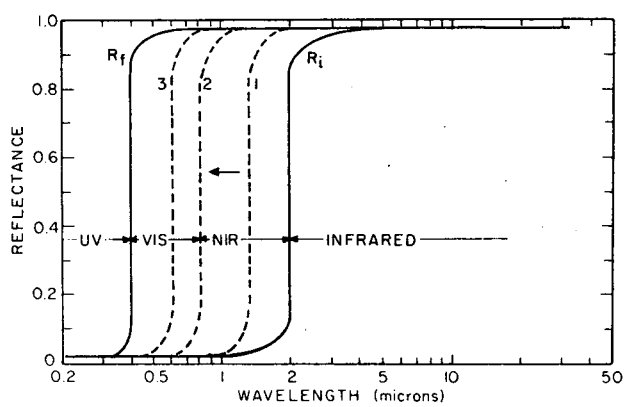


Figure 4. Idealized broadband spectral response desired for a solar optical shutter. This example ignores the effect of absorption and shows a highly transparent film transforming into a highly reflecting one. Such a shutter effect can control certain portions of the solar spectrum to provide or restrict both solar heating and lighting.
(XBL 828-6452)

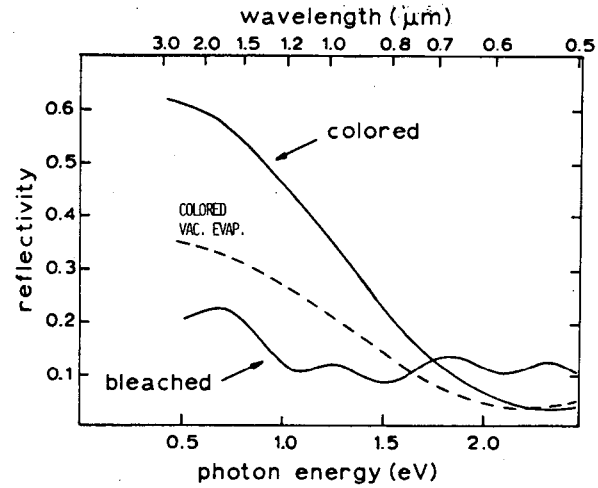


Figure 6. Reflectance spectra of a radiofrequency-sputtered polycrystalline WO_3-type film. Structurally modified, this material can behave as a near-infrared switch. An evaporated film is shown for comparison. (Adapted from R.B. Goldner.[5]) (XBL 8311-4670)

been studied as extensively as WO_3 but may nevertheless have useful properties for optical switching. The overall electrochromics research effort includes basic materials characterization, better device design, and development of transparent ion-storing counterelectrodes. LBL efforts focus on characterizing and developing improved electrochromic materials, initially NiO_2.

Materials for use as photochromic and thermochromic optical shutters were also studied. Our overview investigation covered a vast number of previously recognized but poorly characterized phenomena. Some photochromic inorganic oxides dispersed in polymers may be useful for light-

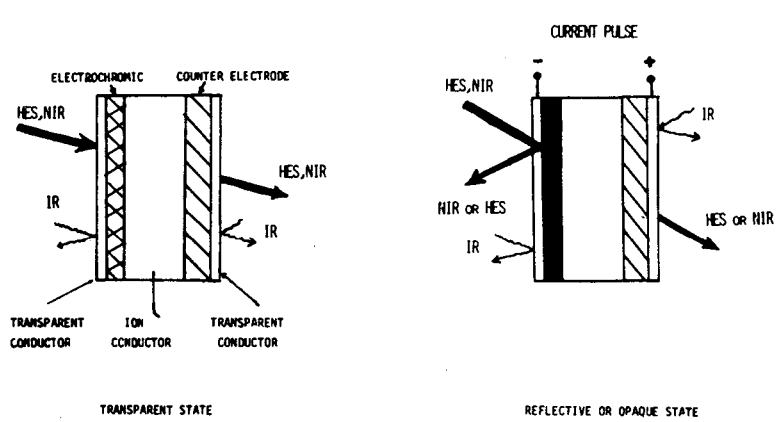


Figure 5. Schematic of an electrochromic optical switch shown in each of two states, transparent and colored. A current pulse causes an ion-based chemical reaction to take place in the electrochromic material (HES, high-energy solar; NIR, near infrared; IR, infrared).
(XBL 841-64)

activated passive switching. Metal halide dispersions in glasses also exhibit many desirable features for use as sunlight-control systems. Chiral nematic liquid crystals and double metal iodide compounds may offer thermochromic (heat-triggered) solar-light control. These, along with other materials research recommendations, have been incorporated into a multiyear research plan.

Planned Activities for FY 1984

Further studies to identify and better qualify options for switching materials will be performed. Research will focus on electrochromic NiO_x films, which can be switched to a dark bronze reflective state. Alternative techniques for depositing the NiO_x films will be studied. A reactive magnetron sputtering system will be used for deposition. Research on thermochromic coatings will focus initially on thermochromic liquid crystals. We plan to synthesize these materials and characterize their properties as a function of temperature and spectral response.

Materials for Improved Daylight Utilization

The intensity and spatial distribution of daylight transmitted through windows and skylights must be controlled in order to reduce electric lighting requirements. Conventional solutions rely on architectural elements and interior or exterior devices to control daylight admission and distribution. Greatly improved performance would result from materials or systems that could: (1) transmit maximum daylight with minimal cooling load impact (i.e., reject solar infrared radiation); (2) collect and distribute daylight beyond the perimeter zones in buildings; and (3) provide angular selectivity in the acceptance and redirection of 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 for collecting and redirecting daylight using fluorescent concentrators is the subject of a patent disclosure.

Accomplishments During FY 1983

Optical systems for daylighting require collection, transmission, and distribution subsystems. In FY 1983, we reviewed alternative approaches, potential performance, and fundamental optical limitations to performance for each major system. We then focused on characterizing the performance of transmission, or light-guide, systems.

Our major effort was to investigate means of transporting daylight deep into buildings. We compared the transmission properties of glass, plastic, and liquid-core light guides, as well as some specialized hollow-core light guides. Some new, low-scattering plastic materials developed for fiber-optics communications have high transmittance for visible light. Figure 7 shows that a PMMA (polymethyl methacrylate) core fiber can transmit more than 60% of concentrated daylight for a distance of 10 meters.

Planned Activities for FY 1984

We will continue transmission measurements and analysis of several different light-guide systems for a range of source conditions. We will also investigate methods of producing low-cost, high-transmittance plastic fibers to determine if substantial improvements are possible.

FENESTRATION COMPONENTS AND SYSTEMS

Analytical and experimental activities in this area have as their objective the provision of experimental and analytical models that can be used to accurately determine the net performance of fenestration in buildings. Many of the new algorithms

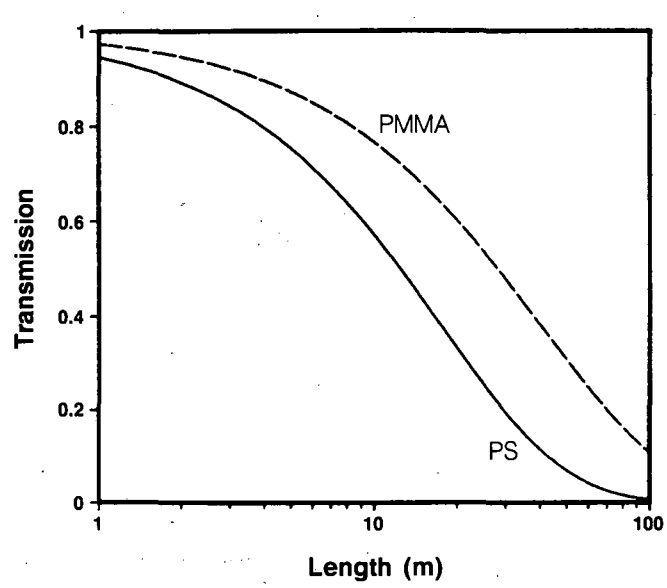


Figure 7. Transmission of daylight by acrylic (PMMA) and polystyrene (PS) optical fibers. (XBL 8412-5272)

and data sets are designed to be incorporated into hour-by-hour building energy simulation programs such as DOE-2.1. To properly analyze fenestration performance in a building context, it is important to upgrade both the thermal and daylighting predictive models. This will not only provide more accurate predictions, but also allow us to predict the performance of new fenestration systems and new architectural designs. Our overall plan for developing and implementing these new features in DOE-2.1 is shown schematically in Fig. 8.

Thermal Analysis

Accomplishments During FY 1983

We used the THERM program, previously developed at LBL, and data from other sources to

