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# Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

## ENERGY & ENVIRONMENT DIVISION

FY 1982 Annual Report

## ENERGY EFFICIENT BUILDINGS PROGRAM CHAPTER

March 1983



**ENERGY AND ENVIRONMENT DIVISION**



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

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# ENERGY & ENVIRONMENT DIVISION ANNUAL REPORT

## ENERGY-EFFICIENT BUILDINGS PROGRAM FY 1982

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# ENERGY EFFICIENT BUILDINGS PROGRAM

## INTRODUCTION

In 1982, the building sector accounted for 35% of United States resource energy consumption. In contrast, the energy burned as gasoline represented only 14% of our energy use. Since the crises in fuel scarcity and the attendant rise in fuel prices that occurred in the 1970s, industry has learned to make radical design changes in automobiles and buildings to enhance efficiency at the lowest possible cost and without compromising previous levels of service. In 1975, U.S.-built new cars averaged 14 miles per gallon; by 1985, new cars are expected to achieve about 28 mpg—a doubling of fuel efficiency. For existing buildings, research has shown that present resource energy use can be similarly reduced by 50% through careful retrofitting. New houses and commercial buildings are already being designed to use only half the energy of their pre-1975 counterparts, but our research findings suggest that, to *minimize life-cycle cost, we should—and can*—further reduce this figure to 20% of 1975 consumption—a factor-of-five increase in efficiency.

Although many of these gains would doubtless occur even without public-domain research programs such as ours, the natural time scale for commercialization is 5 to 10 years for cars and 10 to 20 years for buildings. (The energy efficiency of U.S. buildings is currently climbing at the rate of 3% per year.) Four examples of LBL research advancing the development of energy-saving products and techniques by 5 to 10 years will be given below. Each development—in ventilation, glazing, and lighting products—could save U.S. ratepayers at least $5 billion a year in utility bills, or $20 billion in all.

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, including a 350-unit apartment building in Oakland, a smaller Berkeley apartment house, and a high-rise dormitory at the University of California Berkeley campus.

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 new 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. The ESM will allow cost-effective gathering of long-term data on energy use in large numbers of buildings, thus improving the poor statistics on which many analyses of building energy consumption have been based.

### BUILDING VENTILATION AND INDOOR AIR QUALITY (BVIAQ)

An obvious means of improving the energy efficiency of a building is to reduce air infiltration/ventilation. Lowering the air-exchange rate, however, can trap indoor-generated pollutants within the building and enable them to build up to potentially harmful levels. The goals of this program are therefore to furnish a scientific basis for setting energy-efficient ventilation standards and to develop system designs that promote energy efficiency while maintaining the comfort, health, and safety of building occupants. Activities in support of these goals include: (1) development of new methodologies for measuring indoor air quality; (2) laboratory studies of emissions from building materials, soil, combustion appliances, and household products that may affect indoor air quality; and (3) field monitoring of indoor air quality in different types of buildings (schools, office buildings, residences) under a variety of ventilation conditions.

Closely related to this work is the investigation of strategies to prevent and control indoor air pollution without sacrificing energy efficiency. To this end, the BVIAQ group performs laboratory and field tests of various ventilation systems, including those that incorporate heat recuperation. Such 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. This recuperated heat can be used to preheat either incoming air or domestic hot water.

Although the group was founded to study the hazards of reduced ventilation, it became evident that indoor air-quality problems occur even in "untightened" buildings and, indeed, that indoor air (which after all is only outdoor air with some additional pollutants) needs as much attention and monitoring as outdoor air. Specifically, it has found that, throughout the building stock, there are houses with unacceptably high levels of radioactive radon gas, formaldehyde, and combustion products. The problem in these cases is first to remove the sources of contamination and only then to reduce the ventilation.

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 $\times 10^{15}$ 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 multi-zone and multi-story 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 ultra-violet self-absorption in gas-discharge lamps, and the excitation of the plasma gas at ultra-high 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 University of California 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 two-year test of solid-state ballasts in a large office building showed an electricity savings of 40%; scaled to the entire country, this represents an annual savings of $5 billion. The energy-efficient lamps yield a factor-of-three 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, from both direct field measurements and secondary sources. 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 or state agencies. Individual conservation (or solar) measures can be catalogued in order of increasing unit-cost of conserved energy ($/MBtu or ¢/kWh), with careful attention paid to the interactions among conservation and solar measures that affect certain end uses (notably heating, cooling, and water heating). Using this technique, BED creates marginal cost curves (or supply curves) of conserved energy; these are comparable to the supply curves for other market commodities and show the expected levels of production as a function of unit price.

## RELATED RESEARCH 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, rating systems for auditors and appraisers, and energy and peak-power modeling. The Solar Energy chapter summarizes the research of the Passive Solar Analysis and Design Group.

# ENERGY PERFORMANCE OF BUILDINGS (EPB)*

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The Energy Performance of Buildings Group provides fundamental data on the energy performance of buildings. Our results form the basis of design and construction guidelines for new buildings and help the formulation of retrofit strategies for existing buildings. Two of our primary research areas are air infiltration and wall thermal performance. These studies involve work in the field, in the laboratory, and on computer models. A third research area concerns the development of an instrumented energy audit for residences; this audit was released for public use in FY 1982.

## AIR INFILTRATION

Because air infiltration can account for one-third to one-half of annual space-heating and space-cooling energy use, it has been the focus of the largest ongoing project in the Energy Performance of Buildings Group. Infiltration is any airflow that crosses the envelope of the building, and is caused by either natural or mechanical pressures. The resultant energy loss can be reduced substantially in new structures by changes in design and construction; in existing structures, a lesser reduction can be achieved by careful repair and maintenance. The characterization and prediction of infiltration are important for both comfort and indoor air quality as well as for energy conservation.

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Our work in this area concerns measuring, modeling, and reducing air infiltration in buildings. Our objectives are to develop the theoretical and experimental expertise needed by researchers, architects, and engineers; to provide design guidelines; and to develop construction quality standards for optimal air leakage and infiltration. A major achievement of this program has been the development of a model that predicts infiltration from weather data and a single leakage parameter—"the effective leakage area." The magnitude of leakage area can serve as an important criterion for designers and builders and is a useful diagnostic aid for auditors or "house doctors."

### Accomplishments During FY 1982

Accomplishments included analysis and condensation of data collected in previous fiscal years as well as the measurement and reduction of new data. We completed the analysis of data from three field projects that had been carried out in FY 1981 in Rochester, New York, Midway, Washington, and Eugene, Oregon. We performed both leakage-area measurements in all these houses and measured tracer gas decays and indoor air quality in some of them.

Experience gained in making leakage measurements and retrofitting houses was used to produce a guide, called *The House Doctor's Manual*, for the Bonneville Power Administration following completion of the Midway house-tightening project. The guide is divided into two sections: the first provides a description and overview of the house-doctor procedure, including a discussion of heat losses and the tools available to diagnose and remedy them; the second section describes retrofit techniques performed during a typical house-doctor visit.

One of the most interesting experimental techniques we have developed is called AC pressurization. This is a method for determining the leakage of the envelope of a building at low pressures. It has several advantages over conventional (DC) fan pressurization, which uses a "blower door." AC pressurization has a much higher signal-to-noise ratio (i.e., it is more precise), is capable of working in the low pressures typical of natural infiltration (i.e., 1 to 10 pascals), and combines both pressurization and depressurization results simultaneously. The physical process of AC pressurization changes the effective volume of the test space periodically and monitors the resultant internal pressure change; knowing the size of the volume change and the pressure response as a function of time allows the direct (on-line) calculation of leakage.

The first version of AC pressurization was built to investigate the low pressure leakage behavior of a structure and to validate the technique. It was successful and led to the concept of effective leakage area. The second version was a stand-alone system that did not pierce the building envelope; it was designed to calculate the leakage area in real time. Measurements taken in FY 1982 included a study on a single structure at frequencies in the (sub-audible) range of 0.1-3.0 Hz; they showed that the apparatus could respond in real time to changes in the leakage area of the envelope at driving pressures on the order of 1 pascal. A sample output is shown in Fig. 1. The traces show, from bottom to top: the absolute pressure in the sealed back volume behind the piston; the changes in pressure in the test space caused by the changes in volume; the changes in volume in the test space (called the "volume drive," calculated in real time from the absolute pressure); and finally the leakage area, which is calculated in real time from the volume drive and the test-space pressure. The second version has laid the groundwork for a useful field instrument that could replace conventional fan pressurization; the final instrument may operate with acoustic techniques in the 10 Hz range.

The concept of effective leakage area combined with that of weather-induced pressures led to the development of the LBL *infiltration model*. It expresses natural ventilation as a function of total leakage area, wind speed, temperature, and building configuration and can be used to predict infiltration from weather and blower-door measurements for both short-term and long-term purposes. For short-term measurements, the model has an accuracy of approximately 20%; for longer-term averages, it can predict as well as 5%. The model is used in the computer programs Computerized Instrumented Residential Audit (CIRA), DOE-2.1, and BLAST and is included in the 1981 ASHRAE Handbook of Fundamentals. Other institutions have used the model, including the Naval Civil Engineering Laboratory, Retrospectors, and the Bonneville Power Administration.

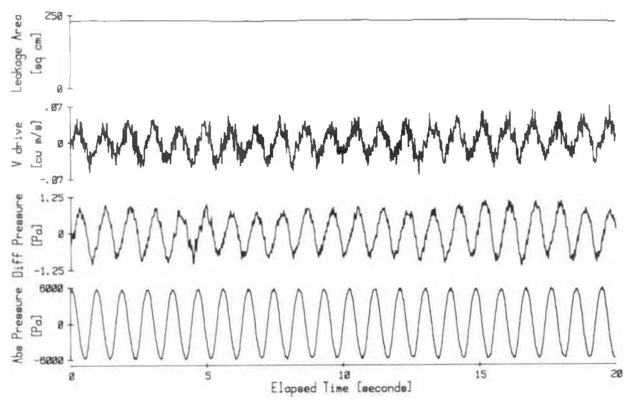


Figure 1. Output from the AC pressurization equipment, which measures effective leakage area in real time without penetrating the envelope of the building. For an explanation of the traces, see text. (XBL 826-10381)

This year we have made several sets of field measurements of infiltration and leakage. Our Mobile Infiltration Test Unit (MITU), a portable, full-size structure, makes simultaneous measurements of infiltration, pressure, wind, and temperature and records them for future analysis. Air infiltration is measured by the Continuous Infiltration Monitoring System (CIMS), which continuously injects a tracer gas. The mobile unit is shown in Fig. 2. Because of

Figure 2. The Mobile Infiltration Test Unit at a site near Fort Cronkhite, CA. (XBB 810-9909)

the value of MITU for understanding and verifying infiltration models, we have continued to make field measurements with it; it was stationed this past winter and spring on the grounds of the Reno, Nevada, airport. Most of our work using MITU has been concentrated on the relationship between measured and predicted infiltration, but we have also used it to monitor independently the interior and exterior pressures on MITU. Figure 3 shows the dependence of the exterior pressure coefficient on angle for one of the faces of MITU. A pressure coefficient is a dimensionless factor giving the increase in pressure caused by the wind. It should be positive for windward orientations and negative for leeward ones.

This summer, we began a project to study the effect of wind on natural ventilation for its usefulness in mitigating cooling loads in hot, humid climates. Three different buildings at the Kaneohe Marine Corps Air Station (KMACS), Hawaii, were instrumented with surface pressure, temperature, humidity, and air velocity probes; on-site weather parameters (air temperature, humidity, wind speed, and wind direction) were also monitored. Field work elsewhere has included an investigation into component leakage in a small sample of houses, and several sets of long-term average infiltration measurements using our low-cost Average Infiltration Monitor (AIM).

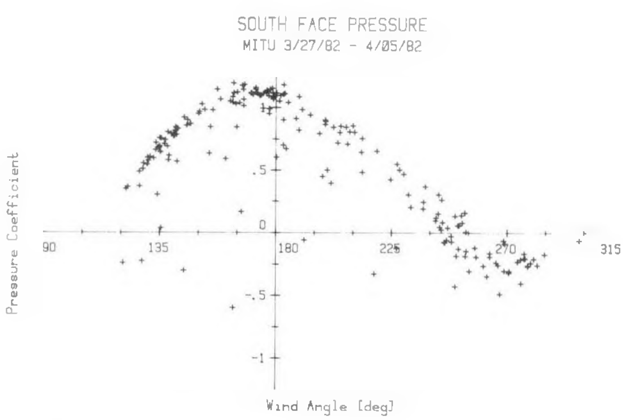


Figure 3. Instantaneous pressure coefficients measured by the Mobile Infiltration Test Unit (MITU) at Reno, NV. (XBL 828-9591)

### Planned Activities for FY 1983

We will continue our research efforts into natural ventilation by analyzing full-scale measurements of wind-induced infiltration; the data from KMACS will continue to be analyzed. If the information is to be useful in hot, humid climates, it will be important to consider comfort levels as opposed to just air temperature in the analysis of the data. As the full-scale work progresses, we will begin to make scaled measurements in a wind tunnel. We plan to develop the AC pressurization equipment into a device that can easily be used to measure leakage area and that would replace the current fan-pressurization apparatus.

In the future, we will extend our investigations into new areas: multichamber infiltration, HVAC interactions with infiltration, and occupancy effects. We plan to instrument a multichamber facility with detailed temperature, pressure, infiltration, and air velocity measurement equipment to study air transport between zones. We plan to use MITU to make full-scale measurements on the interaction between HVAC systems and total ventilation, including flues and chimneys for combustion appliances and vents and stacks (powered or unpowered) for ventilation; we will also consider the effect of duct leakage and total ventilation. Since occupants can make such a large difference to the infiltration and total energy load on the building, we plan to make a large survey of measured infiltration rates in order to extract the occupant contribution to ventilation.

## THERMAL PERFORMANCE OF WALLS

Conduction of heat through a building's walls accounts for a large part of the energy load during the heating season. Although much information is available on the steady-state thermal performance of walls in a laboratory environment, there is very little information concerning actual performance of walls *in situ*. Existing field measurements do indicate, however, that steady-state wall resistances can show significant degradation when compared with standard calculations. The goal of our walls research is to develop a complete methodology for determining the dynamic performance of walls. The methodology contains two relatively independent constituents: (a) a measurement apparatus capable of both controlling and measuring instantaneous, dynamic heat flows and surface temperatures on both sides of an arbitrary wall and (b) a calculation procedure capable of interpreting heat flows and surface temperatures in terms of physical wall parameters. Once complete, this system can be used in the field to determine the behavior of a wide variety of wall constructions and placements and assess their impact on overall energy consumption.

## Accomplishments During FY 1982

Over the course of FY 1982, the major thrust of our walls research program has been to improve our measurement device, the Envelope Thermal Test Unit. Our first field test prototype, ETTU 1.2, built in FY 1981, was field tested early in FY 1982. The device consists of two insulation blankets fitted with computer-controlled heaters and temperature sensors. Tests on walls in the laboratory and in the field showed that lateral heat conduction within the wall and the insulating blanket caused unacceptable inaccuracies in the computation of the heat flux going through the wall.

During the middle part of FY 1982, major modifications of the ETTU 1.2 apparatus led to ETTU 1.3, illustrated in Fig. 4. These modifications were designed to eliminate the lateral heat conduction problem, increase measurement reliability in field tests, and incorporate our "Simplified Thermal Parameter" wall model into the algorithms which control the heat fluxes in the device. To eliminate lateral heat conduction, the surface of the primary heater was divided into a central and an edge region with independently controlled heat fluxes. The heat flux of the edge region is controlled to insure that the surface temperature of the wall near the edges is equal to that in the center section. Combining this control with that of the heaters on the exterior of the insulating blanket, ETTU 1.3 can be described as a hotplate guarded against both lateral and transverse heat losses. The control algorithms for the two "guard" heaters use the "Simplified Thermal Parameter" wall model to account for the dynamic nature of the heat transfer within both the device and the wall. From the mechanical viewpoint, the ETTU 1.3 modifications also reduce the differential thermal expansion that causes the structure to bow during operation.

## Planned Activities for FY 1983

The early part of FY 1983 will be spent preparing ETTU 1.3 for field testing. The hardware will be made more rugged to reduce costly breakdowns during field use. These modifications will also make setup in the field easier. Before the initial field tests, simulations of the apparatus and the wall will be performed using a dynamic three-dimensional finite-difference program. These simulations should allow for quicker field validation, since they provide an independent check on the measurement results.

The Envelope Thermal Test Unit will spend the latter part of FY 1983 at the National Bureau of Standards, serving as a field test device in its first application outside the Energy Performance of Buildings' wall research program.

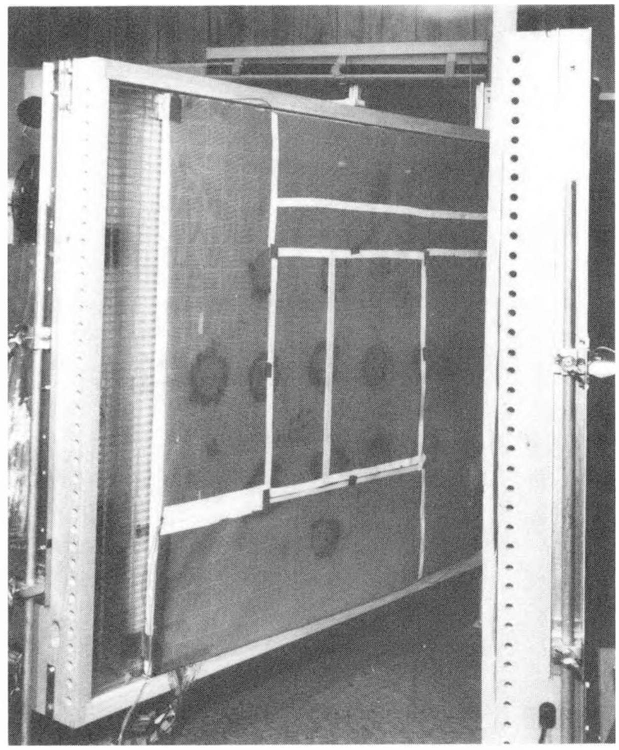

Figure 4. The Envelope Thermal Test Unit (ETTU 1.3). (CBB 832-1129)

# COMPUTERIZED, INSTRUMENTED RESIDENTIAL ANALYSIS (CIRA)

Building energy professionals such as government officials, architects, energy auditors, engineers, and contractors often need to know projected energy use in a given house; sometimes they may need to maximize energy savings within a fixed budget. Although several paper-and-pencil procedures exist to do these tasks, they always require lengthy calculations. Computerized procedures often require strict adherence to a particular input format, or knowledge of a special language. Two recent events promise to lessen the burden of calculations: the introduction of microcomputers and the development of user-friendly programs. Microcomputers have become cheap, and many different brands are available. User-friendly programs do not require the user to describe a building in some rigid format or special language. These programs ask multiple-choice questions in plain English; the user selects the appropriate answer.

Computerized Instrumented Residential Analysis (CIRA), a user-friendly microcomputer program, couples the state of the art in interactive features with the latest developments in simplified computer models of building energy analysis. Its output is either such engineering parameters as month-by-month energy use ("design energy analysis"), or a list of the most economic retrofits to perform on a house. Output is available both on the screen and in printed form as shown in Fig. 5.

Figure 5. Viewing output from the Computerized Instrumented Residential Audit (CIRA) on a video terminal and a printer. (CBB 829-8281)

## Accomplishments During FY 1982

CIRA development has proceeded in two stages. The first, which occurred in FY 1981, was the development of building energy use algorithms suitable for microprocessor applications. This stage included original research into solar storage and thermostat setbacks, the evolution of variable-base degree-days, and the writing of a sophisticated, user-friendly, file-oriented data base language for data input and output. Space heating and cooling predictions using this method have been shown to approximate the results from the DOE-2.1 building simulation program within ±10%. Preliminary comparisons with measured energy consumption data from 42 houses have shown a comparable correspondence between measured and predicted yearly heating and appliance energy consumption, with higher discrepancies for month-by-month consumptions. The second stage was the evolution of algorithms to select the optimal package of retrofits for any given building. This work was carried out in FY 1982.