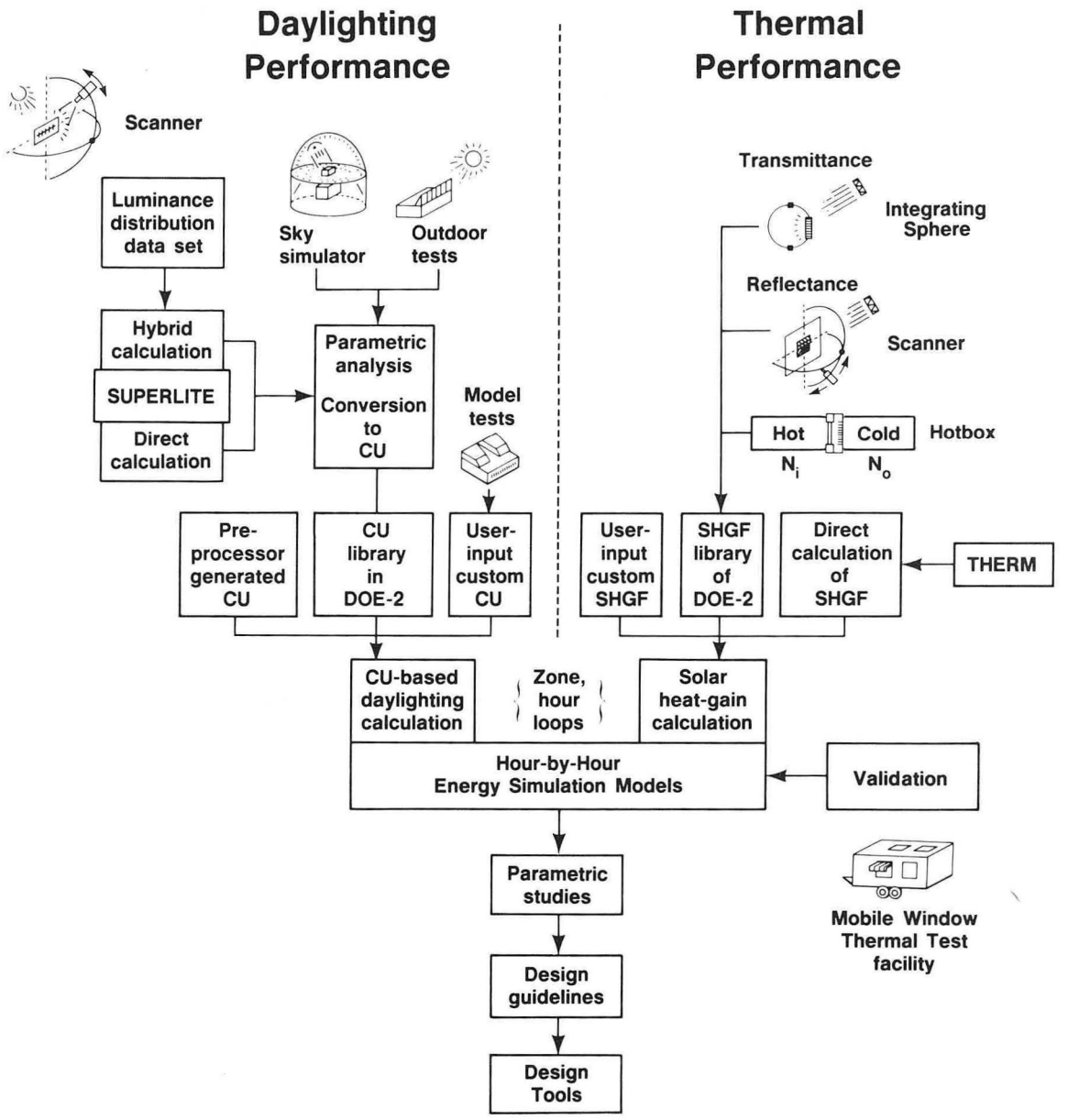


Figure 8. Schematic diagram of DOE-2.1 fenestration modeling capabilities under development. The new solar heat-gain model is shown on the right, the new illuminance model on the left. Both can be generated in a preprocessor, called from a library, or input by the user. (XBL 8212-4972A)

develop the technical basis for revisions to the fenestration chapter in the ASHRAE *Handbook of Fundamentals.* These include calculation of the properties of windows with (1) low-emittance coatings, (2) low-conductance gas fills, and (3) various convective and temperature-dependent boundary conditions. We also participated in an International Energy Agency task group (Annex XII) on fenestration analysis. We will jointly calculate the thermal properties 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.

Planned Activities for FY 1984

We will complete our work on the ASHRAE Handbook's fenestration chapter and continue to participate in the IEA fenestration tasks. The work of Annex XII will continue in 1985.

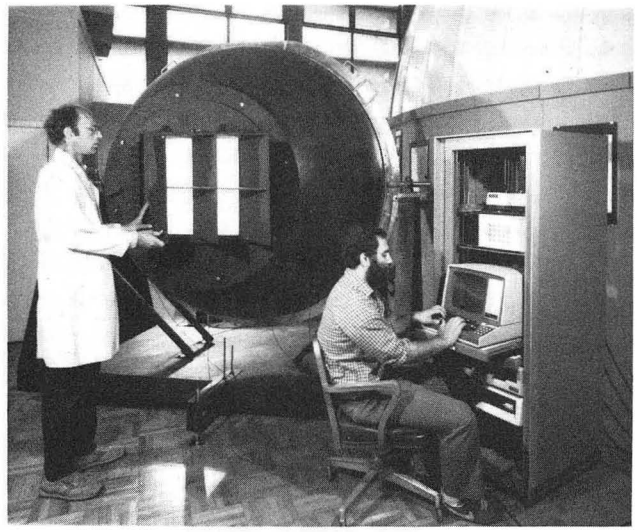


Figure 9. The integrating sphere. (CBB 837-6399)

Solar Optical Models

Accomplishments During FY 1983

The solar-related 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 (Fig. 9) with the window system mounted in a port and illuminated either with an electric source or solar radiation. Construction is nearly completed on this 2-m-diameter sphere. Preliminary results were obtained for shading devices, and comparisons with data obtained from other sources were made. For each sun position, total reflectance will be calculated by integrating measurements of bidirectional reflectance obtained from a scanning radiometer, soon to be constructed.

Planned Activities for FY 1984

The integrating sphere will be completed, and a calibrated series of measurements will be made on commercial and nonstandard shading devices, using both electric and solar sources. The scanning radiometer for total reflectance measurements will be fabricated and tested.

Fenestration Laboratory

In 1977, we established a 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 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 a range of optical properties of glazing materials and coatings to fully characterize their performance.

Accomplishments During FY 1983

The facilities of the Fenestration Laboratory were used primarily to prepare sensors and instrumentation for the Mobile Window Thermal Test Facility and for development of the heat-flow meter, both described later in this report. This work will continue through FY 1984.

Daylighting Analysis

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

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

In previous years, we developed several simplified daylighting calculation methods (e.g., the QUICKLITE program) that are now widely used in the architectural and engineering professions. In FY 1983, we focused on further development and validation of advanced daylighting computational models and related experimental facilities.

Superlite, A Daylighting Illuminance Model

Accomplishments During FY 1983

In order to evaluate the daylighting performance of complex shading devices in SUPERLITE, we adapted a computational approach analogous to that used with electric luminaires. As with many luminaires, direct computation of illuminance from a specific complex fenestration system is often not feasible when the geometrics are complicated and/or the optical properties of the surfaces are complex. Instead, for each specific sun and sky condition, we define a candlepower distribution for the window, which specifies the relative emitted flux at each viewing angle. These distributions can be measured experimentally, as described later. The data are stored in tabular or equation form and used at appropriate points in the calculation procedure. This approach makes it possible for SUPERLITE to model a sun-shading system, as long as the bidirectional transmittance of the material or device (or model) can be measured. Modifications were completed to SUPERLITE to allow it to accept these candlepower distribution data sets. Additional modifications were also completed to permit it to model several standard electric lighting designs. This will allow us to examine the total illuminance patterns due to combinations of electric light and daylight.

In addition to this expansion of the program capabilities, we rearranged the code and modified the input subroutine to reduce the effort required to prepare input. This more compact version of the program is designed to make it available to users who have access only to small-memory computers. We also initiated work on a user's manual to facilitate eventual dissemination of the program beyond our group.

Planned Activities for FY 1984

Testing and validation of the shading-device modeling capability is planned. Additional capabilities for modeling electric lighting systems will also be tested and validated. The validation studies will include the comparison of measured results from scale models with results from the program.

After validation, we also plan to link the program to a data base of candlepower distribution for various standard electric lamps. Once the scanner is completed, a similar data base for window systems will be developed.

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 that have been precalculated by other illumination models or measured from scale models. The internal calculation of daylight illumination for complex designs is generally not practical because it requires significant computational cost and complexity to obtain reasonably accurate answers for a range of complex architectural solutions.

Accomplishments During FY 1983

We have been developing a new daylighting coefficient-of-utilization (CU) model that links illumination models with energy analysis models. In its present form, the CU model consists of seven equations, each of which represents an illumination component (direct or reflected) from an external source—the sun, sky, or ground. The set of equations is derived, using regression techniques, from parametric analysis of illumination-component values taken from data generated with the daylighting calculation model, SUPERLITE. These regression equations describe the illumination components as functions of position in a room and of the design variables relevant to each component. Sample CU models for a small office space are shown in Figs. 10(a) and 10(b).

Planned Activities for FY 1984

The CU model will be expanded into a more general form for modeling various daylighting design strategies and outdoor conditions. This generaliza-

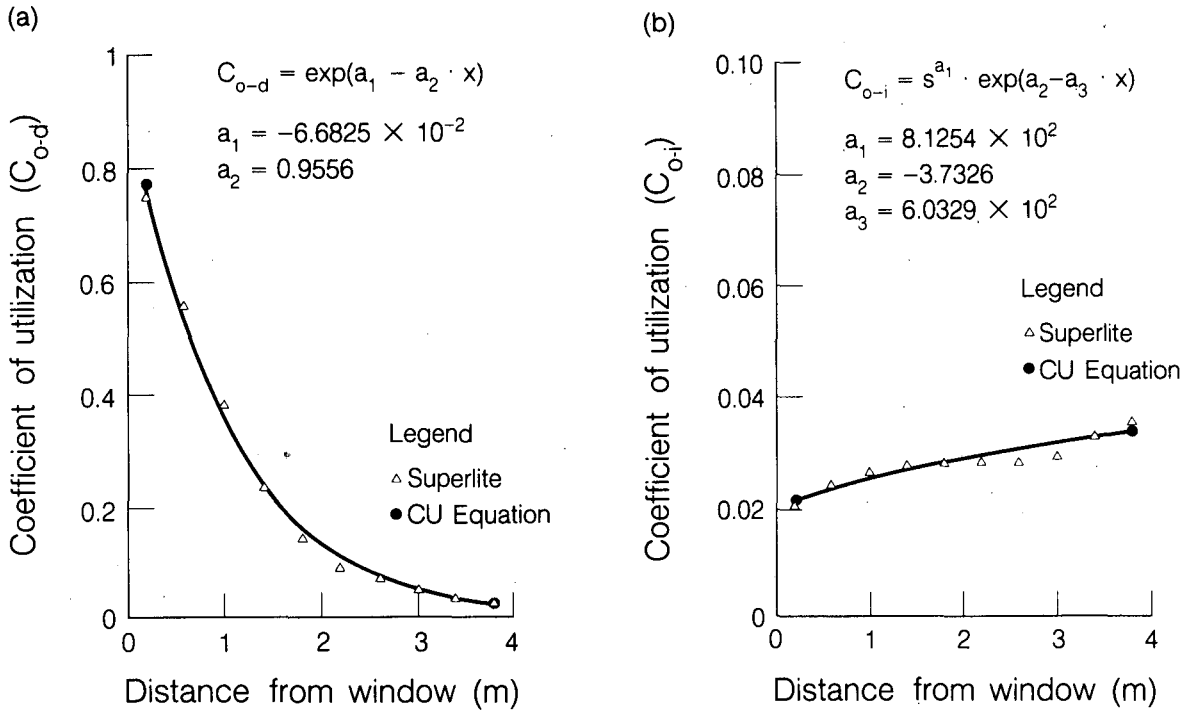


Figure 10. Coefficient of utilization, both (a) direct (C_{o-d}) and (b) indirect (C_{o-i}) components from an overcast sky, for a small office. [(a) XBL 8412-6454; (b) XBL 8412-6455]

tion will require extensive statistical analysis of each component for a range of daylighting variables. A successful CU model not only will provide a more efficient link between illumination models and energy models but also could work as an independent daylighting design tool.