CIRA has a built-in library of retrofit measures from which it must chose the best package, subject to the conditions input by the user. These conditions include maximum investment, discount rate, time horizon, and energy costs and escalation rates. The catalog of possible retrofits approaches 100 items; it includes envelope performance retrofits (such as increased insulation and air leakage reduction), HVAC modifications (such as replacement burners and duct sealing), appliance improvements (such as water-heater blankets and efficient refrigerators) and other miscellaneous retrofits (such as clock thermostats). From the catalog, the program chooses those retrofits which are applicable to the building under consideration, and ranks them by decreasing savings-to-cost ratio. This ratio is defined for each retrofit as the incremental life-cycle savings (energy savings minus future maintenance and replacement costs) divided by the incremental first cost.

Optimizing a mix of retrofits on a building is a tedious process. It may be compared to the textbook case of ranking investments by return on investment. Each retrofit, then, is viewed as an investment in energy savings, and the monetary savings realized over the years to come constitute the return. However, the analogy is incomplete at best, as the returns on retrofit investments are a moving target. With each retrofit that the "investor" acquires, the rates of return on all remaining retrofits change, generally becoming lower.

In theory, a separate calculation of yearly energy consumption should be carried out for every retrofit to find the energy savings. To reduce the potentially large number of calculations to be carried out during optimization, a scheme has been developed to estimate energy savings by means of partial derivatives of yearly energy consumption. This method has been shown to yield reliable results. From the estimated energy savings, savings-to-cost ratios are calculated.

During optimization, retrofits are chosen in order of individual savings-to-cost ratio until the annual energy consumption has been reduced by an estimated 25%. At this stage, the chosen retrofits are "installed" in the house in the computer memory, the energy consumptions and derivatives are recalculated, and the estimated savings from the installed retrofits are adjusted so that the sum of the savings is correct.

This process of choosing, installing, and adjusting is repeated until either the dollar limit is reached or no more retrofits exist with savings-to-cost ratios greater than one, and the output is then printed.

The strategy used by CIRA to find the mix of retrofits with the largest net life-cycle savings is essentially that used by a blind person to find the highest point of a hill: follow the line of steepest ascent. That is, keep re-rating retrofits and implement those with the highest savings-to-cost ratio until the available budget is used up or the remaining retrofits point down. This pragmatic method is simple but effective. Figure 6, a graphical presentation of the CIRA output, shows how the lifetime savings for a sample house in Washington, D.C., vary with the amount of money invested in an optimal sequence of retrofits.

The yearly energy consumption of a building is neither a linear nor a simple function of the building parameters, let alone of the retrofits affecting these parameters. Furthermore, there is often little correlation between the cost of different manufacturers' wares and their thermal effectiveness. Therefore, unless radical assumptions are made about the cost structure of retrofits and unless the energy calculations are considerably simplified, the elegant analytical techniques of optimization under constraints are difficult to apply. It is partly because of these difficulties that the numerical, tedious approach to retrofit optimization was taken in CIRA. Rating retrofits by estimated savings and installing them in batches also enables the method to be efficient for microcomputer applications.

The economic optimization program was completed and tested, and in March, 1982, the complete CIRA program was released for public use. Response from the buildings community was favorable—several hundred requests for information are received each month—and by the end of FY 1982 approximately 60 copies of the program (which includes a 500-page user manual) had been distributed. Feedback from CIRA users has shown areas where the algorithms need to be improved, and has helped indicate directions where further research is required. It is hoped that the CIRA-users community will quickly become self-supporting.

Algorithm development continued after the program was released. Data from studies at Brookhaven National Laboratory (BNL) were used to produce a function describing the dependence of furnace efficiency on part load ratio, and work continues on the cooling system subprogram. A program was written to produce CIRA weather files from hour-by-hour weather tapes, and files were constructed for 180 U.S. cities. Information is being given to users in Canada, England, France, and Italy to enable them to construct their own files from local weather data. Development of a retrofit selection program was

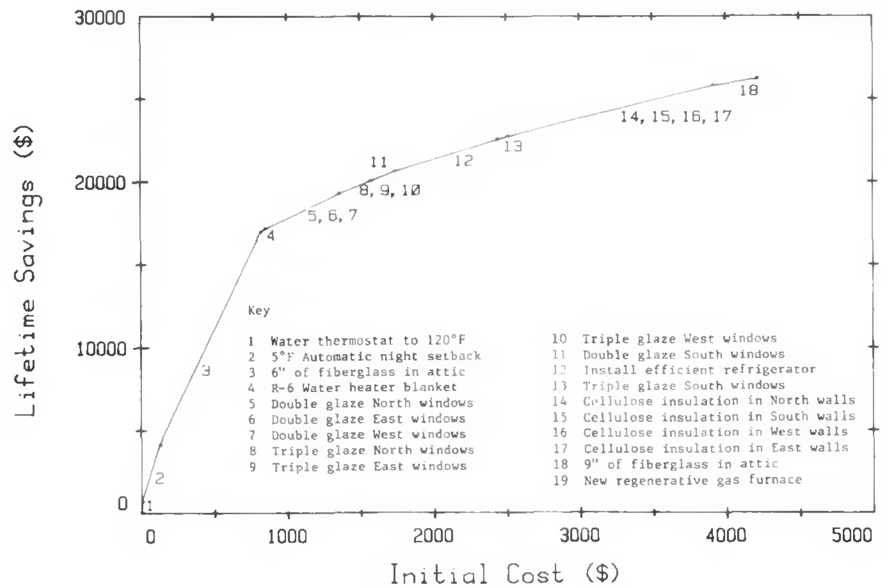


Figure 6. Lifetime savings from an optimized series of retrofits for a sample house in Washington, DC, weather. The data come from an output of the CIRA program. (XBL 8212-12434)

begun; this program will enable the user to choose which retrofits are to be installed at any cost, which are to be considered, and which are not to be considered. The program will also allow the user to change the cost of a retrofit.

### Planned Activities for FY 1983

In the year ahead, we plan to complete the retrofit selection program and to begin two other projects. The first is to adapt the program for small commercial buildings. This will require a re-orientation of the questions asked, and the development of new algorithms for the heating, ventilating, and air conditioning (HVAC) system subprogram. We plan to make use of survey data to ensure that this "commercial buildings" CIRA will find general applicability.

The second project is a longer-term effort: to split off the design energy section of CIRA from the retrofit optimization section. At present, both sections use the same energy calculation programs, CIRASTD and CIRAEGY. These programs are somewhat of a compromise between accuracy and speed. During retrofit optimization, CIRAEGY is used a number of times, once for each loop through the retrofit-sorting program, so it must be quick. An improved algorithm that required an added two seconds of computer time for each monthly calculation would therefore be unacceptable, because it would would increase total calculation time for a 10-loop retrofit optimization by 2 $\times$ 12 $\times$ 10 seconds, i.e. 4 minutes. However, this same improved algorithm would be acceptable for the design analysis, since the added computation time would be less than half a minute; design energy analysis requires one loop only. By splitting the two paths, a more sophisticated set of algorithms could be written for the design energy analysis and the original fast version could continue to be used for retrofit optimization. This project is expected to be completed in FY 1984.

## MULTI-UNIT ENERGY MONITORING

The aim of this project, which started in FY 1982, is twofold: firstly, to quantify design variables and occupancy effects that affect energy use in multi-unit housing, and secondly to work with the private sector in exploring energy utilization in multi-unit buildings. About half of 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, inter-unit air exchange, and heat stealing by adjacent units.

### Accomplishments During FY 1982

We identified a 15-story, 325-unit apartment building in Oakland, California, and secured permission from its board of directors to obtain the submetered billing records by guaranteeing anonymity of the occupants. Data analysis has been done to identify significant physical parameters accounting for the up to five-to-one variation in energy use among units with identical floor plans. Preliminary investigations as to the cause of such large variations have so far met with little success.

### Planned Activities for FY 1983

The second stage of the project is to conduct an extensive occupant survey to understand occupant behavior. Earlier work by other research groups has shown that much of the observed variation in energy for space heating in identical single-family dwelling units is due to occupant effects. On the basis of those results, we expect that occupant behavior will account for a large part of the variation in energy use at these apartments.

To resolve the remaining unexplained variation (if any remains of significant size), we will install Energy Signature Monitors (ESMs, described in the next section) in a selected sample of units. This information should be of great value to electric utilities, especially when correlated with occupant characteristics. In a subsequent funding year, we intend to install retrofits in selected units, matched with a suitable number of controls that have no retrofits installed. This focus on individual units is necessary since the building manager has already requested an energy audit, as a result of which he lowered the building hot water temperature and relamped the common areas.

In a separate project, we will work with a local architecture firm, Hirshen/Gammill/Trumbo, which designs multi-unit housing projects for low-income and elderly populations. During FY 1983, we will use CIRA to evaluate plans for a large multi-unit project having large heating and cooling requirements. Construction details will be reviewed for air tightness, using our past experience with energy-efficient tract housing construction in New York state. In a later year, we hope to install sensors during construction for detailed submetering of all fuel uses, and temperature measurement; this will be done with the collaboration of the local utility. We also hope to evaluate construction quality using fan pressurization. A long-term goal is to structure the project so that builders, designers, and occupants are accustomed to measurement/feedback/learning patterns.

## ENERGY SIGNATURE MONITOR

Long-term measurements of energy utilization in buildings have traditionally used one of two approaches: either analysis of utility bills on a relatively large sample of units, or highly sophisticated instrumentation installed in a few test houses. The first approach may give statistically significant but relatively unspecific information on energy utilization in residences. The latter may be best suited to validate thermal calculation algorithms in computer simulation models; it is not a very cost-effective way to gain information that could be generalized to large classes of houses.

The Energy Signature Monitor (ESM), along with its attendant data analysis software, is designed to bridge the gap by trading some accuracy for much cost. The ESM installation procedure should take less than one man-day of technician time. To realize this goal, most sensor wires will be in an area close to electric service entry (typically a basement), and all sensors will be non-intrusive, that is, installed without interrupting electric or gas lines.

Preliminary data analysis is an integral part of ESM. The electronically stored data will always contain full information as to the sensors used and the house and site identity to avoid time-consuming cross-referencing with logbooks and installation reports. Transformation of raw readings to physical units will be done automatically by the data analysis software without further input by the user.

### Accomplishments During FY 1982

The ESM concept was developed, the prototype unit shown in Fig. 7 was built, and a number of sensors were designed and built. The software for data collection was written. At the end of the year, the unit was given a preliminary field test. ESM has a built-in microprocessor, 4K read-only memory (ROM), 4K random-access memory for intermediate storage, 24K physically removable erasable programmable read-only memory (EPROM), and up to 8 analog and 8 digital ("on-off") low-cost sensors with built-in signal conditioning. A typical installation may monitor the main electric power, heating and cooling systems, water heater, refrigerator, dryer, stove, indoor temperatures, outdoor temperature, solar flux, and humidity (the latter three channels may be "rotated" when several residences are monitored at the same site). EPROMs require no attendant reading or recording devices (ESM fills both of those functions); downloading a full month of data from an EPROM takes less than 30 seconds. Hourly values for each data channel are stored in EPROM, which can hold up to 5 weeks' worth of data. The EPROM is contained in a removable module for on-site replacement and mailing to a central data processing location. Data are retrieved from the EPROM by using an identical ESM unit connected to a microcomputer, a terminal, or a mainframe over a standard RS-232 interface. (In other words, ESM units can be used both to "write" and to "read" data.)

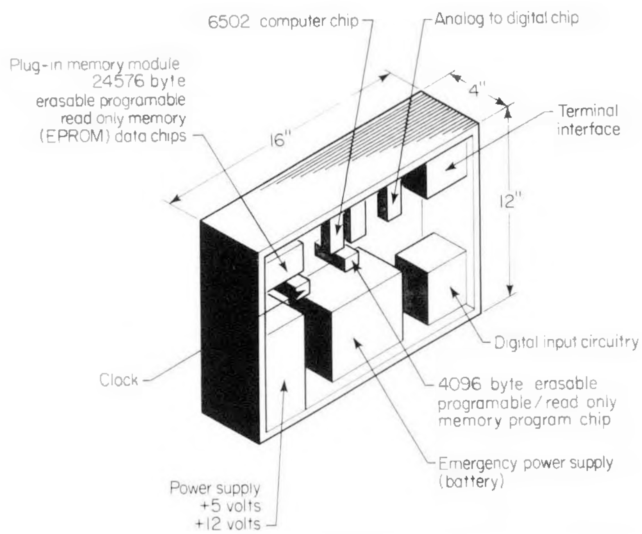


Figure 7. A schematic of the prototype Energy Signature Monitor (ESM). For details, see text. (XBL 831-1000)

### Planned Activities for FY 1983

The ESM with EPROM data storage will be completed. A small number of ESMs will be built, debugged, and field tested. Development of low-cost sensors will continue. Special attention is being paid to non-intrusive sensors for electric power and for gas appliances. A user-friendly software environment will be developed that will perform the functions of data splicing (for periods with missing data), data recovery (for erroneous data), and preliminary summarizing.

# BUILDING VENTILATION AND INDOOR AIR QUALITY*

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Indoor air quality concerns are rapidly becoming a part of the public consciousness. The safety of kerosene heaters, adverse responses to formaldehyde emissions from building materials, the health effects of passive smoking, growing awareness of the "sick building" syndrome, and concern about exposure to radon are among the issues that provoke discussion and controversy. Much of this controversy is caused by a lack of information about pollutant concentrations, their sources, and their health effects.

Environmental questions about air pollution are not new; what is new is a concern about indoor air. Air quality standards exist for outdoor air (the National Ambient Air Quality Standards of the Environmental Protection Agency) and for the indoor work environment (the Occupational Air Quality Standards of the Occupational Safety and Health Administration). However, there are no federally accepted standards for air quality in buildings with general public access. Outdoor and indoor occupational standards are not applicable to general-purpose indoor spaces for several reasons: (1) the time spent indoors is considerably longer than time spent outdoors; (2) many pollutant sources that do not contribute to outdoor pollution are found inside buildings; and (3) occupational standards assume an 8-hour exposure to healthy adults—a description that does not apply to the general population exposed to indoor pollutants. These observations, coupled with the knowledge that ventilation rates are often being reduced to conserve energy, combine to focus concern on air quality within buildings.

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The goals of the Building Ventilation and Indoor Air Quality (BVIAQ) Program are to characterize sources and concentrations of indoor air pollutants, to understand the interplay between building design and operation and indoor air quality, and to develop energy-efficient ventilation strategies that maintain the health and comfort of building occupants.

The BVIAQ program is organized into four project areas: (1) passive samplers and organic contaminants, (2) radon and radon progeny, (3) pollutant emissions from combustion appliances, and (4) indoor air quality control techniques. Major funding sources for the projects are the Department of Energy through its Office of Conservation and Renewable Energy and its Office of Health and Environmental Research. Other funding sources include the Bonneville Power Administration, the Environmental Protection Agency, the Consumer Product Safety Commission and the Office of Environmental Programs of the Department of Energy.

## PASSIVE SAMPLERS AND ORGANIC CONTAMINANTS

Field studies of indoor air quality and the effect of reduced ventilation have been limited because of the high cost of employing continuous monitors. Inexpensive passive samplers capable of measuring daily or weekly integrated contaminant concentrations without attention from trained technicians, external power, or accessories (e.g., pumps or chart recorders) offer a promising means of extending these studies. Large-scale audits could be conducted with these samplers to ensure that the implementation of energy conservation programs does not have adverse effects upon occupant health and safety. Passive samplers would also make possible large-scale surveys of the indoor air quality of existing buildings. Epidemiological studies, which have often relied upon exposures derived from distant, fixed monitors, could be improved by using passive samplers as personal monitors.

### Accomplishments During FY 1982

We have constructed an automatic calibration and exposure system to perform laboratory tests, evaluations, and calibrations of passive samplers. This system allows us to test the effects of temperature, humidity, and pressure as well as the effects of possible interfering gases. The system is controlled by a microprocessor, and the data are logged on magnetic tape. A second facility for testing, evaluating, and calibrating formaldehyde passive samplers has been constructed and used extensively. Recent improvements to this system include the development of a stable source of airborne formaldehyde[1] and the addition of a mass-flow-controlled double dilution system using a high-flow clean-air generator to provide a wide range of formaldehyde concentrations.

*Formaldehyde Passive Samplers*

A diffusion sampler similar to the Palmes nitrogen dioxide sampler[2] was developed for formaldehyde using a glass filter impregnated with sodium bisulfite as the trapping agent and chromotropic acid as the analytical technique.[3] Most of the laboratory tests are complete for this sampler. Limited pre- and post-exposure stability tests demonstrate stability of at least 2 weeks. The quantification range for a 1-week sampling period was determined to be 0.018 ppm to over 1 ppm with good linearity, more than adequate for residential applications. Laboratory tests have also determined that the accuracy of the device is reduced when the average relative humidity exceeds 60% at 25°C. A recent field validation[4] of this sampler was completed in a variety of occupied residences (mobile homes, energy-efficient homes, passive solar homes, and homes with urea formaldehyde foam insulation). As illustrated by Fig. 1, the performance of the passive sampler compared favorably with a reference pump/bubbler sampler, demonstrating good linearity and precision over a wide range of formaldehyde concentrations. The results of the laboratory and field validation tests are summarized in Table 1.

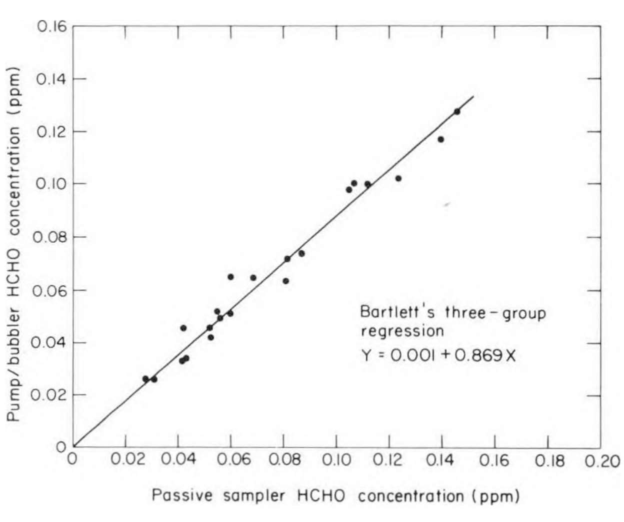


Figure 1. Passive-sampler formaldehyde (HCHO) concentrations versus pump/bubbler sampler concentrations for 21 field comparisons. (XBL 826-824)

Table 1. Description and specifications of the LBL formaldehyde passive sampler.

| CONTAMINANT: Formaldehyde (HCHO) | |
|---|---|
| SAMPLER: | Passive diffusion sampler; area, 3.98 $cm^2$; path length, 9.4 cm; collection medium, $NaHSO_3$ impregnated glass fiber filter |
| ANALYSIS: | Chromotropic acid spectrophotometric analysis, NIOSH P&CAM No. 125 |
| SAMPLING RATE: | 4.02 $cm^3$/min (0.296 $\mu$g/ppm-hr) at 1 atm and 20°C |
| SAMPLING PERIOD: | 1 week (168 hours) |
| SAMPLING RANGE: | 0.018 ppm to more than 1 ppm for 168 hours |
| ENVIRONMENTAL EFFECTS: | Independent of pressure, only slightly dependent on temperature |
| | Accuracy reduced when average relative humidity exceeds 60% at 25°C |
| INTERFERENCES: | No identified significant interferences in residential environments |
| SHELF LIFE: | 2 weeks minimum |
| SAMPLE STABILITY: | 2 weeks minimum |
| OVERALL PRECISION: | Mean coefficient of variation = 6.7% |
| BIAS: | +13% based on field comparisons with reference method; true concentration = 0.87 × passive sampler concentration |
| OVERALL ACCURACY: | True concentration ± 95% confidence interval of 14% |

*Carbon Monoxide Passive Sampler*

We have identified a class of compounds reactive with carbon monoxide that could form the basis for a carbon monoxide sampler.[5] One analytical technique investigated uses the reflectance change that occurs in paper impregnated with one of these compounds upon exposure to carbon monoxide. We have developed a passive sampler based on this technique that has good sensitivity and linearity and have greatly stabilized its response to humidity.

*Nitrogen Dioxide Passive Sampler*

We have conducted extensive tests of the Palmes $NO_2$ samplers, including stability, temperature-dependence, humidity-dependence, and constant-exposure/variable-concentration tests as well as a large field comparison with an EPA reference method. These tests indicate a temperature dependence previously unreported despite extensive use of this sampler in field studies by many researchers.

## Planned Activities for FY 1983

The few remaining tests of the formaldehyde passive sampler will be completed. These tests include face velocity tests and extended pre- and post-storage stability tests. Development and laboratory testing of the carbon monoxide passive sampler will continue, addressing such concerns as stability, accuracy, and the effects of possible interferents. In the latter part of FY 1983, field testing of this sampler will begin, again with parallel sampling using a proven active sampler in a variety of environments. We will also begin development and testing of an inexpensive water vapor sampler based upon the weight gain of a molecular sieve in a diffusion sampler. Finally, we will intensify the literature search on techniques suitable for monitoring carbon dioxide and respirable suspended particles and begin preliminary tests on promising techniques.

# RADON AND RADON PROGENY

Radon (radon-222), a naturally occurring radioisotope and the heaviest of the noble gases, 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 as a leaky container, traps radon released from radium-bearing materials. The predominant source of indoor radon in the United States is the soil underneath a structure, but building materials and domestic water from underground wells can also contribute.

Radon decays to a series of four short-lived radioisotopes, known as radon progeny, which are chemically and physically active. An excess incidence of lung cancer among uranium and other hard-rock underground miners has been associated with their exposure to high levels of radon progeny. Based on studies of miners, exposure of the general population to the estimated mean indoor radon level of 1 picocurie per liter (pCi/l) could account for 2000 to 20,000 lung cancer deaths per year in the United States. Research by our group and others indicates that a small but significant fraction of U.S. houses have radon levels in excess of 10 pCi/l; occupants of these houses receive integrated exposures that are comparable to exposures received by miners in whom excess lung cancer incidence was observed.

Our research efforts are directed towards: (1) identifying housing where indoor radon levels are very high; (2) investigating possible measures to control high indoor radon levels; and (3) developing measures to avoid increases in the mean exposure that might result from, for example, residential weatherization programs. Currently, our work focuses on:

- Characterization of soil as a source of indoor radon, including the transport of radon across the soil-house interface.
- Laboratory and modeling studies of the properties of radon progeny relating to attachment to particulates, deposition on room surfaces, and filtration by mechanical devices.
- Development and evaluation of instrumentation for laboratory and field measurements of radon and radon progeny.

## Accomplishments During FY 1982

*Soil as a Source of Indoor Radon*

A single-family residence near Chicago, Illinois, known to have moderately high radon levels, was intensively monitored from February to July 1982 with assistance from Argonne National Laboratory. The AARDVARK instrumentation system[6] was used to measure air-exchange rates, radon concentrations indoors, airborne alpha activity from the soil near the house and above the sump cover in the basement, times of furnace operation, and weather. Air-exchange rates were commonly in the range of 0.1 to 0.4 air changes per hour; at corresponding times, the radon concentration varied from less than 0.5 to 16 pCi/l, indicating a substantial variability in the apparent rate of radon input. The sump and its connecting drain tile system were identified as a dominant pathway for radon entry. Figure 2 is a plot for a 1-week period of indoor radon concentration, radon source strength (calculated on a mass-balance basis from radon concentration and air-exchange rate measurements), and alpha activity rates for the soil probe and sump monitor. Sump activity, radon concentration, and radon source strength show a high degree of both variability and correlation. The chief cause of the variability appears to be whether or not the pipe connecting the drain tile to the sump is occluded by water; when the line is open, a highly permeable pathway exists between the soil and the house, permitting the infiltration of soil gas bearing several hundred picocuries per liter of radon.

Two laboratory projects studying radon release and transport in soil were initiated: A soil column was established to study diffusion and pressure-driven transport of radon through soil; and a comparison of three techniques for measuring radon emanation from soil was conducted. In addition, we began investigating whether airborne radiometric measurements conducted by the National Uranium Resource Evaluation Program could identify regions in the United States where indoor radon is endemic.

*Radon Progeny Behavior*

Efforts in FY 1982 focused on continuing to establish measurement capabilities at the radon research house[7]; conducting experiments on air movement indoors with natural and forced convection; conducting preliminary experiments on the reduction of indoor radon progeny levels due to forced convection; and initiating development of a model of radon progeny behavior based on a physical air-movement model.

*Instrumentation*

We both expanded and improved our capabilities for measuring radon and radon progeny and associated parameters. The AARDVARK system was augmented by the addition of a radon soil probe and a passive-sampling radon monitor ("radon sniffer"). For the radon research house, the continuous radon monitors were rebuilt with 5-cm photomultiplier tubes and scintillation cells adapted from the design of Lucas[8] to achieve far greater stability of response than in the earlier version. The radon daughter carousel, an automated instrument for measuring indoor concentrations of individual radon progeny, is essentially complete; final performance tests are now under way. Work was initiated on a four-detector alpha-counting system with microcomputer-based timing control, intended for measurements of unattached radon progeny concentrations and analysis of progeny activity

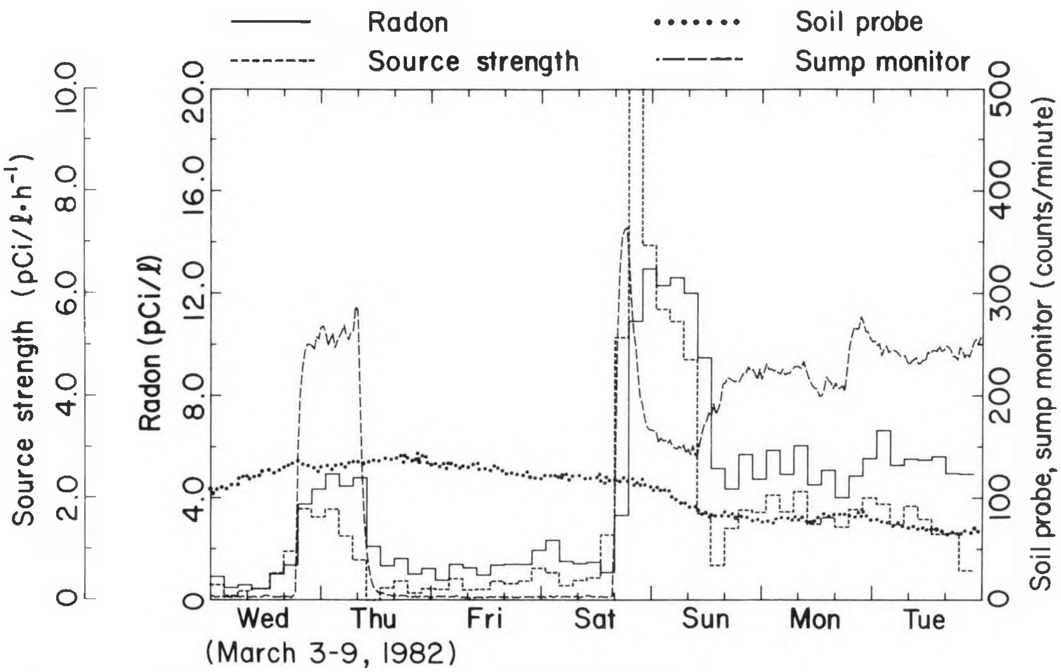


Figure 2. Radon concentration, radon source strength (calculated by mass balance from measured air-exchange rate and radon concentration), alpha activity in soil gas and in air above sump cover in basement of a single-family house near Chicago for the period March 3 through March 9, 1982. For the soil probe and the sump monitor, 100 counts per minute corresponds to roughly 200 pCi/l of radon; these devices also respond to thoron (radon-220) and its progeny and to other airborne alpha emitters so that some counts may not be due to radon. (XBL 8212-12300)

on airborne particulate samples collected with a cascade impactor. The sensitivity of a commonly used procedure for measurement of radon progeny was improved.[9] We began an effort to establish a state-of-the-art particulate monitoring capability for the research house.

Calibration of radon and radon progeny instrumentation continued to receive substantial attention. We continued to participate in the Interlaboratory Calibration of Radon and Radon Daughter Instrumentation.[10,11] We also improved our facilities for primary calibration of radon scintillation flasks, allowing more rapid and precise transfer of radon from the primary standard radium solution to a flask.

### Planned Activities for FY 1983

*Soil as a Source of Indoor Radon*

We plan to conduct two substantial projects in this area during the coming year. The first is a field study of the transport of radon from soil through a crawl space and into a house. The second is a regional assessment of the Pacific Northwest for radon potential based on aerial radiometric data. In addition to these efforts, we plan to complete work on the Chicago field project, and to initiate a study of moisture (and perhaps temperature) effects on radon emanation and transport through soil.

*Radon Progeny Behavior*

Considerable effort will be devoted to completing our particulate monitoring capability at the radon research house. The system is designed to make multi-point measurements of particle number concentrations and size distributions over a range of 0.01 to 5 microns with a cycle time of less than 5 minutes per sampling point. It will be used in conjunction with radon and radon progeny measurements to test the effectiveness of devices to control particulates and radon progeny. We also expect data from these tests to be useful in furthering our understanding of radon progeny attachment and deposition, and in the ongoing development of models of radon progeny behavior.

## 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. Specifically, increased indoor 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 1982, the BVIAQ program conducted detailed laboratory and controlled field tests on unvented gas-fired space heaters and unvented portable kerosene-fired space heaters.[12-14]

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

### Accomplishments During FY 1982

We conducted laboratory investigations of the two major types of portable kerosene-fired space heaters, convective and radiant, measuring their emissions of $CO_2$, CO, NO, $NO_2$, HCHO, and respirable particles, as well as their consumption of oxygen ($O_2$). Tests on portable kerosene-fired heaters were conducted in a 27-$m^3$ environmental chamber, approximately the size of a kitchen or small bedroom. The chamber was operated at a ventilation rate of 0.40 $\pm$ 0.03 air changes per hour (ach). The pollutant emission rates were quantified with a technique we had developed previously to determine pollutant emission rates from a gas range.[15] The monitoring equipment used for gaseous and particulate emissions has been described elsewhere.[13]

All four kerosene heaters tested were found to emit $CO_2$, CO, NO, $NO_2$, and HCHO; additionally, both radiant heaters and one convective heater emitted significant amounts of respirable particles. The concentrations of $CO_2$, CO, $NO_2$, and NO measured during and after operation of a convective heater are shown in Fig. 3. For both heater types, $CO_2$ levels from a one-hour burn reached twice the 8-hour U.S. occupational standard of 5,000 ppm.[16] Levels of $NO_2$ did not exceed the U.S. occupational standard of 5.0 ppm[16] with either heater but did exceed the California short-term (1-hour) standard of 0.25 ppm[17]—by a factor of seven for the convective heater and by a factor of two for the radiant model. Levels of CO from the radiant heaters exceeded the Environmental

Protection Agency's outdoor 8-hour standard of 9 ppm, but were below its 1-hour standard of 35 ppm.[18] The applicability of outdoor air quality standards to indoor environments has yet to be established, and the comparisons are included here only to provide reference values.

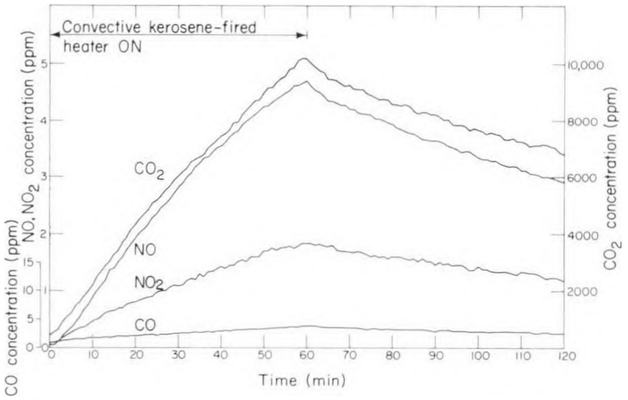


Figure 3. CO, $CO_2$, NO, and $NO_2$ concentrations measured during operation of a portable, convective-type, kerosene-fired space heater in a well-mixed 27 $m^3$ chamber. Fuel consumption was 7830 kJ/hr (7430 Btu/hr), and the air exchange rate was 0.39 ach. (XBL 822-4492)

Laboratory and controlled field investigations of pollutant emissions from unvented gas-fired space heaters (UVGSH) were also conducted. Laboratory investigations demonstrated that, as with kerosene-fired heaters, $CO_2$, CO, $NO_2$, NO, HCHO, and respirable particles were emitted by UVGSHs.[13] Additional tests showed that tuning (i.e., the air/fuel ratio) is extremely important for the emission of CO and HCHO by some heater models. We project that, even under well-tuned conditions, levels of $NO_2$ and $CO_2$ could be well above accepted air quality standards in residences where such space heaters are used and that levels of CO and HCHO could be high, relative to air quality standards, if the appliances are maltuned.

The controlled field investigations confirmed many of the laboratory-based predictions of indoor pollutant levels resulting from the use of UVGSHs.[14] Figure 4 shows the pollutant, temperature, dew-point, and wind-speed profiles during the operation of a well-tuned 31,600 kJ/hr (30,000 Btu/hr) heater in a 240 $m^3$ house at 0.49 ach. The indoor $CO_2$ levels were above the U.S. occupational standard[16] and the $NO_2$ levels exceeded the California short-term standard.[17]

## Planned Activities for FY 1983

We are planning research in three areas. First, we plan to conduct extensive tests of indoor pollutant levels resulting from kerosene heater use under actual field conditions. Various test parameters such as the size of the room heated and the duration of operation will, in part, be derived from a national survey of kerosene heater use patterns. Second, we plan to conduct field tests on pollutant emissions from wood-burning stoves. We plan to test several styles of stoves under controlled, actual conditions. Third, we will be conducting laboratory tests on a new generation of unvented, gas-fired space heaters that incorporate oxygen depletion sensors (ODS). Heaters with ODS devices are designed to minimize CO emission, and our tests will evaluate their effectiveness.

# INDOOR AIR QUALITY CONTROL TECHNIQUES

Techniques for controlling the indoor concentrations of air contaminants include: (1) source suppression or exclusion (i.e., reducing the rate of contaminant entry into the indoor air), (2) ventilation with outside air that has a lower concentration of contaminants, and (3) air cleaning (removing contaminants from the indoor air). Studies at LBL of indoor air quality control techniques include evaluations of the performance of residential mechanical ventilation systems with air-to-air heat exchangers (MVHX systems) and development and evaluation of air cleaning techniques. MVHX systems supply outdoor air with a low concentration of indoor-generated contaminants to the residence and exhaust an equal amount of indoor air with a higher concentration of these contaminants. A MVHX system includes an air-to-air heat exchanger in which heat is transferred between the incoming and exhaust airstreams (without mixing of the airstreams), thus saving energy by preheating the incoming ventilation air in the winter and pre-cooling the incoming air in the summer. Prior to FY 1982, we measured the energy and fan performance of residential MVHX systems in the laboratory,[19,20] assessed their impact on indoor air quality in a field study,[21] and performed a preliminary economic analysis[22] of their use. In FY 1982, we continued our investigation of MVHX systems and initiated studies of air-cleaning techniques, as described below.

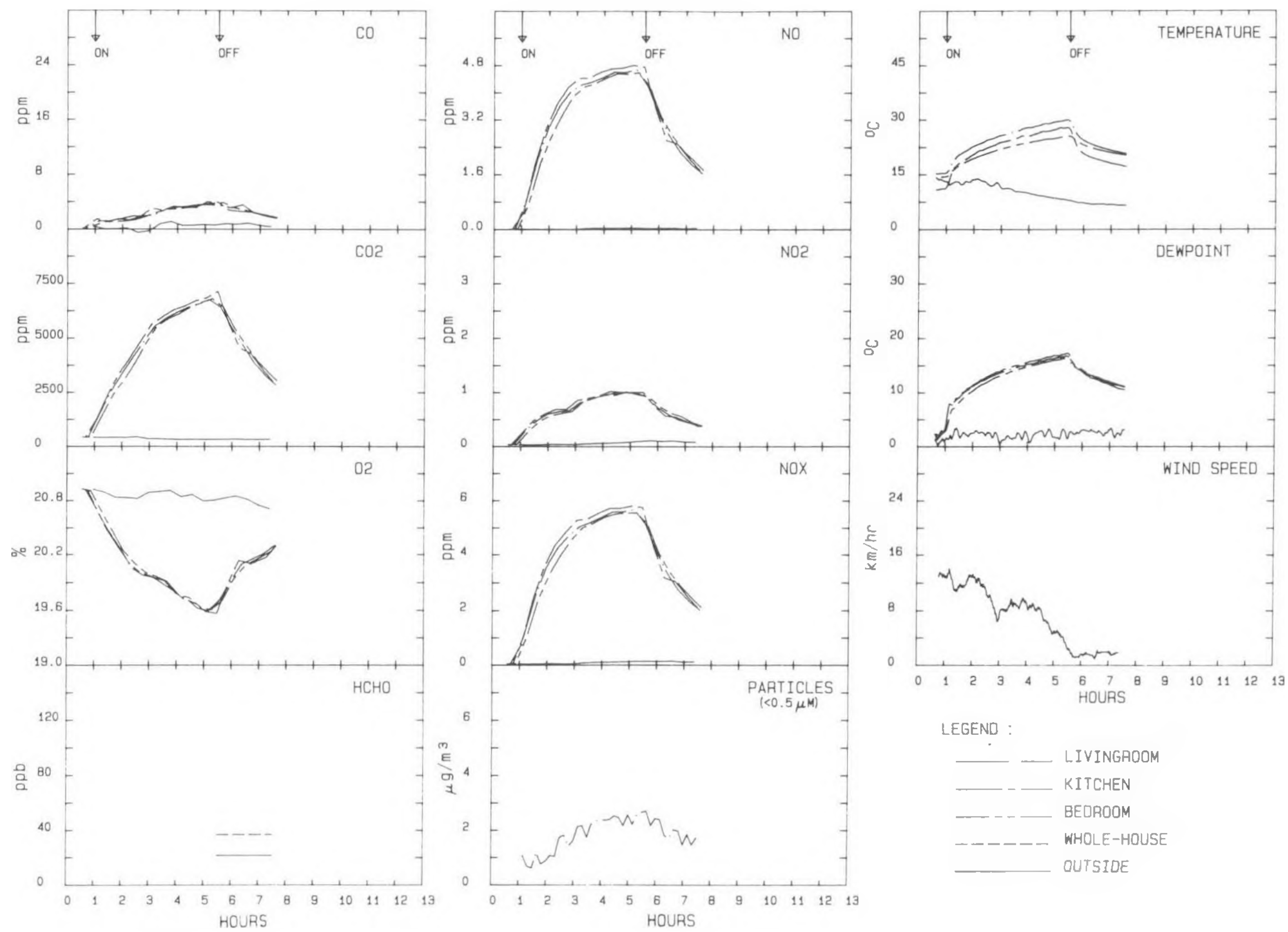


Figure 4. Profiles of pollutant concentration, temperature, dew point, and wind speed measured during the operation of a well-tuned 31,600 kJ/hr (30,000 Btu/hr) unvented gas-fired space heater in a 240 $m^3$ house. The air exchange rate was 0.49 ach. (XBL 8210-4790)

## Accomplishments During FY 1982

*MVHX Systems*

Laboratory research in FY 1982 investigated the problem of freezing within MVHX systems and evaluated the ventilation efficiencies of MVHX systems that use no ductwork for air distribution. In addition, a computer model was developed to assess the economics of MVHX systems. These efforts are discussed below.