DOE-2 Daylighting Models

Accomplishments During FY 1983

As a result of collaborative efforts with the Building Energy Simulation Group, we completed development and testing of an operational daylighting model in DOE-2.1B. 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. This new daylighting model forms the technical basis for performance optimization studies now in progress.

Planned Activities for FY 1984

The daylighting model will be expanded to simulate more complicated sun-shading devices and more sophisticated daylighting solutions such as light shelves. This improvement will be based on a new coefficient-of-utilization model derived from SUPERLITE calculations or model tests. The new model should enable the program to simulate, without additional revisions, the performance of building designs of arbitrary complexity. The planned procedure for calculating daylight illuminance and solar gains in the next version of DOE-2 is shown in Fig. 8.

Daylight Availability Studies

Using computers to perform energy analysis in building design requires accurate daylight availability algorithms derived from long-term measured data. No reliable source for such data currently exists for most of the United States. To create such a data base, we established, in 1978, a daylighting measurement station on the roof of the Pacific Gas and Electric Company (PG&E) building in San Francisco.

An array of nine pyranometers and photometers collect and record, respectively, the total solar and visible portions of the radiation available at all building orientations.

Accomplishments During FY 1983

We completed analyzing the San Francisco daylight availability data for 1978–1982. 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 sky luminance distribution data agree well with data from currently accepted European models. These results were presented in papers at the International Daylighting Conference. (Sample results are shown in Fig. 11.) To better coordinate research efforts on daylight availability, we organized and hosted a highly successful meeting at LBL in May, which was attended by 10 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.

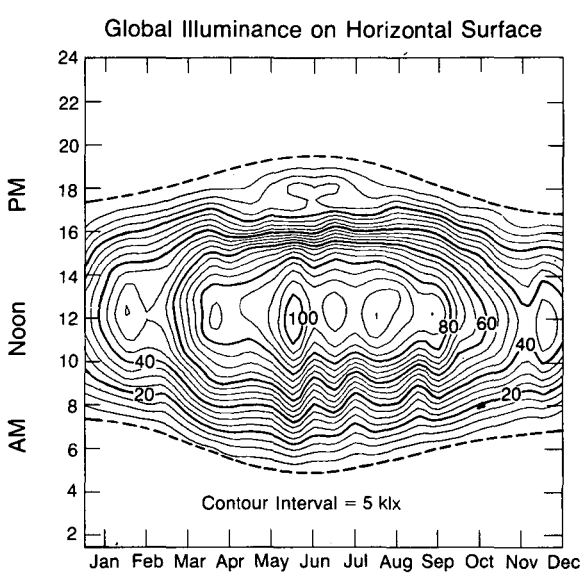


Figure 11. Daylight availability plot. (XBL 844-10362)

Planned Activities for FY 1984

We will use the San Francisco data set to validate a series of algorithms from energy analysis computer programs. The final major analysis task is to determine the dependence of luminous efficacy on atmospheric parameters. We then plan to shift the measuring station to a Berkeley location and add new measurement techniques and instrumentation for future studies. These new instruments will include a sky luminance mapper developed by Pacific Northwest Laboratories (PNL) in Richland, Washington. Collaborative analysis of the data will be undertaken by PNL, Florida Solar Energy Center, and LBL. Continued analysis of our existing data base and these new measurement capabilities should enable us to better understand topics requiring detailed research and to develop data for more standardized daylight-availability models for designers in U.S. climates. The impact, and thus importance, of errors in availability models on energy predictions is not well understood. A small effort will be continued to quantify these errors.

Daylight Physical Modeling—The Sky Simulator

A 24-foot-diameter hemispherical sky simulator (Fig. 12) was designed and built on the University of

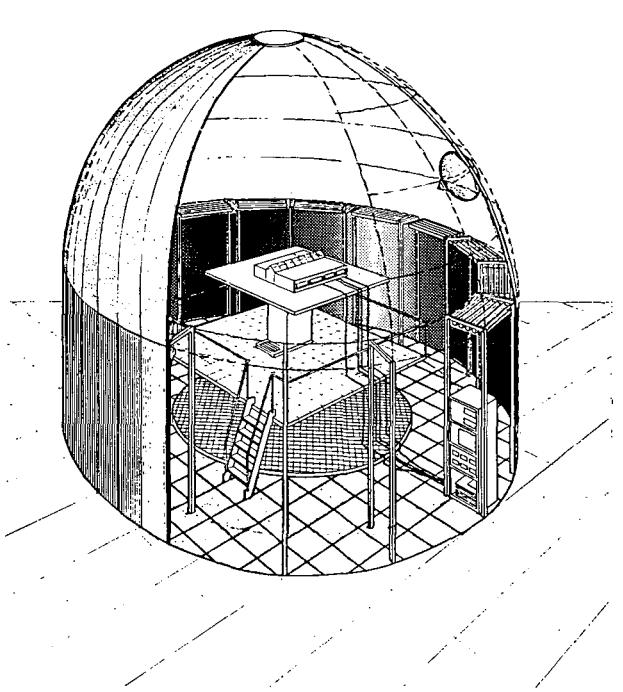


Figure 12. Schematic of 24-foot-diameter sky simulator showing model on platform. (XBL 8412-5328)

California's Berkeley campus in 1979. It has been in operation since 1980 and can simulate 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.

Accomplishments During FY 1983

We completed the design and installation of a 30-inch-diameter sun source in the sky simulator (Fig. 13). This artificial sun is motorized, moving from horizon to zenith on a track. The facility was completely rewired with a new dimmable fluorescent lighting system. A new computer system was installed to control the dimmable fluorescent system, and appropriate operating and data-collection software were developed to facilitate model studies. The sky simulator has already been used to collect test data from scale models to validate a series of computer models and design tools for daylighting design. The sky simulator has also been used by UC graduate students at the School of Architecture and in several instances by design firms to test proposed design solutions.

Planned Activities for FY 1984

The sky and sun simulator will be used to collect performance data in order to study in detail fenestration systems for buildings designed to incorporate daylighting. We plan to use these modeling capabilities primarily in a validation study comparing computer-model predictions with scale-model measurements. We will also use the facility to study the daylighting performance of shading devices and atria. Results of this model study will be entered into a data base that has been developed as an archival source for model measurements.

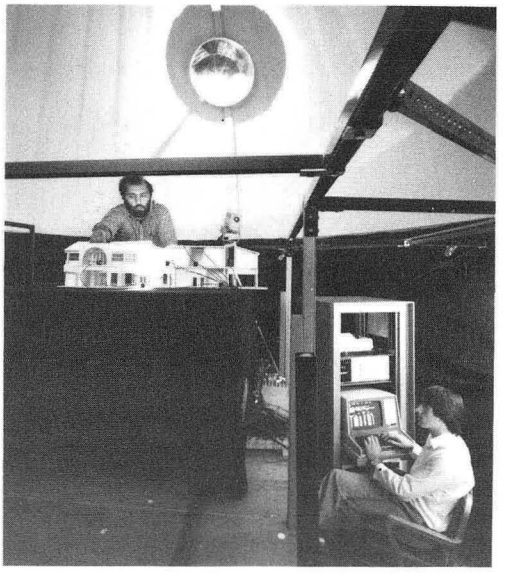


Figure 13. Sun source for sky simulator. (CBB 837-6377)

Daylighting Physical Modeling—Outdoor Scale-Model Testing

Accomplishments During FY 1983

A 3000-square-foot deck was constructed on the roof of Building 90 at LBL. We designed and built four platforms on this deck for scale models. These platforms can be oriented in different directions for simultaneous studies. We installed a new computerized data-acquisition system with 60 photometric sensors. Data collection software was developed to facilitate model studies under outdoor sky conditions.

Planned Activities for FY 1984

The facilities on the roof of Building 90 will be used to collect test data in parallel with our indoor model studies. Differences between these two sets of studies will help us understand how closely results from the standardized sky distributions in the simulator will predict results under real outdoor conditions.

Hemispherical and Bidirectional Transmittance Testing

Accomplishments During FY 1983

The integrating sphere described in the section on solar optical models can also measure hemispherical visible transmittance of materials, devices, and building facades when an appropriate photometric sensor is used. Initial photometric measurements on a number of shading devices were made in conjunction with the thermal analysis testing described earlier. Plans for the scanner, which will measure bidirectional transmittance (or reflectance), are under development.

Planned Activities for FY 1984

Further calibration, testing, and data collection are planned for the integrating sphere. Efforts will

focus on better understanding the properties of shading systems. The scanner prototype will be built and will undergo initial testing.

Design Tools

Accomplishments During FY 1983

During the past 5 years, developing research-specific design tools has been our focus. The potential for accelerating the transfer of these design tools for daylighting and window design to various elements of the building design community was addressed during FY 1983.

We determined that, although we had a number of specific tools either developed or under development, there was an unmet need to compare existing and emerging tools. We initiated an informal collaboration with staff at the Tennessee Valley Authority to develop such a comparison package. An evaluation procedure of this kind will allow users and developers to compare their tools, using a published data set and procedure.

In most cases, the technical development of specific daylighting design tools by our group or by subcontractors was completed during FY 1983. Technical development was completed for four design tools, including:

- *Clear Sky Protractors.* Developed with Harvey Bryan at the Massachusetts Institute of Technology (MIT), the protractors consist of a series of transparent overlays to be used with 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 for an IBM Personal Computer, with color graphics and user's manual, is being developed by Harvey Bryan at MIT.
- *SUPERLITE 1.0.* Responding to numerous requests for this mainframe state-of-the-art computer model, and after developing several versions over the past 3 years for research purposes, we streamlined the program and began development of a user's manual.
- *Daylighting Nomographs.* A manual and set of nomographs to estimate potential and peak-load savings in commercial office buildings was completed. This set of nomographs was reviewed and evaluated by more than 30 users, and changes were made in response to their comments.

Planned Activities for FY 1984

Initial components of the procedure for evaluating daylighting design tools will be developed and tested. A plan will be developed for completing the full procedure.

All four design tools are complete as far as technical content is concerned. Additional testing, graphic development, packaging, and dissemination will be conducted during FY 1984.

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 cooling loads must be minimized, solar gains in winter and useful daylight throughout the year reduce conventional energy requirements. Optimization of window systems thus involves complex tradeoffs between competing requirements. Furthermore, fenestration performance must be analyzed in the context of overall building performance if accurate conclusions are to be drawn. The optimum solutions may be a sensitive function of climate and building type, orientation, and operating parameters. We examine fenestration performance in buildings from three complementary perspectives.

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 building design community. Our work originally focused on thermal performance in residential buildings but has shifted during the past 5 years to an emphasis on nonresidential buildings, including daylighting and peak-load management 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 roomlike chamber, while eliminating or reducing many of the uncontrolled parameters one finds in complete buildings. However, some important performance issues can be understood only by examining them in occupied buildings, so our third approach is a *building monitoring program.*

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 use 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, we know of no prior investigations of the impact of daylighting on peak loads.

Accomplishments During FY 1983

The energy performance of a prototypical commercial office building was simulated with DOE-2.1B for a wide range of glazing properties, window size, lighting load, orientation, and climate. Both skylights and vertical fenestration were included. The first phase of this study examined the impact of fenestration properties, including the effects of daylighting strategies, on office-building energy performance. 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.

A significant result of this study has been the first attempt to quantify the impact of window-management strategies for controlling thermal comfort and glare from windows. Although the specifics vary considerably from case to case (by as much ±50% of an average value of zone energy consumption over a range of typical fenestration parameters), we conclude that, in almost all instances, it is possible to find a fenestration system that outperforms a solid insulating wall, although the solution may not always be cost effective. Daylighting almost always offers the potential for energy savings. For high power densities of electric lighting, this potential is large, but for efficient electric lighting systems having low power densities, daylighting benefits will be smaller and may be quickly overwhelmed by cooling loads from solar gain. We thus conclude that shading design and window management will assume increasing importance for maintaining energy benefits with daylight. Sample results are shown in Figs. 14 and 15.

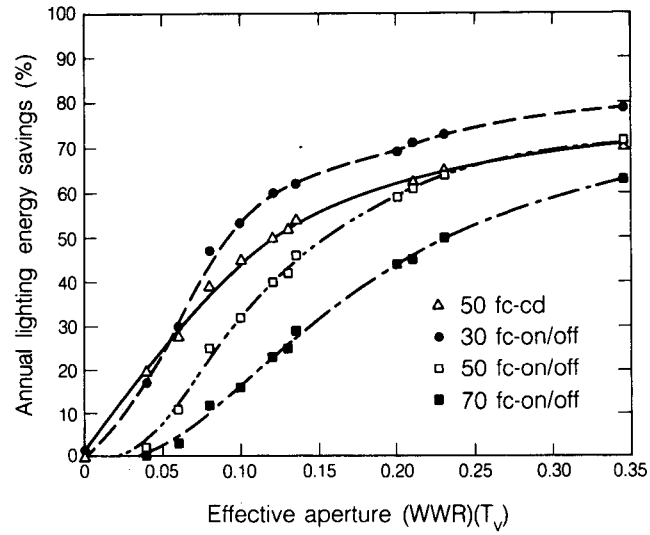


Figure 14. Annual percent lighting energy savings as a function of effective aperture, comparing lighting control type and illuminance variations for Madison, Wisconsin, south zone. (XBL 847-9804)

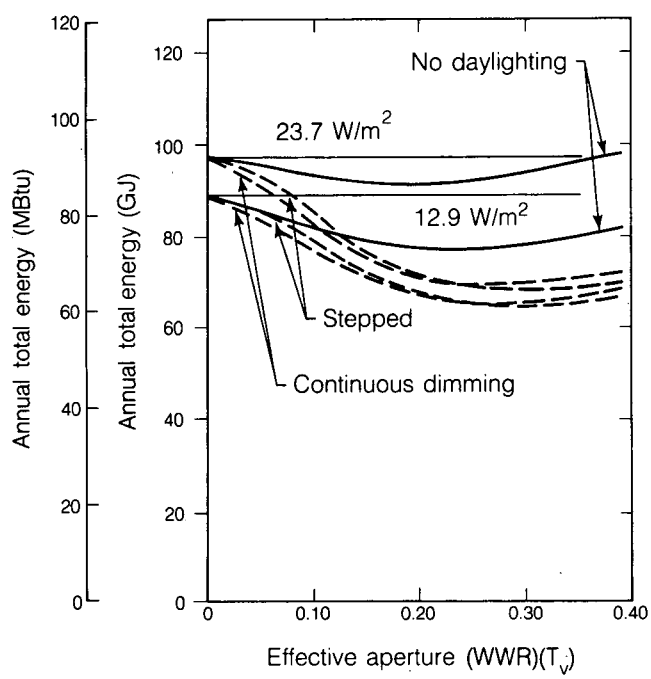


Figure 15. Energy consumption on the south zone of an office building in Madison, Wisconsin, showing the variation in annual energy consumption with window area and transmittance for an opaque exterior wall (thin horizontal lines), a nondaylighted case, and a daylighting case with two types of lighting controls and at two lighting power densities. (XBL 847-9811)

The second phase of this work concentrated on providing quantitative information on the peak-shaving potential of daylighting. Results show that daylighting can significantly reduce the peak 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 due to daylighting, and cooling load increases due to increased solar gain—help determine the combination of window properties that minimize building peak loads. The breakdown of the peak-load component during annual peak conditions for a sample office building is shown for both daylighted and nondaylighted cases in Fig. 16.

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), and cooling loads rise rapidly to adversely affect net annual energy performance. Sample results for several climates are shown in Fig. 17.

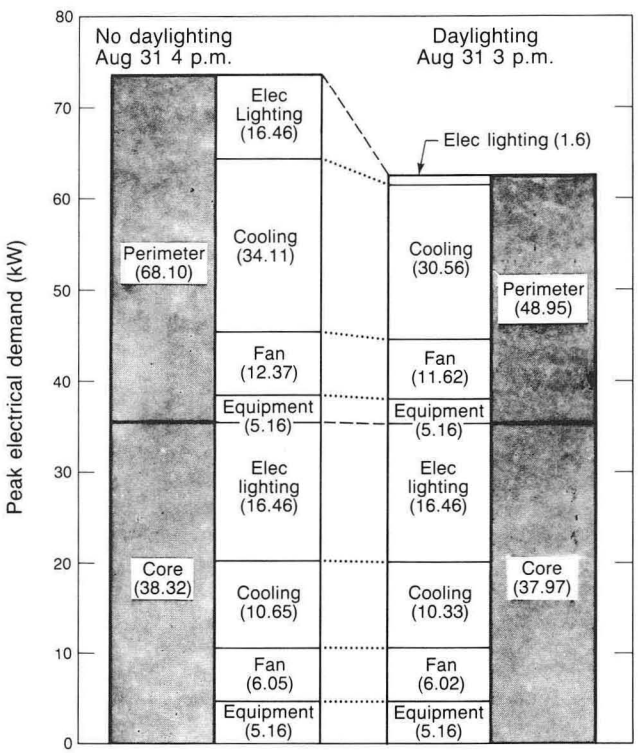


Figure 16. Peak electrical demand breakdown by components, showing distribution between a 10,000-ft^2 cone and a 6,000-ft^2 perimeter for Madison, Wisconsin. Glazing area 71% of floor-to-ceiling; visible transmittance is 0.69; lighting power density is 18.3 W/m^2 (1.7 W/ft^2). (XBL 8312-7444)

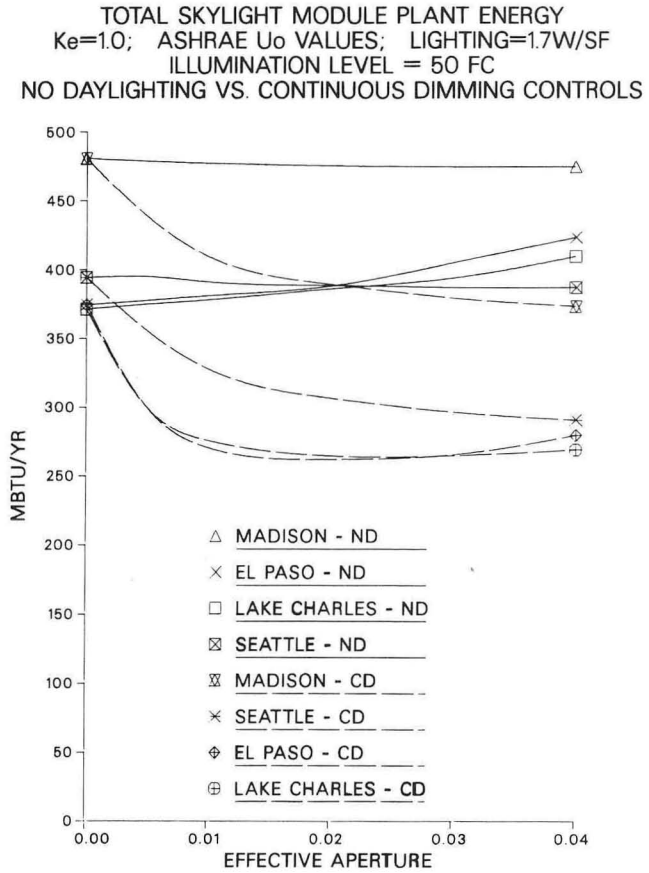


Figure 17. Energy consumption in a skylighted zone, showing variation in net annual consumption with skylight area and transmittance for a nondaylighted and a daylighted case in four climates. (XBL 8411-4635)

The large number of DOE-2.1B parametric runs for window and skylight studies provided a data base sufficiently large to allow use of multiple regression techniques to develop analytical expressions of energy requirements as functions of glazing parameters. The large-scale parametric studies and resulting expressions provide a technical input to an ASHRAE committee developing new voluntary building energy guidelines for nonresidential buildings.

Planned Activities for FY 1984

Optimization studies to date have examined the energy impacts of many of the more important fenestration parameters within reasonable limits of design. Important additional fenestration parameters will be studied, including variations in window-shade energy performance and management strategies, advanced glazing materials, the effects of fenestration performance on HVAC, and the effects of various HVAC options on fenestration performance. The impact of

fenestration design and daylighting on peak electrical demand will also be examined in greater detail.

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.

Simulation Studies—Residential

In previous studies, we examined the impacts of movable insulating systems on fenestration performance in residences. We also compared the performance of several multiglazed insulating window alternatives. In FY 1983, we initiated a new phase of this work to examine in more detail the tradeoffs between conductance and transmittance of window systems. The study will use the regression analysis techniques developed in our commercial building studies and will be included in an International Energy Agency cooperative study on fenestration performance.