If a residential MVHX system is operating when the outdoor air is sufficiently cold, ice or frost can form within the core of the air-to-air heat exchanger and degrade the system's performance, reducing the amount of heat recovery and the flow of the exhausted airstream. In FY 1982, we initiated a study with the following objectives: (1) to determine the indoor and outdoor conditions for which freezing becomes a problem in various MVHX systems, (2) to determine the impact of freezing on system performance, and (3) to evaluate a simple freeze protection strategy that uses periodic defrost cycles. Measurements on one model indicated that, depending on the indoor humidity, freezing begins when outdoor temperatures range from −8 to −3°C. Typical curves of supply-stream effectiveness and exhaust-stream mass-flow rate versus time during freezing are shown for this model in Fig. 5. [Supply-stream effectiveness is defined here as the temperature rise of the incoming (cold) airstream divided by the difference between indoor and outdoor temperatures.] As the figure indicates, freezing causes a substantial degradation in performance.

Our studies included an evaluation of the ventilation efficiencies of two commercially available MVHX systems that are designed for installation through walls or windows.[23] This type of MVHX system is used in the United States more often than systems that require ductwork. To assess their ventilation performance, multi-point measurements of tracer-gas concentration versus time (starting with an initially uniform concentration) were made with the MVHX systems operating in two multi-room structures. Tests were performed to determine the impact of installation location, electric baseboard heater operation, central furnace fan operation, and simultaneous operation of two units.

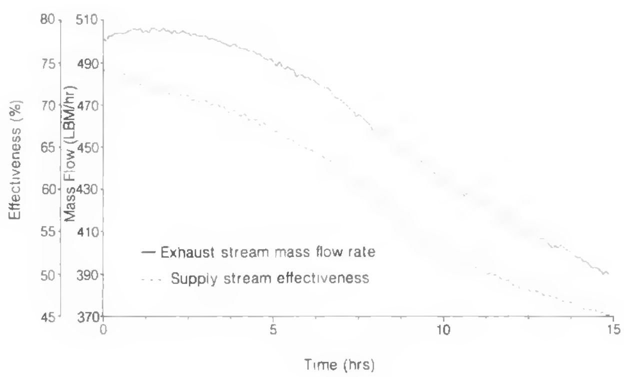


Figure 5. Typical curves of supply-stream effectiveness and exhaust-stream mass-flow rate versus time while freezing is occurring in the core of a cross-flow air-to-air heat exchanger. The temperature and relative humidity of the inlet exhaust stream were approximately 20°C and 30%, respectively. The temperature of the inlet supply airstream was approximately −11°C. (XBL 8211-7330)

Two measures of ventilation efficiency were calculated from the data. The nominal ventilation efficiency compares the measured average spatial increase in tracer-gas decay rate during operation to the increase that would occur for a reference case, assuming perfect mixing of the indoor air and no leakage between the two airstreams of the MVHX system. In 14 tests, nominal ventilation efficiency ranged from 0.44 to 0.66 and averaged 0.54, which indicates that these units provided on the average only 54% of the ventilation that would occur in the reference case.

The other measure is local ventilation efficiency. This was also calculated for the six indoor locations at which tracer concentrations were measured. Local ventilation efficiency compares the measured increase in the local air-exchange rate during system operation with the increase that would occur in the reference case. [A local air-exchange rate is the equivalent rate of air change with 100% outside (tracer-free) air that would cause the observed rate of change in tracer concentration.] A comparison of local ventilation efficiencies at different locations indicates how well the ventilation air supplied by the MVHX system is distributed. When the local ventilation efficiency of a room separated from the remainder of the structure by a closed door in four of the tests is excluded, the difference between the maximum and minimum local ventilation efficiencies ranged from 12% for one test to 63% for another test and averaged 33% for the 14 tests. The ventilation air was therefore not evenly distributed throughout the test spaces. As expected, the uniformity of air distribution was affected primarily by the location of MVHX system. The highest local ventilation efficiencies were at locations near the MVHX system and the lowest were in a room separated from the remainder of the structure by a closed door. This room received essentially no ventilation except when a central furnace fan was operating.

A third component of our study of MVHX systems was the development and use of a computer model to estimate energy savings and costs. The model was applied to MVHX systems with ductwork in new homes (with gas, oil, or electric heat) and to MVHX systems without ductwork installed as part of a weatherization program for electrically heated homes in the Pacific Northwest. For both analyses, we compared energy savings and energy costs in a typical house with those in a more airtight house having the same total ventilation rate but with some of the ventilation provided by an MVHX system. We also considered the winter heating season in four cities with different climates. Economic parameters calculated include net present benefit, benefit-to-cost ratio, discounted payback period, and cost of conserved energy.

The analysis of MVHX utilization in new homes[24] indicated an annual reduction in the load on the furnace system that ranged from 5.3 to 18.0 GJ. The MVHX's fan system required 2.2 to 3.6 GJ of electrical energy per year. The net present benefit and discounted payback period ranged from −$1350 to $2400 and from 5 to over 30 years, respectively. MVHX system performance, ventilation rate, climate, and heating fuel type had a large impact on the economic results. For the analysis of MVHX utilization in electrically heated, weatherized houses,[25] net annual energy savings were smaller, ranging from 1.7 to 2.7 GJ, discounted payback periods were greater than 30 years, and the cost of conserved energy ranged from 7.1 to 9.7 cents/kWh. MVHX systems did not appear economical for this weatherization program largely because of the low electricity prices in the Pacific Northwest. However, the analysis indicated that these systems would be economical in regions with cold climates and high electricity prices.

*Other Accomplishments*

A literature survey of techniques for controlling indoor radon and formaldehyde concentrations was completed,[26] and studies of air cleaning techniques were initiated. A theoretical analysis was performed that indicated the feasibility of employing air washing to remove formaldehyde from indoor air. In preparation for laboratory studies of air washing and other techniques for formaldehyde control, a system that produces airstreams with a controlled temperature, humidity, flow rate, and formaldehyde concentration was designed and fabricated and is undergoing tests. In addition, we made preparations for a study of simultaneous particulate and radon daughter control by means of particulate control devices.

### Planned Activities for FY 1983

In FY 1983 the study of freezing within MVHX systems will be continued, laboratory measurements will assess the feasibility of air washing for control of indoor formaldehyde concentrations, and a study of simultaneous control of indoor particulate and radon daughter concentrations will be performed. In addition, further evaluations of the efficiencies of mechanical ventilation systems may be performed.

## COORDINATION AND SUPPORT OF INTERNATIONAL RESEARCH AND STANDARDS

Members of the BVIAQ program provide technical and administrative support for many indoor air quality issues in the worldwide research community. In FY 1982, this involvement included the following:

- Program members helped organize and coordinate the First International Symposium on Indoor Air Pollution, Health, and Energy Conservation held in Amherst, Massachusetts, in October 1982.
- Members of the BVIAQ Program were major contributors to the National Academy of Sciences publication, *Indoor Pollutants*, published in December 1981.[27]
- A.V. Nero (LBL) and W. Lowder (DOE) served as guest editors of a special issue of *Health Physics* devoted to indoor radon. This issue will contain 38 articles, reflecting the breadth of interest and involvement in this subject; eight of the papers were written by the staff of the radon project at LBL.
- Members of the program helped prepare the "Position Statement on Indoor Air Quality" of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) published in July 1982.[28]
- The BVIAQ program continues to participate as a U.S. representative in Annex IX, "Minimum Ventilation Rates," of the International Energy Agency.
- The program contributes expertise to the American Physical Society "Panel on Public Affairs" on a regular basis.
- The staff participates in reviews of proposals for DOE and the Electric Power Research Institute (EPRI) and referees papers for *Environment International*, *Health Physics*, *ASHRAE Transactions*, and *Energy and Buildings*.
- The group is active in ASHRAE in both standards preparation and the work of technical committees. In particular, we have contributed to the preparation of Standard 62-1981, "Ventilation for Acceptable Indoor Air Quality"[29] and will be participating in its revision as members of the Special Project Committee that has been formed to revise Standard 62-1981.

We consider these support activities to be an essential part of our program and will maintain them in the future.

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## WINDOWS AND DAYLIGHTING*

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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 from the perspective of electron microscopy at one extreme and perform field tests and *in-situ* experiments at the other. We have developed, validated, and now use a unique and powerful set of interrelated computational tools and experimental facilities that enable us to address the major research issues in our field.

It is also critically important that technical data developed by our program be effectively communicated to design professionals and to other public and private interest groups. We participate actively 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:

- Analytical and physical models of fenestration performance
  —Thermal Analysis
  —Daylighting Analysis
- Materials science studies
- Fenestration optimization studies (thermal and daylighting)
- Field testing and *in-situ* performance characterization

## ANALYTICAL AND PHYSICAL MODELING—THERMAL ANALYSIS

### THERMAL MODELS

#### Accomplishments During FY 1982

Analytical models of thermal performance provide a technical basis for much of our research program. We have improved these general models of window heat transfer, as well as our optical and thermal models for windows having multilayer thin-film coatings, such as low-emittance heat-mirror coatings. In FY 1982, we initiated a study to determine thermal conductance, solar heat gain, and relative energy performance as a function of variation in solar optical properties for a variety of window configurations incorporating heat mirrors. Preliminary conclusions

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suggest that environmental conditions (such as wind conditions and temperature gradients) and the placement of the low-emittance film in the window can have a moderate effect on nominal performance values.

The fundamental optical properties of glazing materials must be known to calculate the thermal properties of the complete window system in which they are used. We derived a procedure for obtaining optical constants from photometric properties measured on sheet materials. We had previously completed a study to characterize the long-wave infrared emittance of thin plastic films of polyethylene terephthalate (PET). The emittance of glass should be well-known, but, surprisingly, we continue to find a wide range of contradictory values cited in technical literature. We are therefore completing a study to provide all the optical and emittance data necessary for thermal modeling of glass sheets.

The solar optical properties of windows change with the sun's angle of incidence. For geometrically complex shading systems (such as "egg crate" louvers), no adequate models exist to predict solar heat gain as a function of angle of solar incidence. 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 based on a standard series of laboratory measurements of the fenestration system's optical properties. Transmittance will be measured using a large integrating sphere with the window system mounted in a port in the surface and illuminated with a sun simulator. For each sun position, total reflectance will be calculated by integrating measurements of bidirectional reflectance obtained from a scanning radiometer. The calculation of solar gain based on these optical measurements is computationally efficient and sensitive to sun position, making it useful in hour-by-hour energy analysis programs. Small prototypes of the integrating sphere were constructed and successfully tested in FY 1982.

### Planned Activities for FY 1983

We will make further refinements to our window heat-transfer models and complete additional validation studies. The study of the thermal properties of window systems incorporating heat mirrors will be expanded. Major new efforts will focus on developing the new solar heat-gain computational model and associated experimental apparatus. We will complete a full-size (7-foot-diameter) integrating sphere; a scanning radiometer for total reflectance measurements will also be fabricated and tested. The new solar heat-gain model to be incorporated into DOE-2.1 is shown schematically in Fig. 1.

## AIR INFILTRATION MODEL

During FY 1982, we extended the basic models developed by the Energy Performance of Buildings Group; our new models predict, as a function of window and building properties and of climate, the annual energy savings due to reductions in air leakage of windows in residences. We concluded that the annual energy consequences of window air leakage are often seriously overstated because of improper extrapolation from instantaneous test results to annual average performance.

## LABORATORY FACILITIES

### Accomplishments During FY 1982

In 1977, we established a Building Technology 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. Testing facilities include a calibrated hotbox (Fig. 2), which is being used to test the thermal performance of windows and associated energy-conserving window accessories. A sample of devices now on the market was tested to establish a baseline against which to compare future improvements in window performance. Data from this test facility have also been used to validate our computer models. Air leakage tests on windows are made in this laboratory by measuring air flow for a range of positive and negative pressure differentials across a window. We have also developed capabilities for measuring a range of optical properties of glazing materials and coatings to fully characterize their performance.

During FY 1982, the facilities of the Building Technology Laboratory were used to prepare sensors and instrumentation for the Mobile Window Thermal Test facility and for heat-flow meter development, both described below.

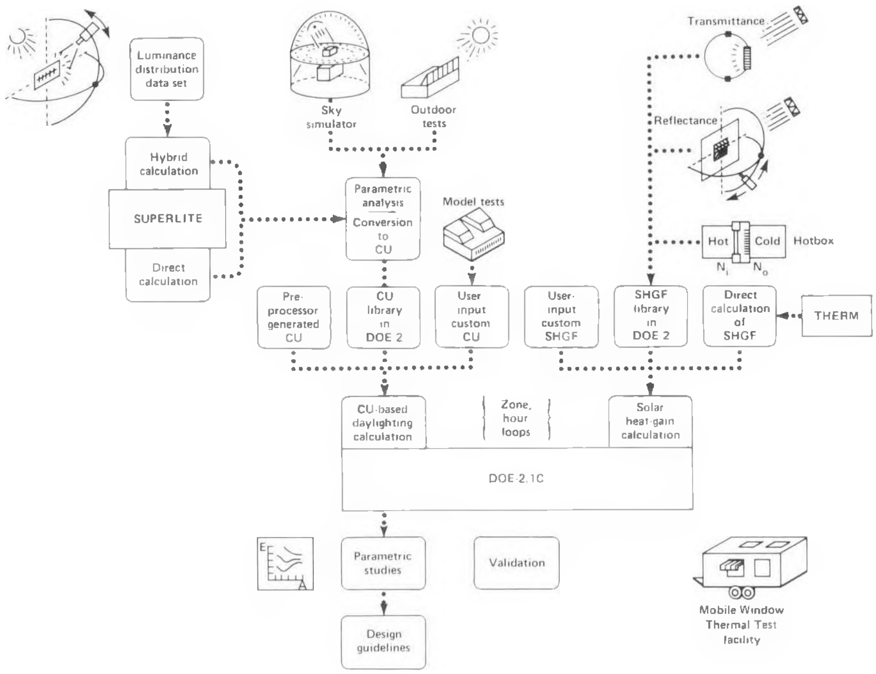



Figure 1. Schematic diagram of DOE-2.1 fenestration modeling capabilities under development. The new solar heat-gain model is shown on the right, the new illuminance model on the left. Both can be generated in a preprocessor, called from a library, or input by the user. (XBL 8212-4972)

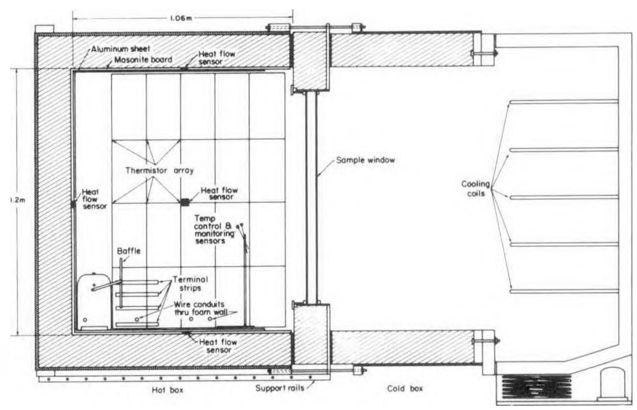



Figure 2. Cross section of calibrated hotbox showing hot and cold chambers and sample window. (XBL 799-2921A)

## ANALYTICAL AND PHYSICAL MODELING—DAYLIGHTING ANALYSIS

To predict the energy consequences of daylighting strategies, one must be able to predict the daylight illuminance distribution pattern in a building from any window or skylight under all types of sun and sky conditions. Since no single approach provides the best solution, we use a variety of techniques to assess different aspects of daylighting performance.

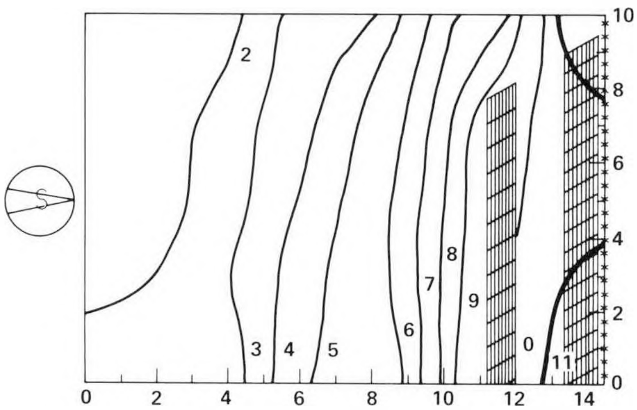
In previous years, we developed several simplified daylighting calculation methods (e.g., QUICKLITE) that are now widely used in the architectural and engineering professions. In 1982, we focused on further development and validation of advanced daylighting computational models.

### SUPERLITE, A DAYLIGHTING ILLUMINANCE MODEL

#### Accomplishments During FY 1982

This large, main-frame computer program was developed in cooperation with researchers at the University of Southern California. The program will calculate interior daylight illuminance under any sun and sky condition for a variety of nonstandard building configurations. Sample results are shown in Fig. 3. Calculated results for typical building cross sections compare well with data measured in scale models. Validation studies for more complex buildings are in progress. A version of the program, SUPERLITE 1.0, was readied for public release.

We modified the methods for inputting sky data so that the program can provide hourly results on a daily, monthly, or seasonal basis. The program can now predict interior illuminance under four types of skies—uniform, overcast, clear sky without direct sun, and clear sky with direct sun. Several other reporting capabilities, such as calculation of average illuminance on the workplane and total light flux through windows, were added to the program.




**Sky is clear**

**Sun position: 65° off zenith**

**30° off S to E**

**Horizontal illumination**

**Direct sun: 2407 fc**

**Sky: 1298 fc**

| Contour Number | Illum. Level (Ft-candles) |
|---|---|
| 1 | 20.0 |
| 2 | 40.0 |
| 3 | 60.0 |
| 4 | 80.0 |
| 5 | 100.0 |
| 6 | 150.0 |
| 7 | 200.0 |
| 8 | 250.0 |
| 9 | 300.0 |
| 10 | 400.0 |
| 11 | 500.0 |

**Windows marked by *******

**Sunny areas are hatched**

Figure 3. Isolux contours of daylight illuminance on the workplane in a 10 ft × 15 ft room that has a lower view window, a horizontal light shelf, and an upper clerestory window. Shaded portion shows where direct sunlight penetrates. (XBL 831-1155)

## Planned Activities for FY 1983

New algorithms are being added to SUPERLITE to allow the program to model illuminance from fenestration devices too complex for direct mathematical solutions. We measure an angle-dependent luminous transmittance function over a hemispherical field of view, which is entered into the program in functional form or as a data array. The program treats the device as a "black box" with specified luminous exitance properties. In 1983, we will build and calibrate an experimental facility to make the required optical measurements and test the new subroutines in SUPERLITE.

# DOE-2 DAYLIGHTING MODELS

## Accomplishments During FY 1982

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 allows us to determine the direct effects of daylighting on lighting electrical consumption as well as on associated thermal loads. The model can simulate, on an hourly basis, the use of simple operable shading systems by altering the window solar optical properties in response to occupant requirements for thermal and visual comfort. New output reports not only indicate average hourly and monthly savings for each zone but also provide several types of statistical data summaries and frequency plots that enable us to examine the details of annual energy performance. The new daylighting model forms the technical basis for performance optimization studies now in progress.

## Planned Activities for FY 1983

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. 1.