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 the derived from a window or window improvement. This is a dynamic property, essential for predicting the performance of managed window systems (windows having thermal/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 currently exists for measuring the net performance of windows *in situ.*

Accomplishments During FY 1983

In 1981, we began constructing a Mobile Window Thermal Test (MoWiTT) Facility to fill this experimental gap (Fig. 18); the facility consists of one or more measurement modules and an instrumented van. The measurement modules, comprising twin guarded calorimeters, will enable dynamic studies to be made of combined solar, infiltrative, conductive/convective, and radiative heat transfers as a function of window type and orientation. During 1983, the major subsystems were checked out, deficiencies identified, and appropriate corrective actions taken. Much of the work to outfit the second calorimeter was completed. By the end of the fiscal year, the facility was nearly ready for its overall calibration tests (Fig. 19). Initial calibration of the

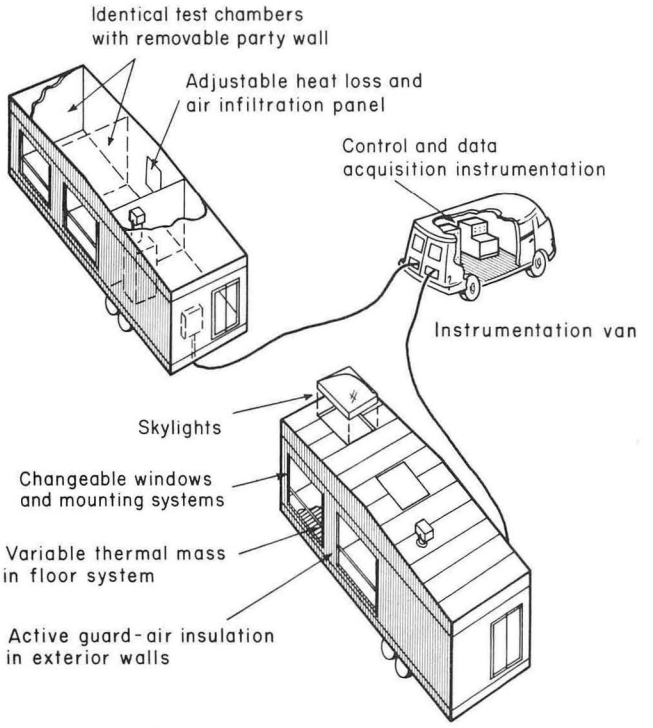


Figure 18. Schematic of Mobile Window Thermal Test (MoWiTT) Facility. (XBL 811-30)

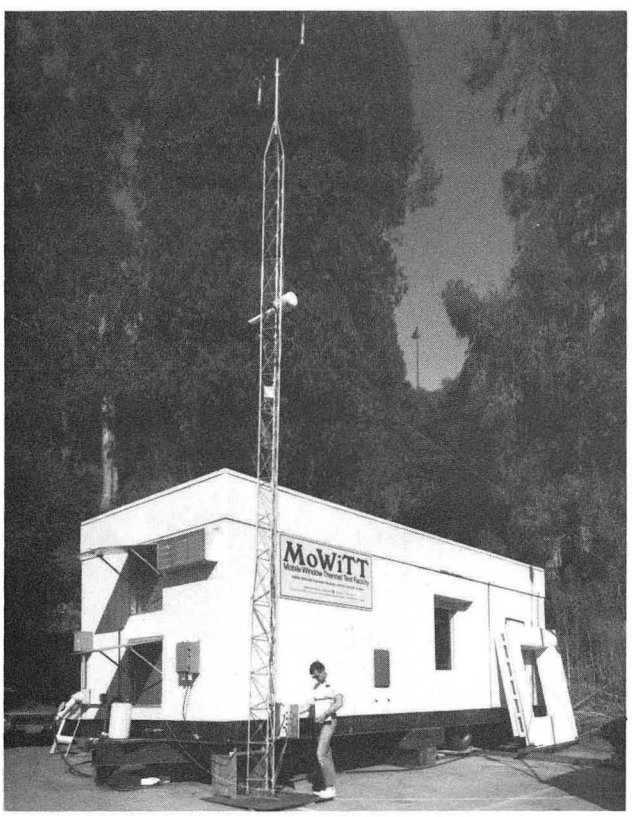


Figure 19. The MoWiTT facility during tests at LBL. (CBB 830-9555)

metering chambers was under way, a draft first-year testing plan had been developed, and preparations were being made to identify and set up a winter test field site.

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 alternating-current 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 1981, a successful one-foot-square prototype was built and tested, and this work was extended to optimize the design parameters for larger units, which were built during 1982. A large calibrated hotplate for calibrating the full-size units was also begun. The hotplates became operational in 1983, and calibration of the heat-flow sensors was begun. By the end of the fiscal year, the heat-flow sensors had been installed in the first calorimeter chamber (Fig. 20).

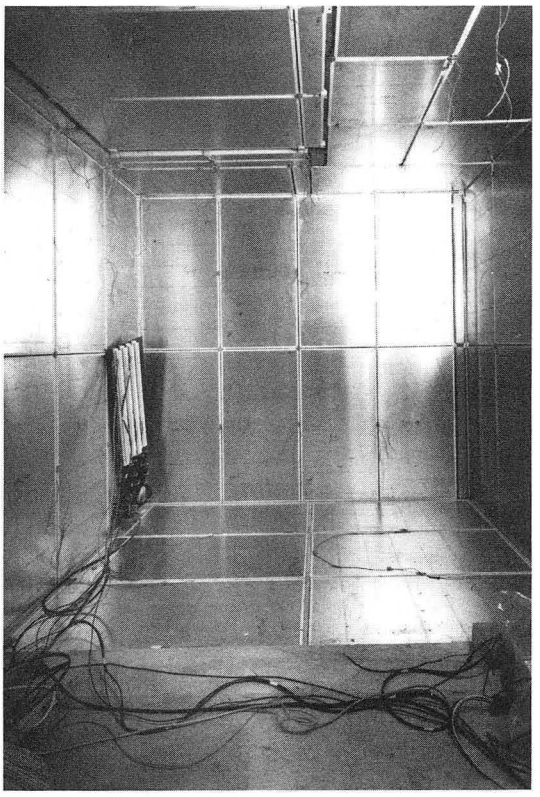


Figure 20. A MoWiTT calorimeter chamber completely instrumented with heat-flow sensors. Window will be mounted in far wall after calibration is complete.
(CBB 838-7737)

Planned Activities for FY 1984

We will finish calibrating the first calorimeter chamber and complete both heat-flow sensor installation and calibration of the second chamber. Preliminary window measurements will be made at LBL to gain operating experience with the facility. The MoWiTT will then be moved to a field site to begin field experiments.

Monitored Buildings

Buildings are rarely built as designed and probably even less frequently operated as planned. For measured energy performance to be accurately quantified, it is essential to monitor fenestration performance in occupied buildings. Results of these studies will be of critical importance to building owners and utility companies. In 1983, with support from Pacific Gas and Electric Company, we developed plans to monitor an award-winning 500,000-ft^2 office building that incorporates a number of innovative daylighting and fenestration systems. The objective of this work will be not only to better understand how the fenestration systems perform, but also to develop a building monitoring approach that collects better data, useful for quantifying fenestration performance, at lower cost than has been possible in the past. We expect to complete development of the monitoring plan and begin deploying instrumentation in FY 1984. We also hope to identify other buildings with innovative fenestration systems that might become part of this monitoring program.

FENESTRATON IMPACT STUDIES

Occupant Response to Fenestration and Lighting Control Systems

Both fenestration controls for daylighting and electric lighting controls must be designed to limit costly cooling and heating loads while providing thermal and visual comfort for building users. To facilitate environmental control, more and more systems, along with advances in computers and applicable software, are becoming available. Yet, in many office buildings where automated fenestration and lighting controls have been implemented, occupants are dissatisfied with their performance. The reasons for their negative responses are complex, and we must study them carefully before we draw conclusions.

Accomplishments During FY 1983

In 1982, to study office-worker responses to lighting and fenestration controls, we developed a survey methodology. The methodology includes a written questionnaire and related physical measurements. The questionnaire asks each office worker to rate his/her responses to lighting and related thermal and acoustical conditions. Also included are demographics characterizing each office worker, including sex, age, and type of workplace, including 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 indicated that the surveys have 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.

Planned Activities for FY 1984

We will complete analysis of results to date, further refine the methodology, and conduct quick walk-through surveys of buildings to better define key issues and to help select candidate buildings for more extensive studies.

REFERENCES

For additional references, see Publications List, pp. 3-91 through 3-93.

1. Hunt, A. J. (1982), *Microporous Transparent Materials for Insulating Windows and Building Applications—Assessment Report*, LBL-15306.
2. Rubin, M. and Lampert, C. (1983), "Transparent Silica Aerogels for Window Insulation," *Solar Energy Materials 7*, p. 393.
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5. Goldner, R.B., *et al.* (1984), manuscript to be published in *Appl. Phys. Lett.*

Building Energy Simulation Group*

J.J. Hirsch, B. Birdsall, W.F. Buhl, J. Bull, D.J. Connell, R.B. Curtis, A.E. Erdem, J.H. Eto, D.J. Hopkins, S. Nozaki, K.H. Olson, R. Sullivan, and F.C. Winkelmann

The purpose of this project has been to create, test, document, and maintain a user-oriented, public-domain computer program that will enable architects and engineers to perform design studies of whole-building energy use under actual weather conditions. The development of this program, known in its successive public generations as Cal-ERDA, DOE-1.4, DOE-2.0, and, finally, DOE-2.1, has been guided by several objectives:

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

As can be seen in Fig. 1, DOE-2 is composed of two major segments: the Building Description Language (BDL) processor, which accepts quasi-English descriptions of building components, and the LOADS, SYSTEMS, PLANT, and ECONOMICS (LSPE) processor, which uses building descriptions to simulate building energy performance. Details of the development and structure of the DOE-2 program are available in past annual reports[1–4] and other published material.[5–9]