## AVAILABILITY STUDIES

Studies of potential annual energy savings from use of daylight in buildings require data on daylight availability, including the frequency and intensity of daylight. No reliable source for such data currently exists for most of the United States. In 1977, the Pacific Gas and Electric Company (PG&E) building in San Francisco was instrumented to collect and record the amount of solar and visible radiation available at all building surfaces. An array of 9 pyranometers and photometers was installed to collect data at 15-minute intervals.

### Accomplishments for FY 1982

Analysis of the data from the PG&E building continued in 1982 in preparation for two papers to be presented at the International Daylighting Conference in early 1983. We coded and implemented algorithms for solar irradiance calculations and for correcting data for various experimental biases such as ground reflectance, daylight savings time, and shadow-band corrections. Analysis focused on the relationship of measured illuminance and irradiance to atmospheric parameters such as turbidity. Analysis was conducted to determine functional relationships between these parameters and luminous efficacy, zenith luminance, and illuminance values. Sample results are shown in Fig. 4.

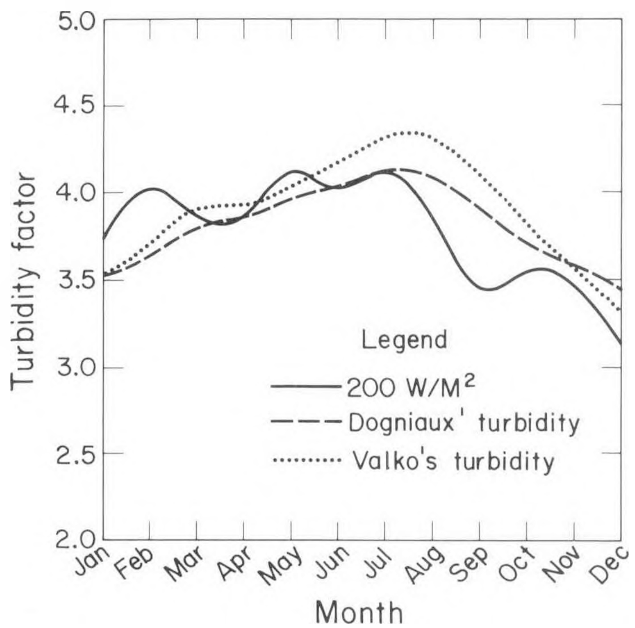



Figure 4. Comparison of measured turbidity factor (for direct solar radiation greater than 200 W/m$^2$) with predictions from two models using an annual average value for the Angstrom turbidity coefficient ($\beta$ = 0.0876) with monthly values of water vapor content. (XBL 833-1332)

### Planned Activities for FY 1983

We will complete analysis of the first several years of daylight-availability data and explore techniques for displaying results in a format useful to building designers. We will also use the results to upgrade the algorithms in our daylighting computational models and to work with other researchers to develop standard availability models for U.S. climates. We expect our results to suggest new areas for more detailed research, such as the time-dependent variability of daylight, spectral and polarization effects, and microclimate influences.

## DAYLIGHTING PHYSICAL MODELING—SKY SIMULATOR

A 24-foot-diameter hemispherical artificial sky [Fig. 5(a)], designed and built on the U.C. campus in 1979 to facilitate model studies for daylighting, became operational in 1980 with the simulation of luminance distributions for an overcast sky. In 1981, we designed and installed improved lighting controls in the dome in order to simulate complex luminance distributions for clear skies. Sky luminance distributions are reproduced on the underside of the hemisphere; light levels are then measured in a scale-model building under the artificial sky. From these measurements, we are able to predict daylighting illuminance patterns in real buildings.

### Accomplishments During FY 1982

The sky simulator was used to collect test data from scale models to validate the SUPERLITE and DOE-2 computer models and to help develop a new coefficient of utilization illuminance model. Toward the end of the year, the entire facility had to be moved 10 feet to accomodate the addition of a wind tunnel in the room. The move and other building renovations closed the facility for three months but provided the opportunity for several major additions.

We installed a new computerized data-acquisition system with 60 photometric sensors [Fig. 5(b)]. We designed a sun simulator that will travel from horizon to zenith and provide a 30-inch-diameter collimated beam. Design work was completed on a new lighting control system that will use dimmable electronic ballasts and permit precise control of the light output of every lamp in the system.

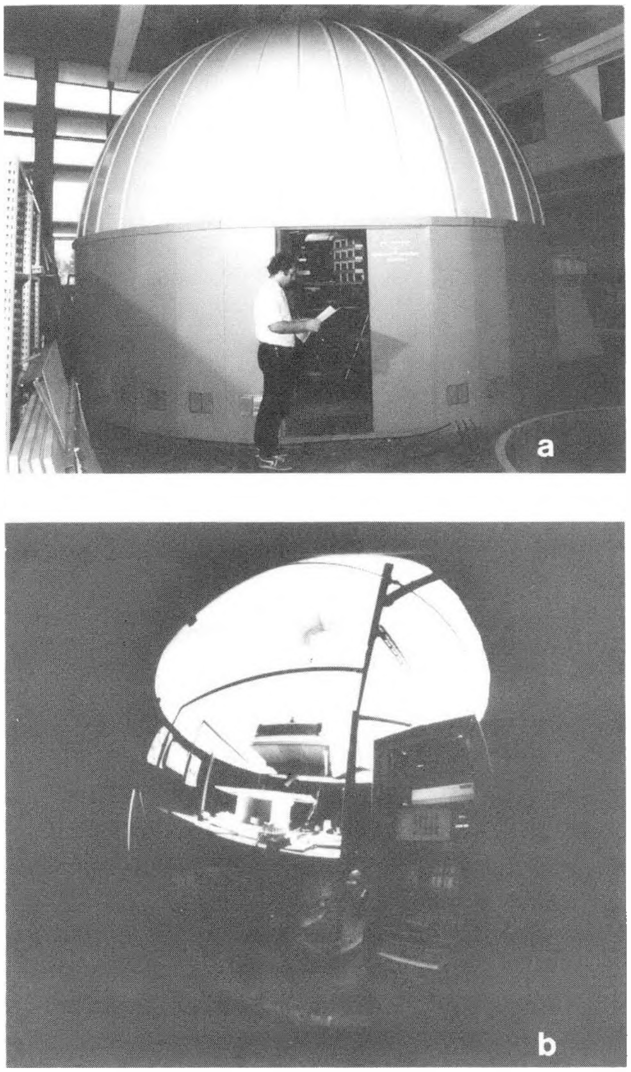


Figure 5. Hemispherical sky simulator: (a) exterior; (b) interior. [(a) CBB 823-2768C ; (b) CBB 833-2304]

### Planned Activities for 1983

The sun simulator will be completed, installed, and tested in the dome. A ground reflectance simulator has also been designed and will be installed in 1983. The facility will be completely rewired with a new dimmable fluorescent system, and appropriate operating software for the computer control system will be developed. By the end of the year, we hope to complete arrangements to make the facility available to design firms on a cost-recovery basis.

## MATERIALS SCIENCE STUDIES

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 glazing materials and modifications to existing materials should lead to substantial reductions in building energy consumption. During the past 6 years, the Office of Building Energy Research and Development at DOE has supported research studies on heat-mirror films, electrochromic coatings, and graded-index materials as well as a number of smaller studies on other materials aspects of fenestration systems. In FY 1982, additional support for related exploratory studies was 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.

### HEAT-MIRROR FILMS

### Accomplishments During FY 1982

The major high-performance optical technology studied in our program's first few years was low-emittance coatings (heat mirrors), which are important for developing low-conductance, high-transmittance windows. These coatings reduce the emittance of glass or plastic substrates from 0.8-0.9 to 0.1-0.2, thus reducing the large radiative component of window heat loss. These coatings, deposited on glass or plastic substrates, make it possible to have windows in the R4 to R10 insulation range while maintaining moderate to high solar transmittance. LBL studies were instrumental in the combined public and private efforts that finally led, in 1982, to market introduction of windows with heat-mirror films.

The first generation of commercially available heat mirrors is based on noble metals incorporated into metal-dielectric multilayer coatings; these coatings must be enclosed in hermetically sealed insulating window units to ensure adequate lifetimes. Because sealed windows are not feasible in many applications, particularly in retrofitting older buildings, there is a need for more durable heat-mirror coatings.

An alternative to the multilayer coating is the use of a single-layer, highly doped semiconductor. The spectral relationship between an undoped semiconductor such as $SnO_2$ and a metal is shown in Fig. 6(a). To give the best heat-mirror properties, the metal's plasma edge must shift to longer wavelengths and the semiconductor to shorter wavelengths. For example, $SnO_2$:F has excellent properties and durability, but it can be used only with high-temperature substrates, and its visible reflectance losses are appreciable. In FY 1982, we initiated a study to see if grading the optical index of the film will reduce those losses.

Another possibility is to use the metallic transition-metal nitrides such as TiN, ZrN, and TaN, which are related to the highly doped transition-metal oxides. Very little is known about the optical properties of these materials. They are commonly used as hard-facing coatings because they provide extremely high durability under mechanical wear. Using LBL Director's funds, we initiated a study of these unusual optical materials in 1982. These nitride films are related to metals by their Drude-like conduction mechanism (free d-band electrons) in the infrared [Fig. 6(b)]. However, in the visible, TiN interband transitions predominate, producing its gold color. It is thought that we can enhance the visible transmittance by oxygen substitution or TiN-$TiO_x$ chemical grading in the film.

## Planned Activities for FY 1983

We will continue and expand our study of the possibilities of reducing the visible reflectance losses of $SnO_2$:F by grading the optical index of the film. We also expect to investigate other promising applications for graded-index films and coatings. The research on TiN-$TiO_x$ will continue and will include analysis of films made by reactive sputtering and plasma-enhanced deposition. We will continue to examine other materials and deposition processes that show promise as high-performance, durable heat-mirror films.

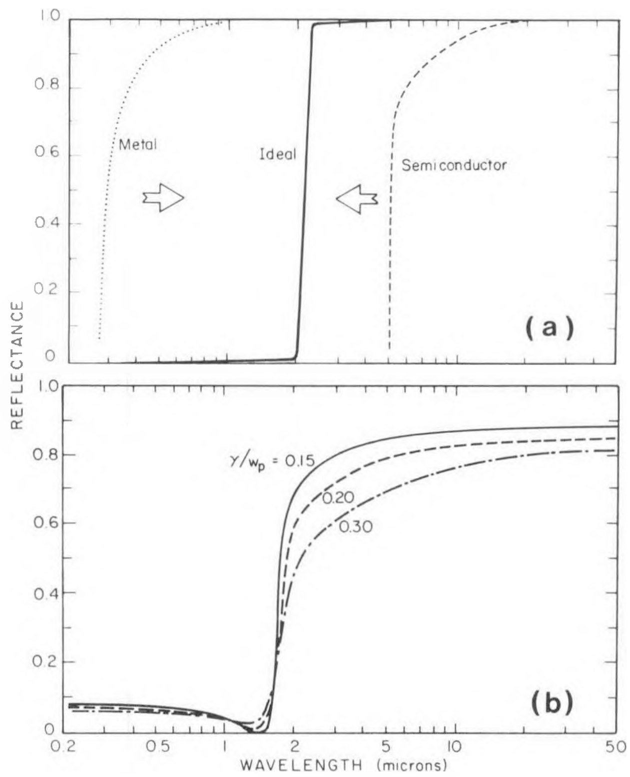



Figure 6. (a) Idealized spectral reflectance relationship of noble metals and oxide semiconductors. By shifting their respective plasma wavelengths, an ideal heat mirror can be produced. (b) Drude modeling of a hypothetical conductor like $SnO_2$ or TiN in the infrared region. The ratio of the relaxation frequency to plasma frequency $\gamma/w_p$ serves as a measure of wavelength selectivity.

[(a) XBL 793-5887A; (b) XBL 811-5131A]

# AEROGEL

## Accomplishments During FY 1982

We initiated research on a new class of transparent insulating materials called aerogels. These materials are formed by supercritically drying a colloidal gel, which leaves an open-cell silica network. Because the particle size is very small (~100 Å), there is little light scattering and the material can be made optically transparent. We completed initial studies of the light-transmittance and thermal properties of silica aerogel (Fig. 7). These studies indicate that window systems incorporating an aerogel layer could achieve an insulating value of R7 per inch with good optical clarity and high solar transmittance, a substantial improvement over current glazing technologies.

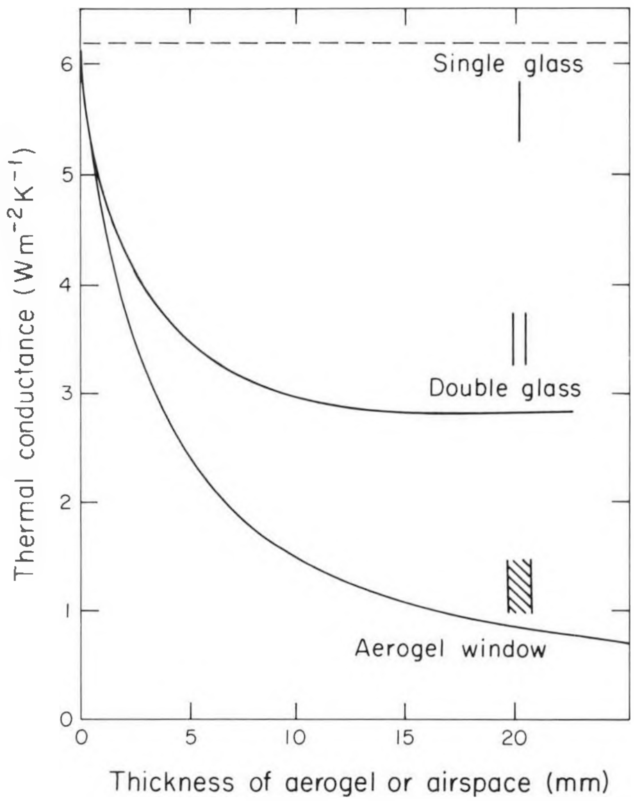



Figure 7. Calculated thermal conductance of aerogel window and of conventional single- and double-glass window vs. spacing between glass panes. (XBL 826-827)

## Planned Activities for FY 1983

Our studies of aerogel in collaboration with the Solar Group at LBL will be expanded to include measurements of angular scattering and mechanical properties. We will attempt to increase the thermal resistance of silica aerogel by using additives that absorb thermal radiation and by using low-conductance gas fills and low pressures to reduce convective and conductive heat transfer. Glazings with high solar transmittance and antireflection coatings will be used to make high-transmittance prototype aerogel windows. We will also investigate methods of sealing these windows against moisture intrusion or gas leakage. Aerogel samples will be produced in a new synthesizing facility now under construction.

Aerogels of other chemical types will be synthesized to determine which material offers the best balance between solar and mechanical properties. We will try to reduce the temperature/pressure requirements and the time required to produce aerogels by physical substitution of solvents having a lower critical point than ethanol.

# OPTICAL SWITCHING PROCESSES AND MATERIALS

Various optical switching materials or devices can be used to control solar heat gain and glare in buildings. An optical switch or shutter is transformed from highly transmitting to totally or partially reflecting (or absorbing) over the solar spectrum in response to changes in light intensity, spectral composition, heat, electrical field, or injected charge. Such a device would be used to control the flow of light and/or heat in and out of a building aperture, based on building energy management requirements. This device could also control illuminance and glare levels as well as transmitted thermal energy loads.

## Accomplishments During FY 1982

Several classes of devices can be considered candidate material systems. In 1982, we expanded earlier overview studies of the most promising systems based on chromogenic reactions such as electrochromism, photochromism, thermochromism, and electrodeposition; electrochromic systems showed the most promise.

While many of these materials have been explored for use in electronic display devices, there has been very little research on the use of electrochromic materials as optical switching devices for windows. An electrochromic material exhibits intense color change due to the formation of a colored compound in a reversible reaction. There are two major categories of electrochromic materials: transition-metal oxides and organic compounds. Organic electrochromics are based on several different materials systems and achieve coloration by an oxidation-reduction reaction, which may be coupled with a chemical reaction.

The inorganic materials that have attracted the most research interest due to their stability are $WO_3$, $MoO_3$, and $IrO_x$ films. A solid-state window device can be fabricated containing the layers shown in Fig. 8: transparent conductors (TC), an electrolyte or fast-ion conductor (FIC), counter electrode (CE), and electrochromic layer (EC). Our research is directed towards developing better electrochromic materials having good optical properties, high cyclical lifetimes, and short response times. This includes study of fast ion conductors and solid electrolytes, essential components of electrochromic systems for window applications.

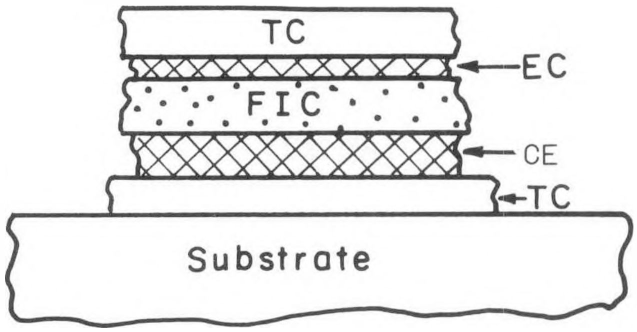



Figure 8. Schematic of a solid-state electrochromic device. (XBL 805-9713)

### Planned Activities for FY 1983

Although new technical studies in FY 1983 will focus on electrochromic coatings, we will complete an overview of the other switching-film mechanisms (e.g., thermochromics) to see if additional research is warranted. A detailed multi-year plan for switching-films research will be developed. Electrochromic studies at LBL will focus on characterizing the optical properties and microstructure of some of the promising but less well known materials systems.

## GRADED-INDEX COATINGS

### Accomplishments During FY 1982

Light reflection at the boundary between two media can be reduced through the use of single- or multiple-layer coatings. A layer having a continuously varying index of refraction can provide a very low reflectance over most of the solar spectrum. We have investigated the effect of adding a single-layer graded-index coating to polyethelene terephthalate (PET). The index of refraction for PET is about $n = 1.65$. With the addition of a graded coating with $n = 1.65 \rightarrow 1.0$, reflection losses can almost be eliminated. We have analyzed an existing steam-oxidized aluminum film on PET and identified the resulting dendritic films as aluminum hydroxide. A computer model was developed to predict the optical properties of dendritic films and other graded-index coatings.

### Planned Activities for FY 1983

Optical losses can be eliminated and system efficiency increased by using chemical or structural grading of a broad class of coatings. In 1983, we will extend these studies to validate our analytical models of graded-index coating performance against measured optical properties of the coatings.

## 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 upon 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.

### Accomplishments During FY 1982

In earlier studies, we evaluated the performance of a variety of devices for daylight acceptance and control based upon 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 initiated a study of the feasibility of using approaches such as fiber-optic systems, hollow light guides, holographic coatings, selective-reflectance materials, and various scattering media. One promising approach for collecting and redirecting daylight is the subject of a patent disclosure.

### Planned Activities for FY 1983

We will complete an overview study to identify and characterize innovative optical materials technologies for daylighting. Several of the more promising approaches will be explored in greater depth.

## OPTIMIZATION STUDIES

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. While heat loss and cooling loads resulting from solar gain 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. The optimum solutions may be a sensitive function of building type, climate, orientation, and building operating parameters. These studies are designed to provide a better understanding of all aspects of optimizing fenestration performance and will lead to guidelines and analysis tools to assist the building design community. Our work originally focused on residential buildings but has shifted during the past 4 years to an emphasis on non-residential buildings, including daylighting and peak-load management issues. In the future, we expect to conduct studies of both building types.

## NON-RESIDENTIAL BUILDINGS

Most building optimization 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, and particularly daylighting strategies, must thus include the impact on peak electrical loads as well as on energy savings. Although the energy impact of daylighting has been under study by our group and others, there have been no prior investigations of the impact of daylighting on peak loads.