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

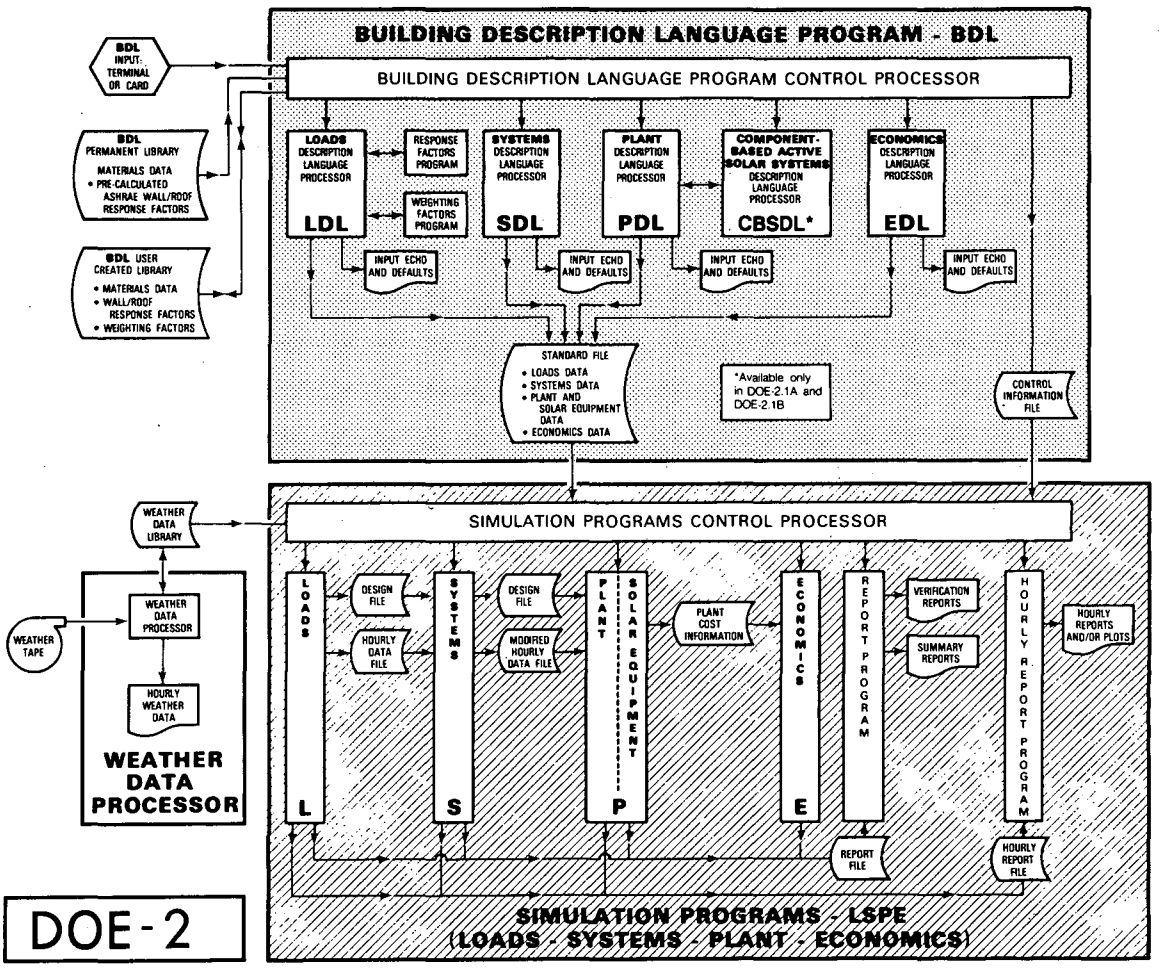

Figure 1. DOE-2 computer program configuration. (XBL 8010-2210A)

ACCOMPLISHMENTS DURING FY 1983

The DOE-2.1B version of the program was released, and updates to the program documentation[10–14] were written and published.[10,11] Additionally, a major update to the *DOE-2 Engineers Manual,*[15] covering the DOE-2.1B daylighting model,[16] was written and released. DOE-2.1B is available on CDC, IBM, and DEC-VAX machines.

Work is well under way on a general revision of the *DOE-2 Reference Manual,*[14] a document of over 1000 pages. It is being divided into two volumes—a basic user's manual, and an advanced reference guide—to improve its use as both a learning tool and a reference.

The Building Energy Simulation (BES) Group also maintains a research effort that continues to develop new versions of DOE-2. (DOE-2.1C is well along.) This ongoing research is divided into three parts. The first involves the introduction of algorithm description techniques into the code. The second centers on modeling building-envelope components and systems. The third is the simulation of heating, ventilating, and air-conditioning (HVAC) equipment and their associated control systems. Major new features of DOE-2.1B and DOE-2.1C in these three areas are described below.

Functional Values

Work was completed on a mechanism for introducing functional values into the LOADS subprogram of DOE-2. This feature will be available in DOE-2.1C and will be extended to SYSTEMS in the upcoming DOE-2.1D. The new capability will allow users to enter one or more FORTRAN-like functions (and even subroutines) directly into the program input; these functions are then compiled by DOE-2 for use in the hourly simulation. We expect this ability to be especially helpful to the research community.

There are two types of applications for the functional values feature:

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

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

The function capability allows simulation of innovative design techniques that could otherwise be handled only by the tedious and expensive process of modifying and recompiling the DOE-2 LOADS program. Figure 2 shows the results of using an input function to model electrochromic glass, an experimental glazing consisting of ordinary glass with a liquid crystal layer whose reflectance can be varied by an applied voltage. In this example, the curve FS is for an electrochromic glass whose reflectance increases linearly in proportion to the amount of solar radiation striking the window. The other curves are for conventional glasses, with and without shading, and the solar radiation.

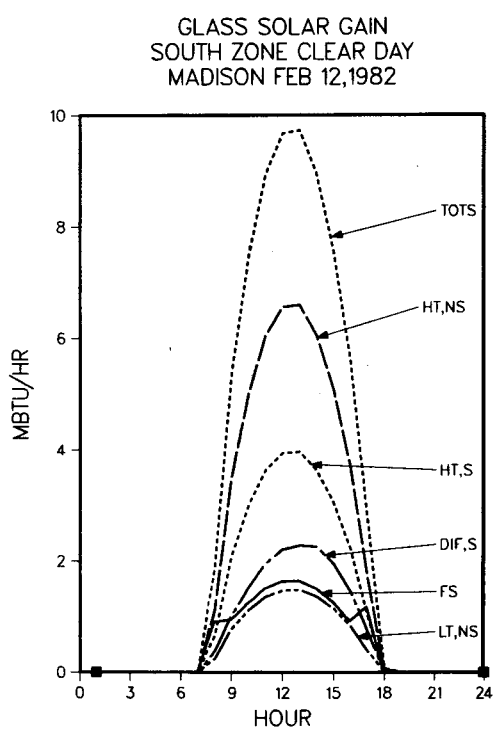

Figure 2. Example of using input functions in DOE-2.1C to model electrochromic glass and compare it with some conventional glasses. Symbols: FS, electrochromic glass (functional shading); HT,S, high transmittance glass with shades; HT,NS, high transmittance glass without shades; LT,NS, low transmittance glass without shades; DIF,S, diffuse solar radiation incident on the glass; and TOTS, total solar radiation incident on the glass. (XCG 849-13261)

Earth Contact Systems Simulation

A major revision dealing with the analysis of earth contact structures such as basements, crawl spaces, slabs, and berms was implemented in a developmental version of DOE-2.1B. The mathematical technique employed the generation of a two-dimensional finite-element model from simplified user-input definitions. From these definitions, weekly response factors were generated for surfaces in contact with the ground. Weekly averaged weather parameters provided the external excitations that define the thermal load within the earth contact space. The revision was based on work previously done to the DOE-2.1A version by Consultants Computation Bureau, a subcontractor to the University of Minnesota's Underground Space Center. Major portions of the revision were as follows:

- Substantial DOE-2.1B input language changes that enable a detailed ground contact model to be defined.
- Transformation of the input language model into a finite-element model that is used to define a set of weekly response factors for surfaces in contact with the ground.
- Addition of routines to the LOADS calculation portion of DOE-2.1B to calculate the ground-contact heat gains and losses, based on the defined set of response factors.
- Generation of a special input to a separate finite element program (ADINAT) from the DOE-2.1B input to verify the calculated response factors.

Construction of the two-dimensional finite element model entailed transformation of the data obtained from the DOE-2.1B input into matrices that define the two-dimensional problem. The input to DOE-2.1B was constructed through the use of several new input language commands and keywords. Underground surfaces were described in a manner similar to the method currently used for exterior surfaces, by defining their layer-by-layer structure as well as their geometric location and size. Similar requirements also exist for the new com-

mands that define the ground structure characteristics.

Testing of these program changes is in progress. The new algorithms must be validated by comparing results with measured data and against other computer programs. The simulation will then be made available in the public version of DOE-2.

Daylighting Simulation

Lighting accounts for about 20% of the total electrical energy consumed in the United States. Using natural lighting is a cost-effective way to reduce this consumption and, at the same time, enhance the quality of the indoor environment. For several years, architects and engineers have used scale models, hand calculator programs, and sophisticated mainframe computer programs (such as LUMEN-II) to determine levels of interior daylight for different building configurations. However, none of these tools determines the annual energy savings from daylighting, information that could have an important effect on design decisions.

For this reason, a daylighting simulation was added to DOE-2. Designers can now quickly and inexpensively determine the hourly, monthly, and yearly impact of daylighting on electrical energy consumption and peak electrical demand, as well as its impact on cooling and heating requirements and, perhaps most important, on annual energy cost.

Taken into account are such factors as window size, glass transmittance, inside-surface reflectances of the space, sun control devices such as blinds and overhangs, and the luminance distribution of the sky. Because this distribution depends on the position of the sun and the cloudiness of the sky, the calculation is made for standard clear- and overcast-sky conditions and for a series of 20 solar altitude and azimuth values covering the annual range of sun positions. The calculations are performed prior to the complete simulation, and the resulting daylight factors are stored for later use. Analogous factors for glare are also calculated and stored.

For the hourly envelope simulation, the illuminance from each window is found by interpolating the stored daylight factors (using the current-hour sun position and cloud cover), then multiplying the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will automatically close window blinds or drapes to decrease glare below a predefined comfort level. Adding the illuminance contributions from all windows gives the total number of footcandles at each reference point.

An example of the daylighting calculation is shown in Figs. 3 and 4. The 400-ft^2 room in Fig. 3 has a 5-ft × 20-ft east-facing window with a glass transmittance of 80%. The window is covered on the inside by fixed drapery having a transmittance of 60%. A 4-ft-deep overhang runs the entire length of the window. Wall, floor, and ceiling reflectance is 50%. The daylighting reference point is located mid-floor at desk height (30 in.). Overhead lighting of 2 W/ft^2 provides 50 fc of illuminance at full power between 8:00 a.m. and 6:00 p.m. The lights can be dimmed continuously to 10 fc at a minimum (30%) power.

The results of a DOE-2 run for a partly cloudy June day in San Francisco are shown in Figs. 4(a) and 4(b). Figure 4(a) shows that the daylight illuminance varies from a minimum of 0.4 fc at 5:00 a.m. to a maximum of 64 fc at 9:00 a.m. Summing over the hours in Fig. 4(b) gives a net reduction in lighting energy use of 59%.

To verify that the DOE-2 daylighting calculation gives accurate results, two types of validation studies have been undertaken.

(1) Parametric analyses have been done to test the sensitivity of each calculation process to key design parameters. For example, the influence of window size, window transmittance, and interior surface reflectance has been examined under a variety of sun and sky conditions.

(2) A three-way comparison has been made among DOE-2, SUPERLITE (a detailed illuminance calculation program[17]), and measurements made in scale models in the LBL sky simulator.[18] Representative results for clear and overcast conditions for a small, single-occupant office model and a large, open-landscape office model are shown in Fig. 5.

DOE-2, with its integrated daylighting model, has already proved to be a powerful tool for researchers investigating fundamental relationships

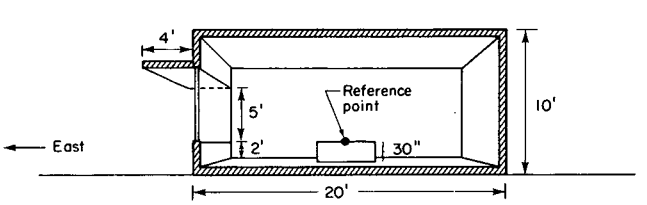

Figure 3. Test model for DOE-2.1B daylighting calculation. (XBL 825-596)

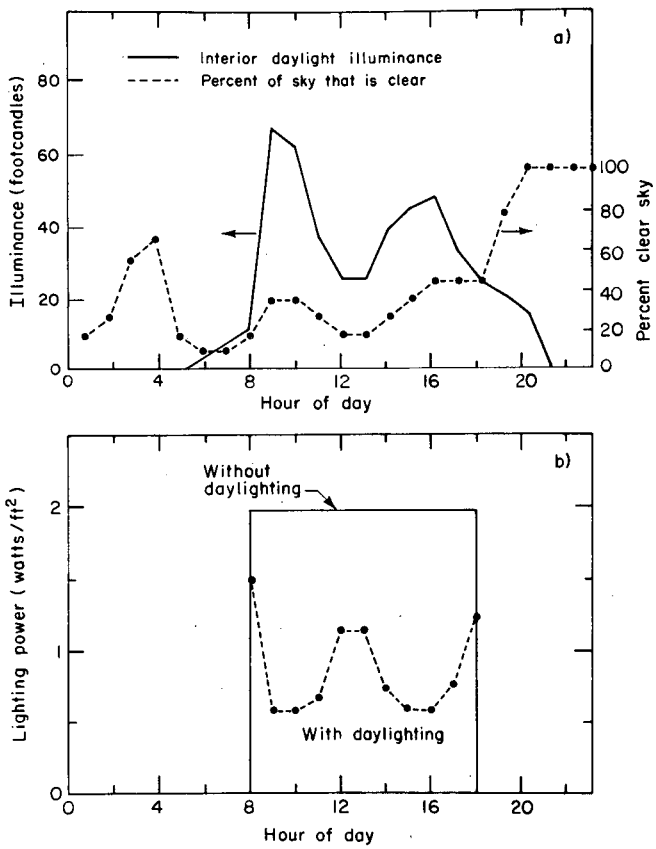

Figure 4. Results of DOE-2.1B daylighting calculation for a partly cloudy June day in San Francisco, for the test module shown in Fig. 3. (a) Daylight illuminance at the reference point and percent of sky that is clear. (b) Power consumption for electric lighting with and without daylighting. (XBL 825-598)

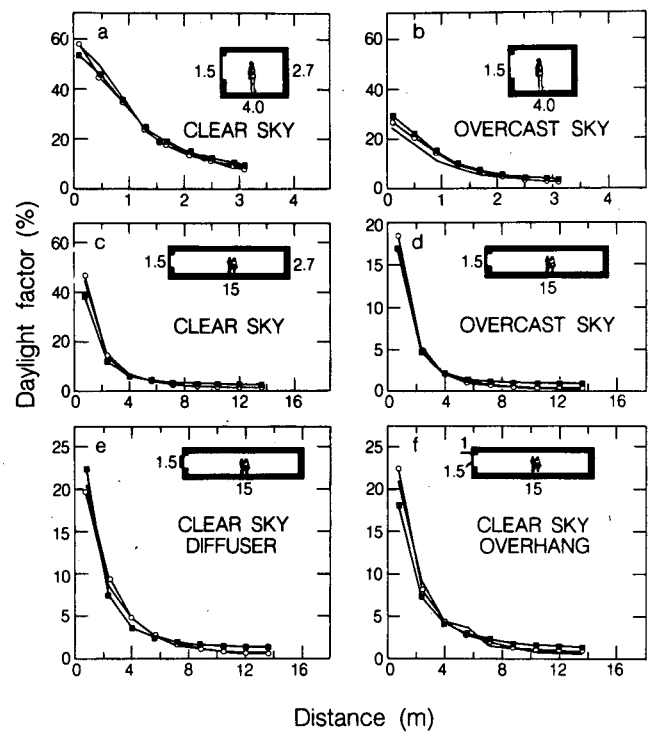

Figure 5. (a)-(f) SUPERLITE (°) and DOE-2 (•) predictions compared with sky-simulator measurements (—) made along centerline of different scale models. Cases of clear sky have solar altitude 50°, azimuth 0°, but exclude direct sun. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, 80% for ceiling. Glass transmittance is 90%; diffuser transmittance in (e) is 60%. (XBL 846-8995)

among fenestration, building energy consumption, and peak electrical demand. For example, DOE-2 was used for extensive parametric studies to investigate building envelope performance as part of a large effort sponsored by the U.S. Department of Energy to upgrade building energy standards.[19] The program is also the basic tool for a series of ongoing investigations of the thermal and daylighting impacts of windows and skylights in office buildings.[20–22]

Sunspace/Atrium Model

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

The new algorithms allow simulation of the different forms of heat transfer between the atrium or sunspace and adjacent rooms. These include (see Fig. 6):

- solar gain through interior glazing,
- convection through vents or open doorways,
- delayed conduction through massive interior walls,
- conduction through interior glazing.

The calculation of the solar radiation that passes directly through the atrium into adjacent rooms is done by using the DOE-2 shadow routines to project the solar image of each exterior window onto the different interior surfaces in the atrium or sunspace. Diffuse solar radiation incident on interior windows is also calculated.

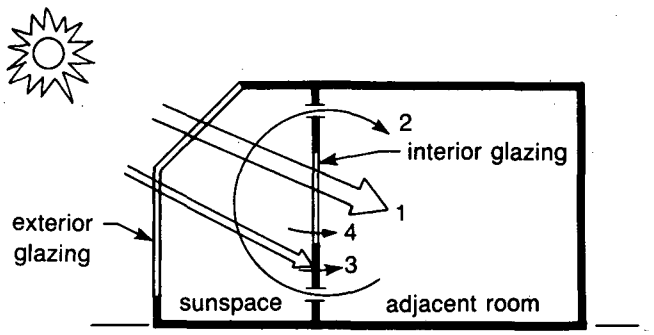

Figure 6. Cross section showing different forms of heat transfer between a sunspace and an adjacent room: (1) solar radiation passing from sunspace to room through interior glazing; (2) natural convection by thermocirculation through upper and lower vents; (3) delayed conduction through interior wall; (4) conduction through interior glazing. (XBL 843-10167)

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

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

Daylight levels in a commercial atrium and daylight in adjacent rooms originating in the atrium cannot be calculated in DOE-2.1B because of the geometric complexity involved. To remedy this situation, the DOE-2.1C atrium simulation allows users (via the functional keyword feature) to input daylight factors obtained from scale model measurements. These factors are then used by the program to calculate hourly daylight illuminance levels and the resulting energy impact.

The French RAMSES group will validate the atrium/sunspace model against its measurements of insolation, temperature, and air flows in different sunspaces in an apartment building near Paris.

Powered Induction Unit (PIU)

As HVAC designers have become more conscious of the need for energy conservation, new systems and configurations have appeared on the market. The DOE-2 program is periodically enhanced to allow it to simulate the most important innovations. A model of one of these, the powered induction unit (PIU), was added to the DOE-2 SYSTEMS simulation in 1983.

Historically, the variable air volume (VAV) system has been the choice for energy conservation. The VAV supplies cold air to a zone in proportion to the need for cooling, thus eliminating much of the need to reheat excess cold air from constant volume systems. As conservation efforts have progressed, some deficiencies in VAV systems have become apparent. One of the easiest and most popular conservation measures in buildings is to reduce internal heat gains, primarily by reducing lighting levels. With conventional VAV systems, however, such reductions can result in very low supply-air flow rates, and little air movement within the space, leading to considerable occupant discomfort. The PIU is an attempt to mitigate this stale-air effect of the traditional VAV system and, in addition, to save energy by reclaiming excess heat from the building core.

The PIU system consists of a VAV terminal box with a small fan or blower that "induces" (i.e., draws) some amount of air from a ceiling plenum. The blower has two functions:

(1) To return warm air from the core zone into the plenum. The fan draws this air from the plenum into an exterior zone requiring heat, thus conserving heating energy.

(2) To provide increased air movement when the VAV damper throttles down the primary air, providing increased occupant comfort. In addition, primary air may be decreased below levels normally allowed in standard VAV systems, thus saving additional energy.

Two types of PIU are modeled—series and parallel. In the series type, as shown in Fig. 7, the fan draws air from both the primary (central system) and secondary (plenum) air streams. The proportion of primary to secondary air is controlled by the VAV damper. The amount of secondary plus primary air

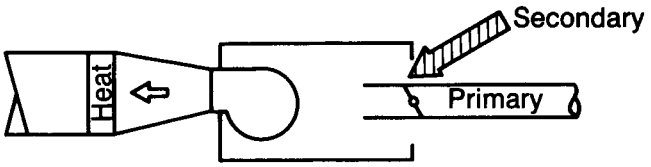

Figure 7. Series powered induction unit (PIU). (XBL 843-10166)

is constant, and the fan runs all the time (when the central fans are on) at constant speed.

The parallel fan unit is slightly more complicated. As shown in Fig. 8, the fan draws air from the secondary air stream only. In addition, the operation of the parallel blower is intermittent. A thermostat set point regulates the turning of the fan on and off. When cooling is required, the fan is generally off. Thus we have normal variable-volume/constant-temperature cooling with the primary air. When the primary air damper is closed and the fan is on, we have constant-volume ventilating/heating. Therefore, total air to the zone is not a constant, as in the series case. The parallel unit may use less energy than a series unit, since the fan runs only when needed.

As originally designed, DOE-2 modeled zones as convectively independent. The exception was plenums—air could be supplied from a plenum to a conditioned zone, or returned through a plenum. However, air could not be taken from a conditioned zone and used as supply air in another zone. With the PIU system, this is now changed. One zone is denoted the supply or "induced air" zone. Return air from this zone is sent through the plenum (or a duct) and is used as part of the supply air for a zone with a PIU box. The induced-air zone is simulated first. The return-air temperature is calculated in the usual way. The return air from this zone is then available at this "return" temperature to be used as part of the supply air for the PIU zones. Frequently, the amount of return air available from the core zone is not sufficient to supply all the secondary air needed for the exterior zones. In this case, the extra secondary air is induced from the exterior zones themselves.