### Accomplishments During FY 1982

The energy performance of a prototypical commercial office building was simulated with a modified version of DOE-2.1B for a wide range of glazing properties, window size, lighting load, orientation, and climate. The first phase of this study examined the impact of fenestration properties, including the effects of daylighting strategies, on office building 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 these studies is a 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. Sample results are shown in Figs. 9 and 10.

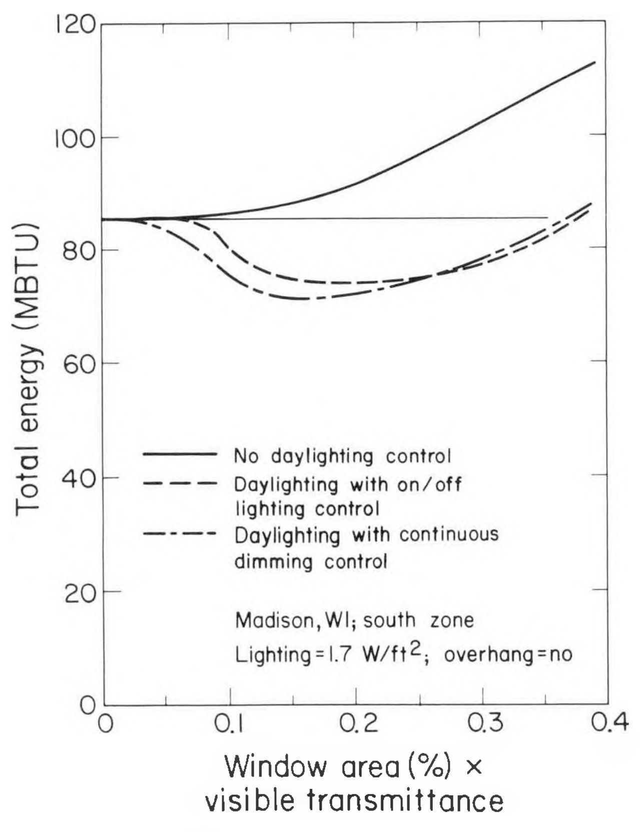



Figure 9. Energy consumption on the south zone of an office building in Madison, Wisconsin, showing the variation in annual energy consumption with window area and transmittance for an opaque exterior wall (thin horizontal line), a non-daylighted case, and daylighting with two types of lighting controls. (XBL 833-1318)

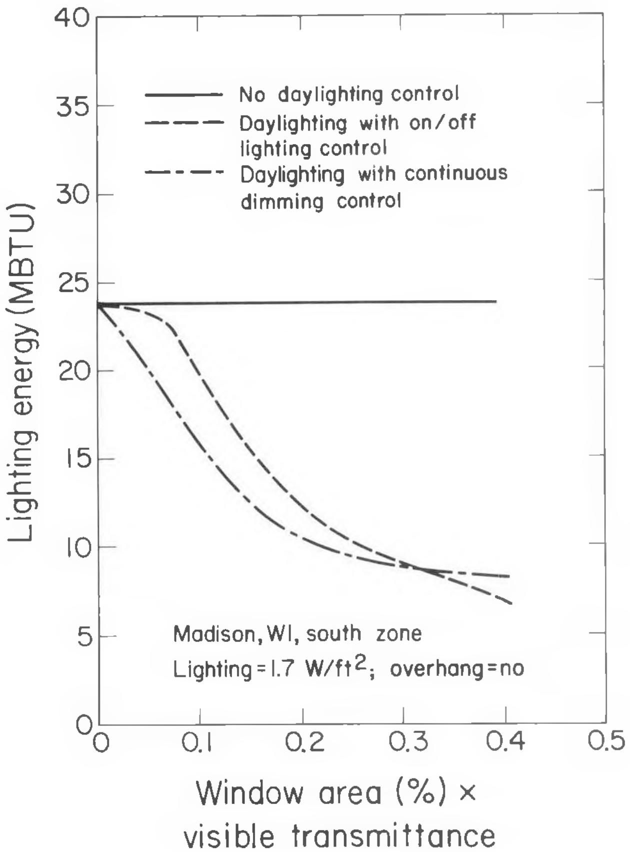



Figure 10. Energy consumption for electric lighting as a function of the product of window area and visible transmittance for a non-daylighted case, on-off lighting controls, and dimming lighting controls. (XBL 833-1317)

The second phase of this work concentrated on providing quantitative information on the peak-shaving potential of daylighting. Results show that daylighting can reduce a significant portion of 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 non-daylighting case. The critical tradeoffs—between electric lighting reductions due to daylighting, and cooling load increases due to increased window 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 the daylighted and nondaylighted cases in Fig. 11.

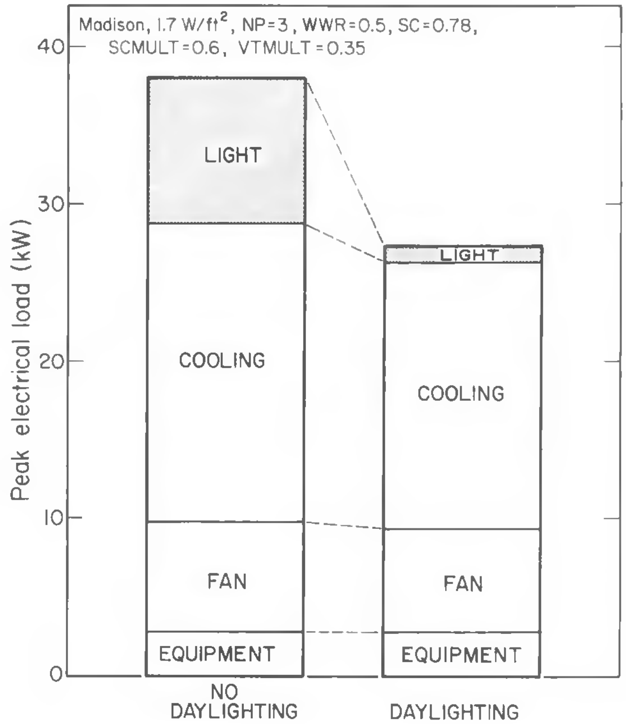



Figure 11. Peak-load breakdown for a five-zone office building in Madison, Wisconsin (1600 ft$^2$). The peak occurs at 4 pm on August 31. The windows are triple-glazed with a visible transmittance of 0.52 and cover 75% of the wall (floor to ceiling). Installed lighting power is 1.7 W/ft$^2$. (XBL 8212-7388)

## Planned Activities for FY 1983

Optimization studies will be extended to include additional fenestration materials and devices, new climates, skylighting systems, and other building types. The performance data resulting from some of these studies will be used by an ASHRAE technical committee as the technical basis for new voluntary building energy guidelines. This work will also lead to an examination of several alternative techniques for developing simplified energy models of fenestration performance. The detailed analysis of the impacts of daylighting on building peak loads will be continued and expanded. This includes analysis of electrical demand characteristics as a function of orientation, breakdown of peak demand into components, and investigation of impacts on cooling from reduced lighting load and fenestration. The benefits to the customer and the utility of reducing peak demand through daylighting will also be studied by adding a model for electric rate structures.

We also expect to resume work initiated in 1979 on residential optimization. The first phase examined the performance of insulating shutter systems. The new phase will emphasize the performance of several high-performance window systems now emerging in the building sector and will also help set performance objectives for window systems under development.

## *In-Situ* TESTING—FIELD VALIDATION

Net energy performance under actual conditions of use in a building 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*.

### MoWiTT

### Accomplishments During FY 1982

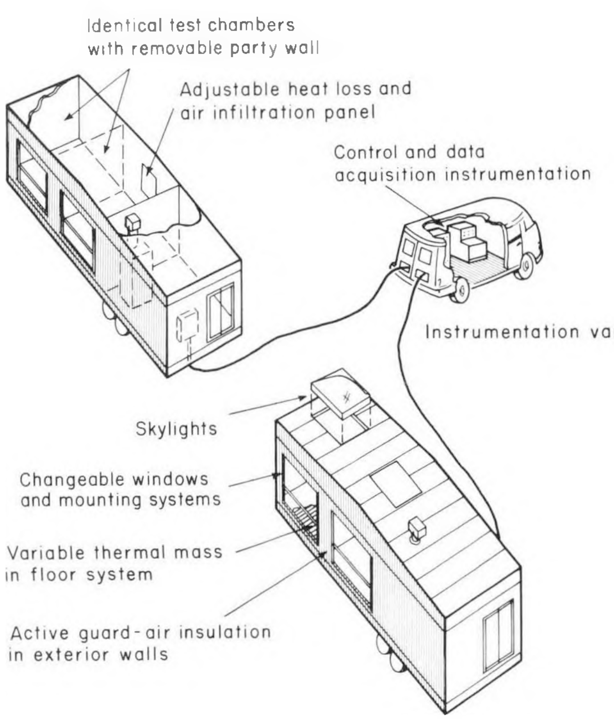



Figure 12. Schematic view of Mobile Window Thermal Test (MoWiTT) facility. (XBL 811-30)

During 1981, we began constructing a Mobile Window Thermal Test (MoWiTT) facility to fill this experimental gap (Fig. 12); the facility consists of one or more measurement modules with an instrumentation van. The measurement modules, which consist of twin guarded calorimeters, will enable dynamic studies of combined solar, infiltrative, conductive/ convective, and radiative heat transfers as a function of window type and orientation. During 1982, the first module was assembled (Fig. 13) and one calorimeter chamber completed. The module was moved to an outdoor test site and check-out begun.

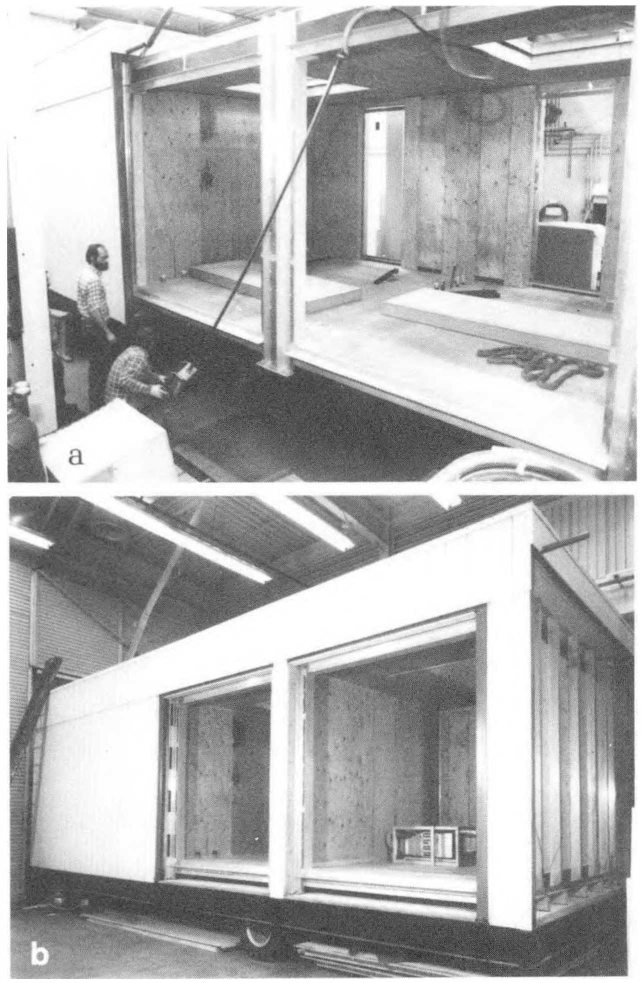



Figure 13. Progress of the MoWiTT facility. (a) Insertion of the calorimeter chambers. (b) The nearly-complete assembly. [(a) CBB 824-3063; (b) CBB 826-5379]

An outgrowth of work on the MoWiTT facility has been the development of a new heat-flow meter. Instead of measuring the temperature difference with a deposited thermopile across a known thermal resistance (the usual method), this heat-flow meter uses

AC resistance thermometry. Such heat-flow meters can be made economically in sizes large enough to cover entire walls, and we intend to incorporate them into the MoWiTT facility.

During 1981, a successful one-foot-square prototype heat-flow meter was built (Fig. 14 shows some test results). In 1982, a series of 1-ft$^2$ prototypes was built and tested in order to fix the design parameters for larger units, and approximately 400 ft$^2$ of full-sized units (up to 2 ft by 4 ft) were produced for installation in the MoWiTT (Fig. 15).

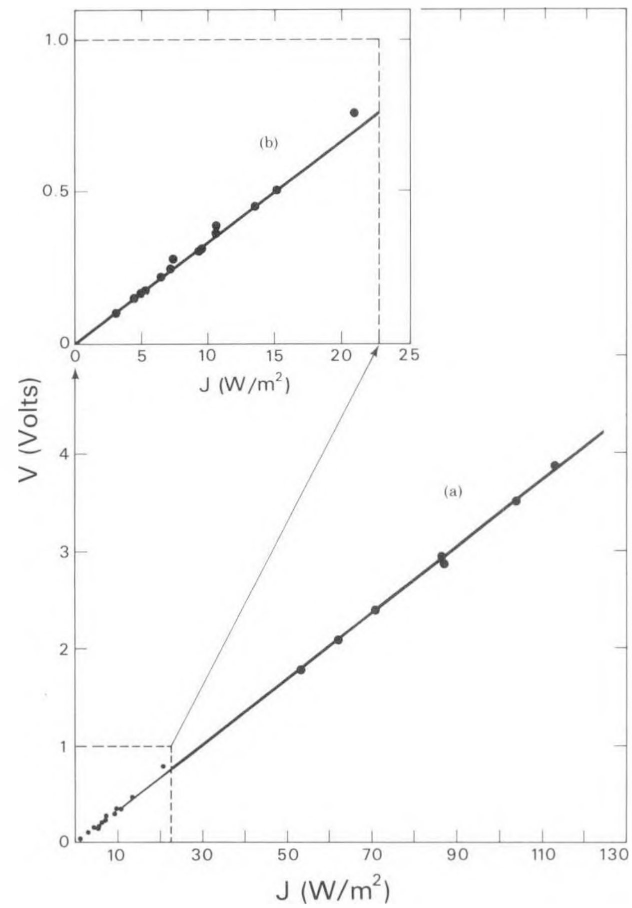



Figure 14. Calibration of a 1-ft$^2$ heat-flow meter prototype. (A) Complete calibration. (B) Expanded view of the small-signal region of the curve. Points are measurements made in the guarded hot plate and corrected to a 25 °C mean sensor temperature. The line is a least-squares fit to the data and has a slope of 37.6 mV(W/m$^2$)$^{-1}$. (XBL 8201-6)

Figure 15. Large-area heat-flow meters for use in MoWiTT. (CBB 828-7550)

## Planned Activities for FY 1983

We will complete the second calorimeter chamber in MoWiTT, calibrate the unit, and begin field testing at summer and winter test sites. The heat-flow meters will be calibrated in a large calibrated hot-plate, then installed in the completed MoWiTT chambers. A multi-year testing program will be developed with input from all sectors of the fenestration community.

## OCCUPANCY STUDY

Fenestration and lighting controls are essential to energy-efficient office buildings. Both daylighting and electric lighting control systems need to be designed to limit costly cooling loads and still provide thermal and visual comfort for building occupants. The availablity of control system components is rapidly increasing, along with advances in computers and hardware. Yet in many buildings where computerized controls have been implemented, occupants have not been satisfied with the quality of the work environment. The reasons are complex but, in general, automated systems do not involve building occupants.

The occupancy study will gather data for developing recommendations concerning fenestration and lighting control systems that will satisfy office occupants in their work areas.

## Accomplishments During FY 1982

We developed two tools to aid our evaluations of occupant response to building control systems: a questionnaire and physical measurements. The questionnaire allows occupants to rate their level of well-being and satisfaction with environmental conditions in their work areas. The related physical measurements include lighting and temperature levels in work areas. Architectural drawings and photography will also document work areas.

Analysis of the questionnaire data for each building will look for correlations between the light sources, their control systems, and work area locations and orientations, as well as differences among occupants such as age, sex, and tenure at their work areas.

## Planned Activities for FY 1983

We expect to locate a suitable office building for pilot and full-scale evaluations. Planned future studies will consider three general office building types: unmodified buildings, buildings with retrofitted shading and/or lighting controls, and energy-efficient buildings.

## REFERENCES

See Publications List, pp. 3-78 through 3-81.

# LIGHTING SYSTEMS RESEARCH*

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

The Lawrence Berkeley Laboratory has managed the National Lighting Program for the Department of Energy since 1966. The primary goal of the past five years was to accelerate the introduction of energy-efficient lighting products and concepts to the marketplace—a strategy intended to accomplish the goal of a 50% reduction in U.S. energy consumption for lighting by the mid-1990s. This savings of energy, more than 200 billion kilowatt-hours, is equivalent to 381 million barrels of oil annually, or more than one million barrels of oil per day.

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

Projects initiated at LBL include development of the solid-state ballast for operating fluorescent lamps, lighting management systems, and energy-efficient light sources, as well as fundamental visibility-performance studies and investigations of the effects of artificial light on human health. As the lighting program grew, it was divided into three sections: the Technical Program—to study the fundamental properties of light sources in order to improve their efficacies; the Building Applications Program—to study advanced, energy-efficient lighting designs and their relationship to overall building energy performance; and the 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. This study will have some influence on the extent to which these energy-efficient systems will be used.

Our lighting program has been responsible not only for the appearance of solid-state ballasts in the marketplace, but also for a more widespread awareness of energy management systems and for light sources that are three to four times more efficient than the incandescent bulb. Our initial, fundamental work on visibility and performance, which reviewed the basis for establishing recommended light levels, suggested that further experiments were required. To execute these projects, three laboratory facilities were established: the Physical Lighting Laboratory, the Visibility Laboratory, and the Health and Environmental Laboratory. These laboratories are staffed with individuals specializing in various scientific disciplines: physicists, engineers, optometrists, psychiatrists, and physicians. Staff members interact closely on lighting and visibility problems selected for study. The LBL lighting laboratories are the only facilities diversified enough to resolve the critical technical problems surrounding the optimal performance of illumination.

The early and successful commercial applications of the technologies developed by the LBL program also introduced new issues—high-frequency operation and flicker—that must be addressed if the new technologies are to find widespread use. In addition, there is a need to expand research in preparation for the next, and more efficient, generation of electrical illumination systems.

To meet these needs, the 1982 Lighting Program included studies on the fundamental properties of plasmas (gas discharges) with regard to electric and magnetic fields; new, high-frequency ionizing materials; the effect of new light sources on visibility and performance; and the effect of these sources and systems on human health and existing electronic systems.

Described below are the highlights of the accomplishments realized in 1982 by our three major efforts—the technical, building applications, and impacts programs—and the activities planned for 1983.

## TECHNICAL PROGRAM

### SOLID-STATE BALLASTS

#### Accomplishments During FY 1982

Finalization of the circuit design of solid-state ballasts began with the delivery of high-pressure sodium (HPS) ballasts. Two contractors delivered their units,[1] and we life-tested them for 6 months. From experiments, we concluded that the efficacy of HPS lamps will not increase with high-frequency operation, but such operation still has some advantages, such as an increase in ballast efficiency of 5 to 10% and improved regulation and constant wattage output of the ballast. These factors contribute to an energy savings of 10 to 20% over the life of the lamps.

One serious problem, known as the acoustic resonance phenomenon, was noticed in the 200-watt HPS lamps. This phenomenon occurs when the frequency of the electrical drive is resonant with the mechanical modes of the discharge tube. The mechanical modes are a function of the physical dimensions of the arc tube. (Resonance was not observed in the 150-W or 400-W HPS lamps.) Several 200-W lamps from different manufacturers were tested, and we found that acoustic resonances occur at various frequencies between 20 and 40 kHz.

#### Planned Activities for FY 1983

The high-frequency operation of gas-discharge lamps will be tested by focusing on parameters such as filament power, crest factor, and critical frequency. The HPS solid-state ballasts and lamps will undergo life tests.

### ENERGY-EFFICIENT LIGHT BULBS (EELB)

#### Accomplishments During FY 1982

All subcontractors delivered prototypes for the energy-efficient light bulb project.[2-5] Each contractor met the goals of the program with regard to system efficacy. Table 1 lists the average performance of the EELBs tested by LBL. The three prototype lamps are shown in Fig. 1.

Table 1. Performance of energy-efficient lightbulbs compared with standard incandescent bulb.

| Type | Light (lumens) | Power (watts) | Life (hours) | Efficacies (l/W) |
|---|---|---|---|---|
| 100-W incandescent | 1750 | 100 | 750 | 17.50 |
| Coated filament | 1650 | 55 | 2500 | 30 |
| Compact fluorescent | 1700 | 34 | 7000 | 50 |
| Electrodeless fluorescent | 1700 | 31 | 10,000 | 55 |

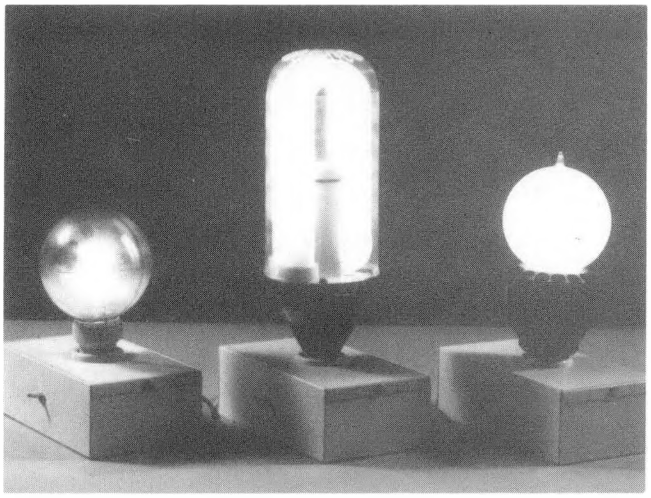


Figure 1. Three prototype energy-efficient light bulbs: (l-r) coated filament lamp, compact fluorescent lamp, and electrodeless fluorescent lamp. (CBB 828-7102)

These new light sources are more than three times as efficient as the incandescent lamp. Although the initial cost is higher, their longer lifetimes (2500 to 10,000 hours) and higher efficiency more than compensate for the higher first cost. With the use of solid-state ballasts in compact fluorescent lamps and further developments in electrodeless lamps, efficacies of 60 to 70 l/W are feasible in the near future.

## Planned Activities for FY 1983

The prototypes received will be life-tested to determine if they meet all performance criteria. In addition, other EELBs in development will be examined for performance.

# ELECTROMAGNETIC COMPATIBILITY

## Accomplishments During FY 1982

One barrier to the introduction of high-frequency lighting systems is the possible effect of the electromagnetic (EM) energy emitted by these systems. To address this issue, LBL conducted a two-day seminar—the Lighting/Electromagnetic Compatibility Conference, co-sponsored by the Institute for Electrical and Electronic Engineers, the Industrial Applications Society, the National Electrical Manufacturers Association, and the Naval Research and Development Laboratories—to identify potential problems and outline solutions. Nearly 100 people from all the major lamp manufacturers involved in high-frequency systems listened to invited speakers one day and exchanged ideas in smaller groups the second day. LBL compiled and published the proceedings.[6] The meeting identified several research needs, including a standard method for measuring electromagnetic interference (EMI), a simple instrument that could measure EMI in the field, some target specifications of the EMI limits that systems would have to meet to assure use in the commercial, industrial, and residential sectors, and coordination of efforts to exchange information, i.e., the establishment of a data base.

## Planned Activities for FY 1983

As recommended by the electromagnetic compatibility conference, we will measure the radiated and conducted EMI from new high-frequency lighting systems. Tests will be made in an open field, a screened room, and office spaces to relate measurements made in different environments. A simple field instrument will be developed for field measurements of EMI from lighting systems.

# FUNDAMENTAL PLASMA STUDIES

## Accomplishments During FY 1982

Building on earlier work, LBL began efforts to reduce the resonant entrapment from the $6P_1^3$ level to the ground state (2537 Å) to increase the efficacy of the low-pressure gas discharge in fluorescent lamps. This UV line excites the phosphor and is the most intense mercury (Hg) line at low Hg vapor pressures. The radiation is produced primarily by excitation of atomic Hg up to the $6P_1^3$ energy level. Natural Hg consists of several isotopes that absorb and reradiate their own resonant radiation. However, as the Hg density increases (at higher lamp temperatures), the entrapment of the resonant radiation becomes predominant, resulting in a net decrease of the 2537 Å radiation exciting the phosphor. The entrapment process can be reduced by creating an optimum Hg isotope mix (about equal proportions of each isotope) through additions of Hg isotopes that are less abundant in natural Hg. For example, Hg isotope 196 makes up only 0.1% of natural Hg.

We calculated the optimum mix of Hg isotopes needed to produce the greatest net increase in resonant radiation and constructed a lamp in which predetermined Hg isotope mixes can be added. Before the crucial measurements are made, we must develop methods to add measured mixes of small amounts (5 mg) of Hg isotopes to the lamp. In conjunction with this study, we supported a commercial laboratory, General Telephone and Electronics (GTE), in devising a commercially viable method of separating the Hg isotopes. Chemical photo-ionization appears to be the most promising method, because it can produce the throughput of $10^5$ gm, the amount required annually to supply the lamp manufacturers.

Another means of reducing the entrapment is to split the $6P_1^3$ energy level into its components by applying a magnetic field (the Zeeman effect). This approach, too, can increase the generation of resonant radiation (2537 Å). Initial theoretical calculations indicate that using natural Hg can produce a two- to fivefold increase in the generation of resonant radiation. We completed most of the experimental setup needed to measure the changes in the intensity of the radiation as a function of magnetic field and gas temperature.

## Planned Activities for FY 1983

Measurements will be made of lamp performance in a magnetic field as a function of temperature and with various Hg isotope mixes. We will compare results with our theoretical calculations. The GTE contract will include the construction of a laboratory scale model of the Hg isotope separator.

Two new contracts are planned. One will explore the feasibility and problems associated with a gigahertz low-pressure discharge lamp. The other study will focus on the development of a high-intensity discharge lamp (HID) operating at high frequency (megahertz). This study should support manufacture of an electrodeless lamp while simultaneously exploring new types of ionizing materials.

## BUILDING APPLICATIONS

### Accomplishments During FY 1982

We completed two major lighting management demonstrations, one at the World Trade Center in New York and the other at the Pacific Gas and Electric (PG&E) building in San Francisco. Several papers were prepared to present some of the early results that show energy savings as high as 50%.[7-9] The data could not be used to validate the CONTROLITE computer program because this program, which predicts the energy performance of lighting systems, is still not complete. We used the QUICKLITE program for inputting daylighting, and this appears adequate.

Figure 2 shows data obtained from the World Trade Center and the reduction in energy from introducing several types of lighting control strategies. This effort identified several major issues in the use of daylighting. One is the method of placing the photocell, which senses and monitors the ambient illumination. Another is the lack of understanding of the interrelationship between the heat dissipated by the lighting system and the heating, ventilating, and air-conditioning systems of the building.

### Planned Activities for FY 1983

We plan to complete the analysis of the two lighting management systems and prepare a three-volume report on the results.

We also plan to study the design criteria for optimum placement of the photocell as a daylighting monitor. The experiments will require the construction of a scale model, which will be placed on the roof of an LBL building. The model will thus obtain daylighting data as well as information on how to maintain constant illumination on a task area.

The CONTROLITE program will be reviewed and errors corrected. In addition, the QUICKLITE program

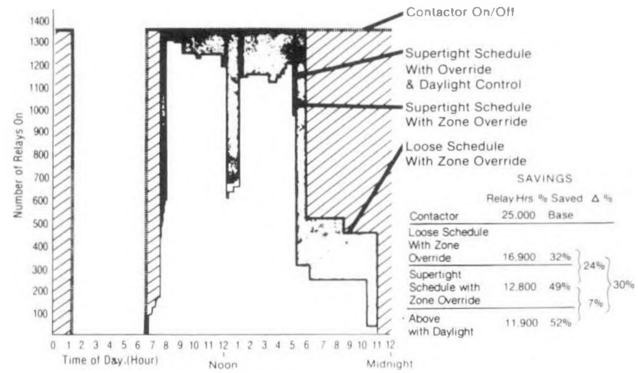



Figure 2. Experimental results showing the energy savings from different control strategies in an office in the World Trade Center. (XBL 823-8666)

will be integrated with the CONTROLITE program. A new advanced lighting design study will be initiated to develop futuristic layouts that use the most energy-efficient lighting systems. Some of these systems are still in development and will be introduced in the late 1980s. This study will provide a basis for future energy design targets for lighting systems.

## IMPACTS PROGRAM

### VISIBILITY AND PERFORMANCE

### Accomplishments During FY 1982

The connection between visibility and productivity continues to be of major interest. In 1981, the International Commission on Illumination (CIE) released its publication CIE 19/2, "An Analytic Model for Describing the Influence of Lighting Parameters upon Visual Performance."

A partial review by LBL of the original data used for the development of CIE 19/2 has revealed serious errors. In addition, data on the target size have been examined. Those data may be an important parameter for light levels. A report has been written on a cost-effective method of establishing light levels.[10]

### Planned Activities for FY 1983

Work will be continued with the aim of defining experiments that may be useful in scientifically establishing a set of recommended light levels related to performance.

# FATIGUE AND VIDEO DISPLAYS

## Accomplishments During FY 1982

The visibility laboratory—established in 1981 in conjunction with the University of California School of Optometry—was completed. This laboratory will assist in studies of fatigue in workers viewing video-display screens. The experimental facility is a test room where subjects are directed to perform a series of visual tasks that induce fatigue. As Fig. 3 shows, the test room has three screens and a ceiling lighting system. This lighting system can be controlled to vary the type of light source (incandescent or fluorescent), the intensity of the illumination, and the amount of flicker. Figure 4 shows the control room in which the experimenters manipulate the visual tasks and ambient lighting. All of the systems have been debugged.

## Planned Activities for FY 1983

Subjects will be selected and tested in the visibility laboratory. In 1983 we expect to identify the primary factors in lighting systems that induce early fatigue. Parameters of particular interest are the interaction of the rate of flicker in lamps and the refreshment rate of the information displayed by the video screen.

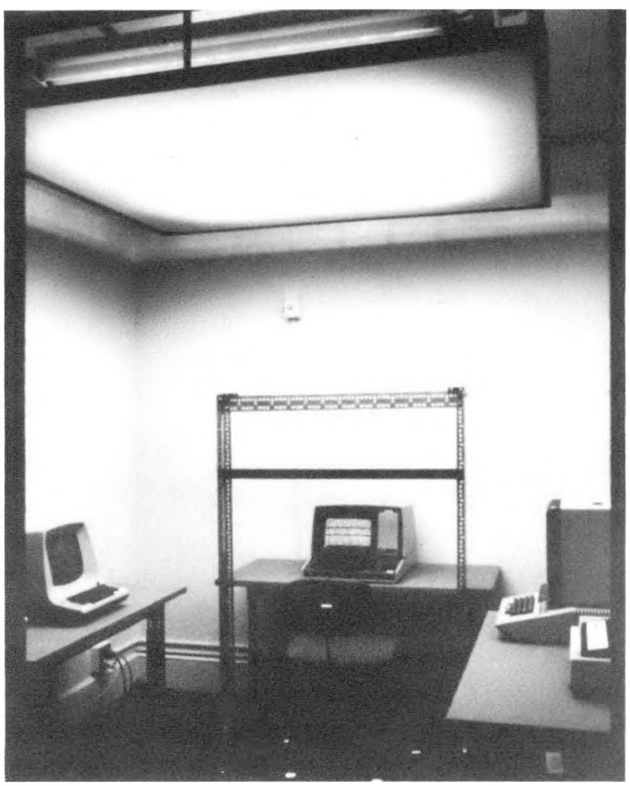


Figure 3. Testing laboratory at the University of California School of Optometry for measuring fatigue from viewing video displays. (CBB 828-7206)

Figure 4. Control room for visibility laboratory at the University of California School of Optometry. (CBB 828-7208)

# HEALTH AND ENVIRONMENT

## Accomplishments During FY 1982

The environmental laboratory, located in the University of California Medical School, San Francisco, was instrumented to measure the effects of illumination and lighting systems upon human subjects. The equipment consists of a large chamber in which a test subject is in a completely controlled environment, i.e., not subject to extraneous light, electromagnetic radiation, or noise. The subject will be exposed to various types of visual tasks; responses will be compiled on a computer. Illumination can be switched among different types (incandescent, fluorescent, or high-pressure sodium), and the intensity, amount of glare, and percent flicker can all be controlled. The object will be to induce stress that can be measured physiologically and objectively by changes in skin temperature, skin resistance, muscle strength, and blood pressure. This will be the first time that causal influences will be controlled and measured. Figure 5 shows a subject seated in the chamber, with an experimenter controlling the tasks and the lighting system. During an actual test, the

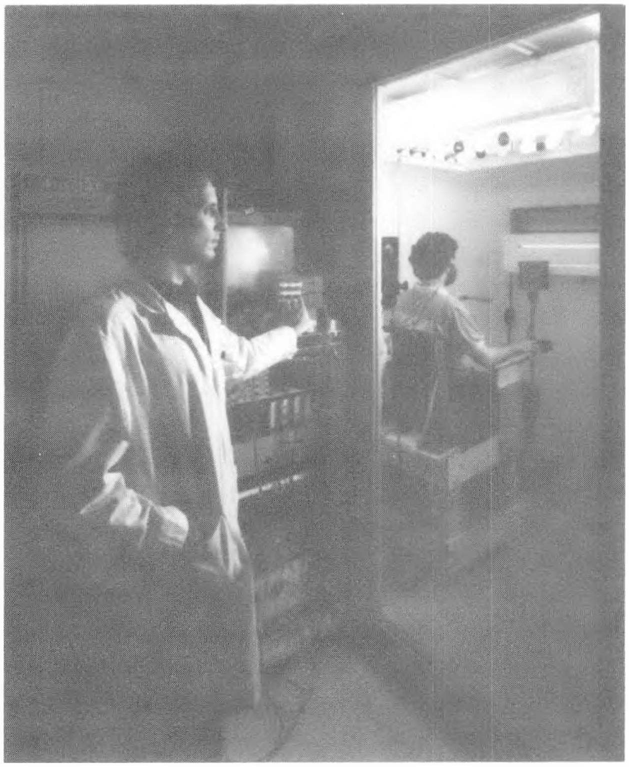


Figure 5. A view of the isolation chamber used to test the effects of lights upon human subjects. (CBB 828-7259)

Figure 6. Close-up view of the test chair; apparatus to left of chair measures muscle strength. Subject uses keyboard in right armrest to perform visual tasks. (CBB 828-7370)

chamber door will be closed and there will be no visual communication between experimenter and subject. Figure 6 is a close-up photograph of the test chair. Behind the left armrest is the instrument for measuring muscle strength; on the right armrest is the keyboard that the subject operates.

Before initiating tests, an advisory committee was selected and convened to discuss all aspects of this program. The advisory committee is composed of internationally renowned physicians, psychiatrists, physicists, and optometrists involved in the health effects of lighting and radiation systems. The instrumentation and test procedures were critiqued and amended to comply with the recommendations of this committee.

## Planned Activities for FY 1983

Initial qualitative experiments will be carried out, using input from the advisory committee and LBL staff. We anticipate that the results of these experiments will determine the future and more quantitative experiments that are required. A government panel is being formed to coordinate these activities with similar studies being carried out in federal agencies. Communication with others in the field is necessary because many of the results of our studies will apply to many occupational situations where stress from lighting conditions could be catastrophic.

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## BUILDINGS ENERGY DATA*

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Millions of homes and commercial buildings have now been retrofitted or managed more carefully to save energy, and many new buildings are designed to be more efficient than conventional construction. But it is difficult to find good data on the energy savings that have actually occurred and the cost of achieving them. Most data have been collected for specific, short-term purposes, and the lack of consistency in definitions, data collection procedures, and reporting formats often makes it difficult to compare results. There is little long-term tracking of energy performance to determine the persistence of savings over several years, nor—until now—has there been any established mechanism to share or exchange energy performance data, or to independently review new data for technical accuracy.

All these constraints can be addressed through a series of regularly updated building energy performance data bases, designed to encourage collaboration and data sharing among public and private organizations. The model of a shared data base is well-established in the physical sciences, as evidenced by LBL's own compilations of international research on subatomic particles, properties of nuclear isotopes, environmental instrumentation, and indoor air quality. Applying this concept to buildings energy research is one sign of the field's growing maturity.

The Buildings Energy Data (BED) Group compiles, analyzes, updates, and publishes data bases on the measured performance, cost-effectiveness, and further potential of energy-saving technologies in new and retrofitted residential and non-residential buildings. A major goal of the BED group is to provide results that cut across traditional research and program boundaries. The data bases incorporate a full range of conservation and solar/renewable measures that reduce purchased energy, peak electrical demand, and costs. They provide a means for:

(1) monitoring changes in energy-related practices in building design, construction, and management;
(2) comparing current practice with estimated technical and economic potentials for saving energy;
(3) examining the range of energy savings and costs in order to identify technical, institutional, or other factors associated with successes and failures;
(4) comparing measured energy and electrical peak demand savings with predicted values and analyzing discrepancies; and
(5) encouraging the continuing exchange of documented conservation results among utilities, government agencies, private industry, and research establishments in the U.S. and abroad.

Updated results appear in the refereed literature and as LBL reports. Conference papers and journal articles help to reach an audience of practitioners as well as researchers.

Our intent is to make the energy performance data bases widely available to:

- designers, builders, and energy managers—to provide them with feedback on the accuracy of their energy analysis methods and the results of past design or retrofit recommendations;

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- utility planners and managers—to help them improve demand forecasts, system planning decisions, and conservation programs;
- energy policy makers and program managers in federal, state, and local agencies—to help them establish a stronger empirical basis for allocating resources; and
- DOE and its national laboratories—to assist them in planning, setting priorities, and coordinating buildings energy research activities.

The BED Group has organized two main data bases and participates, in a limited way, in primary data collection. One data base, called Building Energy Use Compilation and Analysis (BECA), includes measured conservation results in new or retrofitted buildings. The BECA data are subdivided into several elements: low-energy new homes (BECA-A), existing "retrofitted" homes (BECA-B), new and retrofitted commercial buildings (BECA-C), and appliances and equipment (BECA-D). A fifth element includes comparison studies of measured building data versus computer model predictions (BECA-V).

The second data base deals with individual technical measures and provides estimates of the aggregate potential savings from applying today's best practices to the entire building stock. We collect data on the actual, *in situ* performance of today's energy-saving methods and track "advanced" technologies as they progress through research, development, field testing, and commercial production. We have used this data base, in collaboration with utilities and other outside organizations, to develop "supply" curves (marginal cost curves) for conserved energy (see below). Conservation supply curves provide a consistent accounting framework for evaluating the "technological frontier" of conservation in buildings.

The analysis of conservation potential complements our assessment of actual energy savings now being achieved. The BECA data, which reflect current conservation results, need to be compared not only to past inefficient practices but to the highest levels of efficiency that are technically and economically feasible. In turn, data from the BECA project keep our estimates of conservation potential realistic.

Finally, we participate, on a limited scale, in direct data-gathering activities and provide technical assistance to groups such as utilities, energy service firms, builders, and state or local governments, to help them improve the quality of their data; they, in turn make this information available for our own data bases. This role in the practical problems of data collection (equipment reliability, quality control, costs, etc.) also improves our ability to offer realistic advice to others and to properly interpret the data we receive.