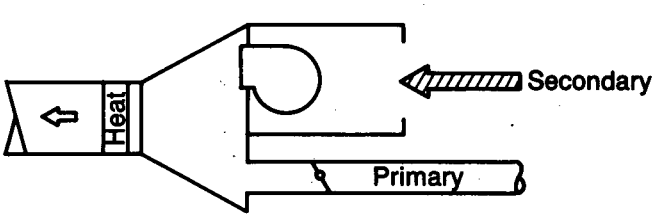

Figure 8. Parallel PIU. (XBL 843-10164)

With the PIU model completed, the DOE-2 group plans to use it to investigate whether the PIU system actually conserves energy and, if so, in what building types and climates.

Heat Recovery from Refrigerated Case Work

Another innovation recovers heat from the refrigeration systems that serve the food display case work in food stores. Almost all new food stores are built with this system. We have therefore added a new set of keywords to the PSZ (Packaged Single Zone) system to allow the simulation of refrigerated case work, with or without heat recovery. The user can specify refrigerated case work with up to three different temperature levels and specify a corresponding load for each level. The temperature levels reflect the evaporator temperatures of different types of display cases for products such as frozen foods, meats, dairy products, and produce. The model can also be used to simulate ice rinks with or without heat recovery.

Other HVAC Simulation Enhancements

The addition of the PIU system was a major enhancement to the program. However, three smaller items, requested by users, were also added in FY 1983:

- *Commercial air/air heat pumps.* Normally furnished with outside-air economizer cycles, these units previously could not be simulated in DOE-2. The heat-pump model was also expanded so that other types of supplemental heating, such as gas furnaces, could be simulated.
- *Updated curves for packaged air-conditioning units and coils.* In 1980, when we first added packaged air conditioning units, we had a great deal of difficulty in getting part-load performance curves from the manufacturers of this equipment. We have since collected better part-load information, making it possible to replace the original curves.
- *Optimum fan start.* Many buildings now have energy management control systems (EMCS) that allow the start-up of fans to be delayed until what is called "optimum start time." Because of its popularity, this energy conservation measure has been added to DOE-2.

Electrical Cogeneration Strategies

The passage of the Public Utilities Regulatory Policies Act of 1978 (PURPA) permits current and potential sites equipped with electricity-generating prime movers (internal combustion reciprocating engines, and gas and steam turbines) to exploit more fully the dual productive outputs of these energy conversion devices. By loosening the constraint that on-site generators meet the entire electrical demands of a facility (PURPA requires utilities to interconnect with cogenerators at equitable rates), the operators of such facilities can now choose an operating mode and schedule that will result in a more efficient use of source energy and yield higher returns.

In FY 1983, work was completed to upgrade the capabilities of PLANT in DOE-2 to simulate the performance of electricity generators under the flexibilities guaranteed to cogenerators by PURPA. The simulations for diesel engines and gas and steam turbines were completely rewritten to use quadratic transfer functions that relate the inputs and outputs of the prime movers directly. The performance curves underlying these functions were taken largely from empirical estimates developed by the Argonne National Laboratory in the late 1970s for the Integrated Community Energy Systems Program.

In conjunction with these revised equipment simulations, the algorithms for allocating loads to the equipment, by default or user-specified operation, were substantially modified to permit the operation of the machines in response to either a thermal or an electrical load, as well as allowing the machines to run full-out.

Researchers and engineers now have a powerful tool for studying cogeneration systems in buildings that can explore the flexibility guaranteed by PURPA. The BES Group performed one such study, examining optimal configurations and operating strategies for cogeneration systems in high-rise office buildings.[23]

New Energy Cost Structure

The passage of PURPA also brought with it a call for regulatory reform in the pricing of electricity and served to underscore the need to upgrade DOE-2 to handle a greater variety of pricing mechanisms for all forms of purchased energy. Thus, as of the end of 1983, a new structure for calculating energy costs neared completion. Symbolized by moving the commands that deal with energy costs from PLANT to ECONOMICS, the new energy cost code is capable of assessing seasonal and time-of-day rates, more complex block rate structures, sophisticated demand ratchets for electricity, and the PURPA-mandated option for the sale of electricity to a utility in the case of on-site electricity generation.

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. It is through involvement with studies such as those described below that the BES Group gathers the information necessary to ensure this relevancy and usefulness.

An extensive thermal and daylighting analysis of building envelopes was undertaken in support of recommendations to upgrade ASHRAE/IES Standard 90. The object of this study was to isolate the energy effects of fenestration and electric lighting designs, to quantify these effects, and to develop simplified analysis tools for compliance use in the building envelopes section of Standard 90. Envelope thermal conductivity, fenestration design, and electric lighting characteristics were parametrically varied through a wide range of values and in a diversity of climates. For these parametric variations, over 5000 DOE-2.1B runs to calculate annual energy consumption were performed. From the resulting data base, a statistical analysis was made in which multiple regression techniques yielded amplified algebraic expressions for important building and climate variables. These equations characterize the annual energy performance trends for cooling, heating, and peak cooling conditions. One result of this work has been a proposed revision to ASHRAE Standard 90A-1980; another is that DOE-2 users can now easily ascertain the energy implications of design options for fenestration, daylighting, and electric lighting.

Following this daylighting and envelope simulation effort, ten real buildings were studied to test the energy conservation effectiveness of the proposed ASHRAE Standard 90E. Each of these ten buildings was reconfigured with two to four typical HVAC systems and then tested across eight climates and three levels of ASHRAE Standards 90-75, 90A-1980, and 90E. Additional analyses were conducted for daylighting on four of the buildings. Approximately 800 test runs were also conducted to isolate the effects of the systems, envelope, and lighting sections of the proposed standards.

The BES Group was also requested to provide technical assistance on a Bonneville Power Administration study to forecast electric energy use over the next 25 years. The forecast was to include the effect of energy conservation measures by the public in

response to energy costs and changes in building technologies. We were requested to help develop building prototypes and review the accuracy of the building modeling portion of the study.

Finally, a study of the effects of fenestration parameters on residential energy use was begun. An initial set of 450 DOE-2.1B parametric runs has been defined for this project. Among the quantities to be investigated are window size, shading coefficient, glass conductance, orientation, and geographic location. Upon completion of the DOE-2 runs, it is expected that a simplified algebraic expression will be developed through the use of multiple regression techniques. This study is somewhat similar to the ASHRAE study described above.

ASEAN Project Support

A research effort analyzing energy use in buildings, funded by the U.S. Agency for International Development (AID), was undertaken jointly by the BES Group and the Energy Analysis Program in cooperation with the Development and Building Control Division of the Public Works Department of Singapore. This project, carried out in Singapore, is one of three AID-funded Association of Southeast Asian Nations (ASEAN)* projects dealing with energy issues affecting ASEAN nations. The results will be transferred and shared among the other ASEAN nations.

The objectives of the project are:

(1) to transfer to Singapore an operational DOE-2 computer code for the analysis of building energy use and the expertise to use it effectively;

(2) to perform jointly a series of analyses that will increase understanding of design and conservation measures, thus increasing the energy efficiency of buildings in Singapore; and

(3) to use the results of the analyses to support the process of extending Singapore's regulations on the energy efficiency of buildings.

The analytical results of this project are described more fully in the report of the the Energy Analysis Program.[24] The BES Group's contribution to the project consisted of training and software transfer.

This began in October 1982, when the IBM version of DOE-2.1A was successfully installed on the IBM-370 at the National University of Singapore. A DOE-2 training session was held in Singapore that December for approximately 15 engineers and architects, using DOE-2.1A. A second training session was held in May, 1983; at the same time, the VAX version of DOE-2.1B was taken to Singapore and installed on the VAX-780 located in the Architecture Division of the Department of Public Works.

*Indonesia, Malaysia, Philippines, Thailand, and Singapore.

PLANNED ACTIVITIES FOR FY 1984

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

The second direction for FY 1984 is to start a project to develop, over the next 5 years, a new building energy use simulation program that is capable of satisfying the current and future needs of the energy-efficient buildings community.

In their present form, all public domain programs are limited in their ability to model not only all the existing building stock, but also new and innovative suggestions for passive solar design and other energy-efficient alternatives. These limitations are built into the structure of the programs and cannot be removed. Research into the potential for energy efficiency in buildings is hindered by these limitations. Consequently, we need to develop a more sophisticated building energy-use analysis computer program that will have the following general properties:

- It will not introduce spurious effects because of its inherent structure.
- It will be modularized with regard to the different kinds of heat-flow phenomena and routes so that (1) different groups can work on different parts of the program synergistically and (2) algorithmic improvements can easily be made to the program as knowledge increases.
- It can be expanded to incorporate new devices and control strategies without altering the rest of the program.

- It will have a "friendly" interface for the researcher so that input will be easy and output can be user-designed.
- It will be portable among the machines of the various major computer manufacturers.

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PUBLICATIONS LIST

This list of publications for the Energy Efficient Buildings Program covers the years 1980–1983. For earlier or more recent publications, please contact each group individually. This list is organized as follows:

- *Energy Efficient Buildings* (EEB)—general reports not specific to any group.
- *Buildings Energy Data* (BED)—reports on the compilation and analysis of building energy performance data.
- *Building Energy Simulation Group* (BES—including DOE-2)—reports concerning computer modeling and programming. (GR stands for Group Report and represents an internal document).
- *Building Energy Performance Standards (BEPS)*—reports concerning DOE's proposed standards for building energy performance.
- *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.

Energy Efficient Buildings (EEB)

1980

EEB 80-1, *Testimony Before the Subcommittee on Energy Development and Applications,* House Committee on Science and Technology, February 20, 1980. A.H. Rosenfeld.

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EEB 80-6, LBL-11332, *Utilizing the Thermal Mass of Structural Systems in Buildings for Energy Conservation and Peak Power Reduction.* C. Barnaby, E. Dean, F. Fuller, D. Nall, T. Shelley and T. Wexler. June 1980.

1981

EEB 81-1, *House Doctor Demonstration, Training, and Retrofit Monitoring Project,* A.H. Rosenfeld, June 1981.

EEB 81-2, LBL-12739, *Accelerating the Buildings Sector's Sluggish Response to Rising Energy Prices,* A.H. Rosenfeld and M.D. Levine, Testimony before the Interior Appropriations Committee, U.S. House of Representatives, April 8, 1981.

EEB 81-3, *Progress in Energy-Efficient Buildings—The Potential for Saving 8 Million Barrels a Day by 2000, at a Cost of $10 Per Conserved Barrel,* A.H. Rosenfeld, Testimony before the Subcommittee on Energy Conservation and Power of the Committee on Energy and Commerce, U.S. House of Representatives, May 20, 1981.

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