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

## BUILDINGS ENERGY USE COMPILATION AND ANALYSIS

### Accomplishments During FY 1982

We continued to refine and expand our data bases on new homes and on retrofitted residential and commercial buildings. We began to compile data on new commercial buildings, as well as results from studies that compare computer predictions with measured building performance (BECA-V). Major results in FY 1982 for each BECA subproject are summarized below.

*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] and have evaluated submetered data for 276 of these homes (mostly single-family), of which 207 have adequate cost data to assess cost-effectiveness as well as performance.

In many of these houses, space heating energy use has been economically reduced to about one-fifth the level required in the average existing house, or about one-third the level estimated for typical new homes. Heating loads for the best superinsulated and passive solar homes in our sample were about 1.5 Btu/(ft$^2$-°F-day) [30 kJ/(m$^2$-°C-day)] per year. The average for 37 homes with the most complete data was 2.5 Btu/(ft$^2$-°F-day) [50], 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 National Association of Home Builders (NAHB). In other words, it is not unusual to find low-energy homes, even in the coldest U.S. climates, where energy use for space heating is roughly the same as that required for heating water or operating domestic appliances.

Figure 1 plots energy performance vs. heating degree-days for a subsample of the best-documented homes in the data base. The low-energy homes are compared with heating usage under the proposed federal energy performance guidelines (labeled "BEPG"), with current building practice, and with the existing stock (all normalized for floor area).

To make valid comparisons among low-energy homes, the metered space-heating energy data must be corrected for variations in inside thermostat settings and internal gains from appliances and occupants, as well as for local weather. Internal gains alone can account for half or more of the total space heating load. We made corrections for "standard" inside temperatures and internal gains for each house shown in Fig. 1.

Use of wood stoves, especially common in new solar and earth-sheltered homes, complicates performance analysis, since the wood represents a significant but unmetered energy flow into the house. Thus far, we have been forced to exclude from the data base all homes where wood stoves were used. In the future, we will urge our contributors to use a monitoring or analysis approach that realistically accounts for wood-stove heat contributions, or else to arrange for occupants to refrain from using the stove during periods of measurement.

New homes must be compared on the basis of cost-effectiveness as well as thermal performance. We obtained data on the incremental costs (materials and labor) of energy-saving features for about two-thirds of the BECA-A entries. The results are shown in Fig. 2, along with "reference lines" indicating the minimum level of gas or electric savings that would be cost-effective, for each added dollar invested in conservation. These reference lines were calculated using 30-year amortization periods and real interest rates of 3 and 6%. The gas and electric prices are current averages for U.S. residential customers. A home is cost-effective under these assumptions if the plotted point lies above the reference line for that fuel type.

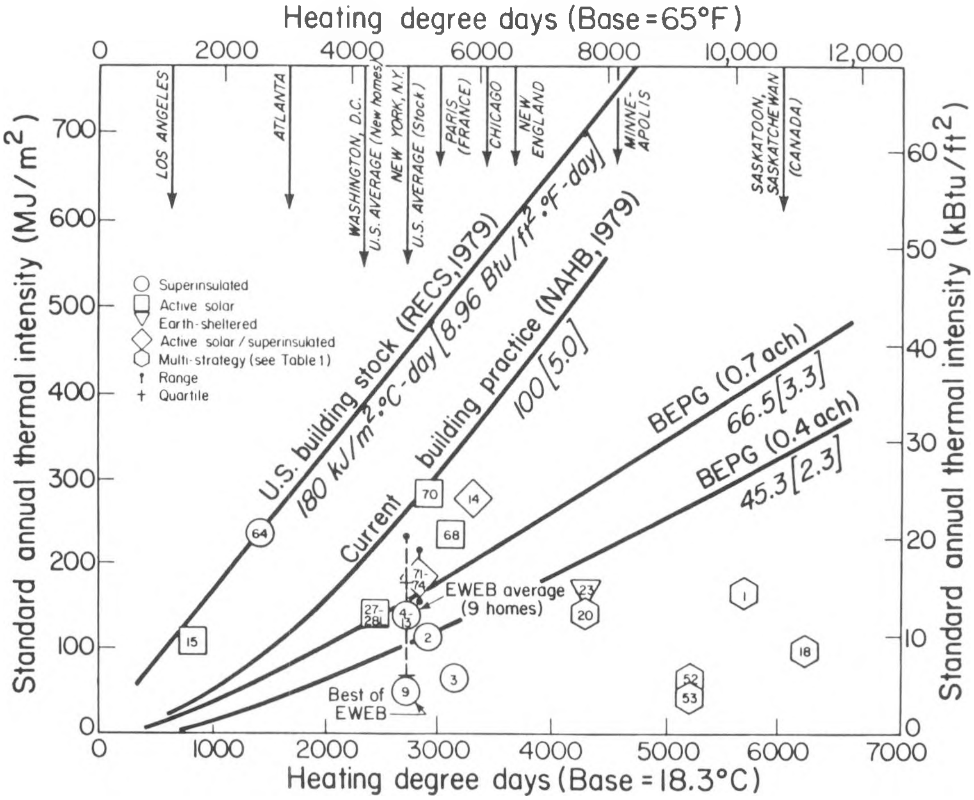



Figure 1. Scatter plot of 37 new homes in the BECA-A data base, "standardized" for thermal intensity (space heating load per ft²) vs. climate. Shown for comparison are lines approximating the performance of all existing homes (RECS), typical new single-family homes (NAHB), and proposed federal guidelines for new construction (BEPG). The average space heating load per degree-day for the 37 homes is 2.5 Btu/(ft²-°F-day) [=50 kJ/(m²-°C-day)], one-half the energy required under current building practice.

(XBL 827-956)

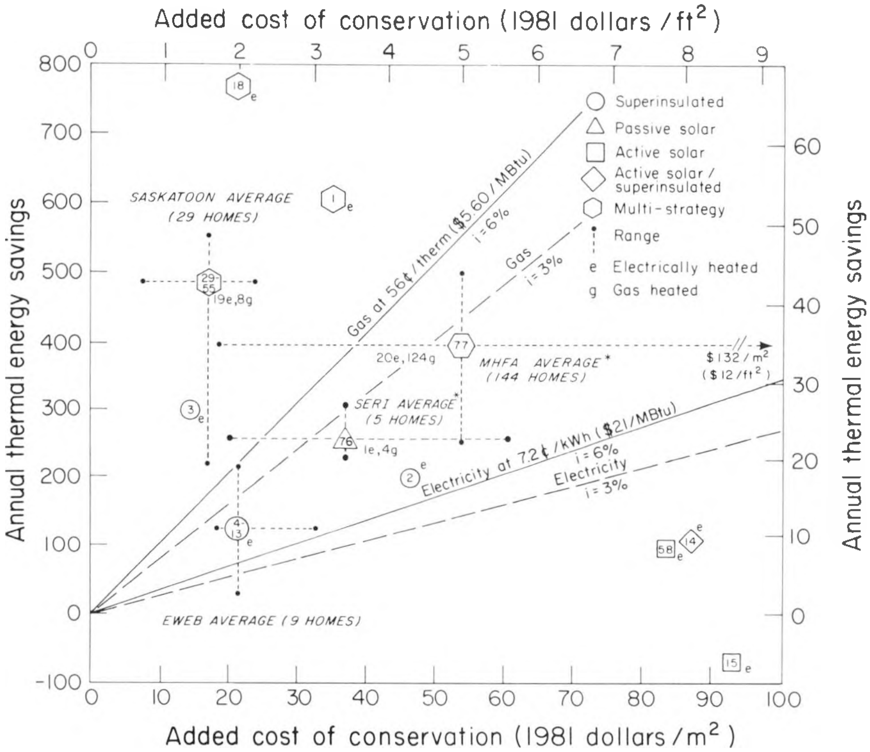



Figure 2. Scatter plot of annual space heating energy savings vs. added first-cost of conservation and solar measures for 237 new homes in BECA-A. Energy savings are calculated as the difference between each home's thermal intensity (space heating load per $ft^2$) and the thermal intensity value for that climate of the "current building practice" line in Fig. 1. Reference lines drawn from the origin represent the cost-effectiveness boundary, using mid-1982 U.S. average residential energy prices ($0.072/kWh and $0.56/therm of gas) and amortizing added first costs over 30 years at 3 and 6% (real) interest rates. A home's conservation features are cost-effective if they are plotted above the reference line(s) for that fuel type. (XBL 8211-7301)

Figure 2 suggests that the added cost of energy-saving features ranges from $2 to $6/$ft^2$ in most cases. The exceptions tend to be homes with active-solar heating or extensive south glazing areas, which cost more. Except for the three active solar homes, almost all the electrically heated homes in our sample were cost-effective, but (using our assumptions) only about half of the gas-heated homes saved energy at a cost lower than average gas prices. The homes that performed best, in both energy and cost-effectiveness, were either superinsulated or included passive-solar features with only moderate south glazing (i.e., not more than 10-12% of floorspace), as well as good insulation.

*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 more than 65 retrofit projects, with sample sizes ranging from 1 to 33,000 homes. Single-home data points are usually research or demonstration projects; the larger samples are from utility-sponsored programs. Most of the retrofits involve insulation or other shell improvements to reduce space-heating consumption, but results for space-heating equipment and water heating are starting to become available. Most of the data include the combined effects of several retrofit measures; it is still difficult to determine the relative contribution of individual measures. Good information on space-cooling performance is also difficult to obtain.

Figure 3 shows space heating energy savings (as a percent of pre-retrofit usage), plotted as a function of retrofit costs. For the overall sample, median space heating energy savings are 24% (28 MBtu/year), achieved at a median cost of about $1100 per home.

For the fuel-heated homes in our sample, the median cost of conserved energy was $3.86/MBtu (assuming a 15-year amortization and a 7% real interest rate). This is substantially less than average 1981 residential-sector prices for natural gas ($4.50/MBtu) and fuel oil ($8.70/MBtu). The 11 data points for electrically-heated homes had a median cost of conserved energy of 3.1 cents/kWh, compared to average residential electricity prices of 6.2 cents/kWh.

Although the data in Fig. 3 show a great deal of scatter, one conclusion may be that, with today's technology and energy prices, there is no evidence that investing more than $2000 in residential (envelope) retrofits yields significant returns. We are continuing to seek measured data on more extensive, but still cost-justified, retrofit projects.

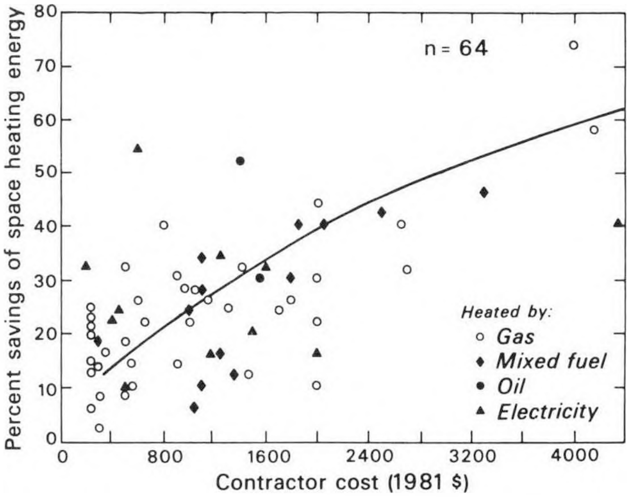



Figure 3 Scatter plot of percent savings in space heating energy vs. contractor cost for 64 residential retrofit projects in the BECA-B data base. There is no obvious correlation for the data points shown, but the "eyeball" relationship shown by the curved line suggests an average relationship that might be expected: about 25% savings from the first $1000 invested and about 40% from the first $2000. (XBL 822-161A)

*BECA-C: Commercial Buildings*

The BECA-C data base currently includes energy savings for 223 retrofitted commercial buildings, mainly schools and hospitals located in the eastern United States. Adequate data on both retrofit costs and energy savings are available for only one-fourth of the sample. In 1982, we began to extend the data base to new energy-efficient commercial buildings and will publish results in 1983.

The 223 sites in BECA-C were originally compiled and evaluated by Ross and Whalen[3] of DOE's Office of Building Energy Research and Development. Figure 4, which summarizes their results, shows a wide range of both absolute and percentage energy savings. Median fuel savings were 21% of pre-retrofit consumption, while electricity savings were 7%—a lower ratio of electricity to fuel savings than estimated in other studies of commercial-sector retrofits.[4] 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.

One characteristic of the buildings in BECA-C was the emphasis on low-cost operation and maintenance measures, implemented in 95% of the buildings. This emphasis was reflected in the low level of retrofit investments (the median was about $\$0.56/ft^2$, compared to typical annual energy costs of about $\$1.50/ft^2$) and in short payback times (the median was 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 rational response to the perceived risks. In fact, about 9% of the buildings used more energy after retrofit than before. These negative results may have been due to poor operation and maintenance, or to product failure (in one case, for example, a window film failed to adhere). More data on "instructive failures" are needed to improve our understanding of such factors.

*BECA-V: Model Validation Data*

The BECA-V data base includes comparisons of predicted and measured building energy performance—ranging from the output of complex computer simulation models to simplified calculations used for energy audits or building efficiency "ratings." Eventually, we hope to collect and translate the most detailed and accurate data sets into standard formats that can be used to validate algorithms (or calibrate input assumptions) for a variety of building analysis models.

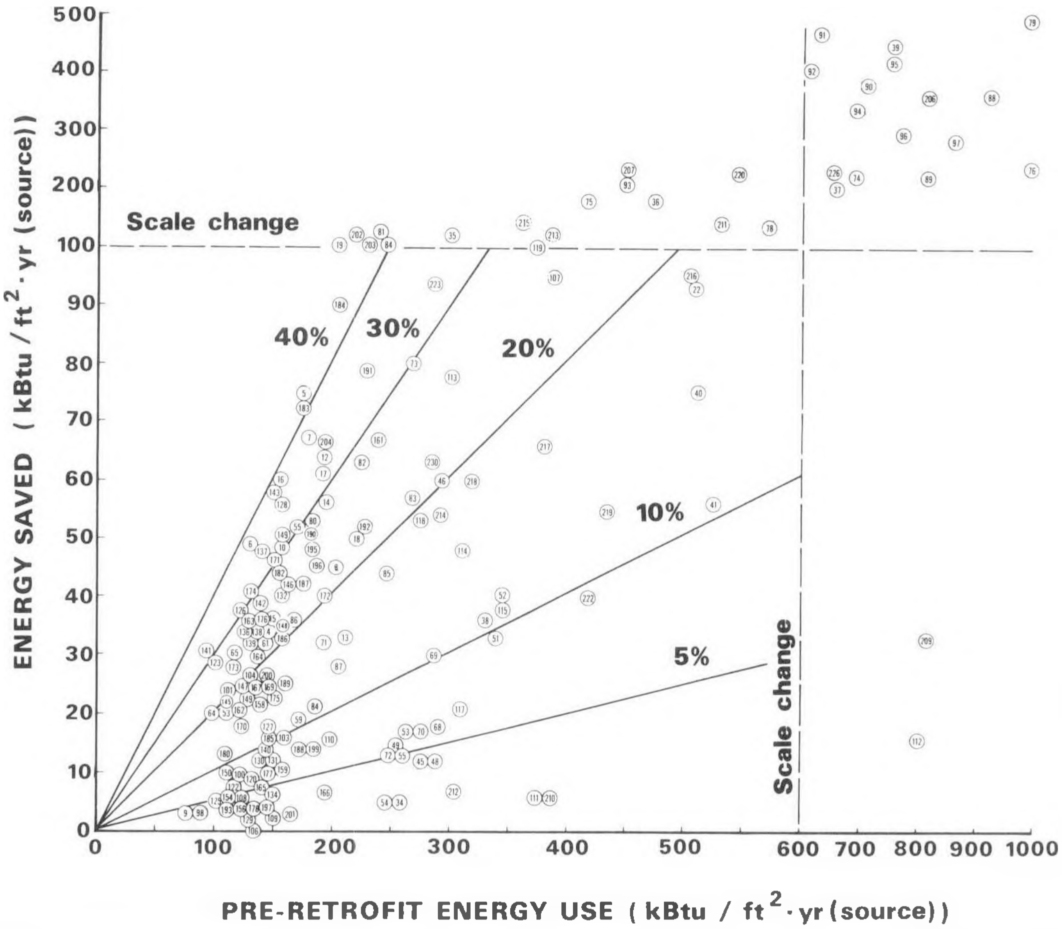



Figure 4. Energy savings vs. pre-retrofit energy use for 223 retrofitted commercial buildings in the BECA-C data base. While one might expect a general trend toward increased savings with larger pre-retrofit consumption, no simple correlations emerge from the current sample. We have plotted lines that bin the data points by percent of energy saved. Note the scale change on both axes, an indicator of wide variance among data points. The axes can be converted to SI units by using the factor 1 kBtu/ft$^2$/year = 11.36 MJ/m$^2$/year. (XBL 826-792)

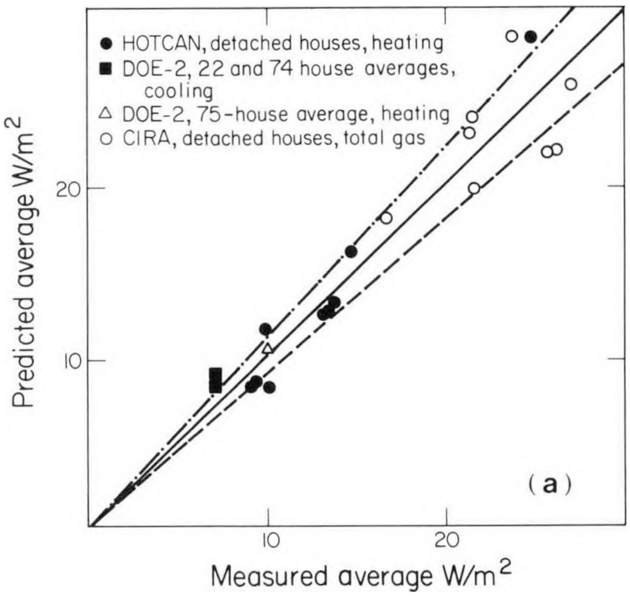
The 12 validation studies examined to date include 63 data points, representing 202 buildings. Preliminary results are summarized in Wagner and Rosenfeld.[5] These studies compared computer model predictions with utility-metered or site-measured energy consumption, both for individual homes and commercial buildings, and for groups of up to 75 buildings. The sample does not include comparisons of measured data with energy savings predicted during an audit.[†]

On the whole, the complex computer models used (DOE-2, BLAST, NBSLD, REAP) were accurate to within 10%, both for total energy use and for space conditioning—provided that correct (i.e., measured or instrumented) input data were used. Simplified calculation procedures, or any program used to analyze a non-submetered building, were accurate to within ±15%. Figures 5 (a) and 5 (b) compare predicted and metered energy consumption (all end uses) for several residential and commercial buildings, or group averages, spanning a wide range of energy intensities. Most of the comparison studies we reviewed did not involve "blind" comparisons, i.e., the analyst had access to metered data while conducting the simulation.

The 12 studies reviewed so far are too limited a sample to justify more than tentative interpretations. However, we observe that space heating performance is easier to predict, with current techniques, than space cooling or other end uses. Predictive accuracy also improves with better input data, and with the training or experience of the model user (the author of a computer model is almost always able to make

† However, very limited subsamples of the BECA-B and BECA-C data bases (9 and 18 data points, respectively) contain both auditor predictions and actual measured savings. The data suggest that predictive accuracy is often poor for savings in individual buildings, but improves somewhat (to within ±20%) for larger groups of buildings. More comparisons are needed to confirm and quantify this tendency, and to identify possible causes.

the most accurate predictions). More data and more analyses are needed to establish the relative importance of these factors.



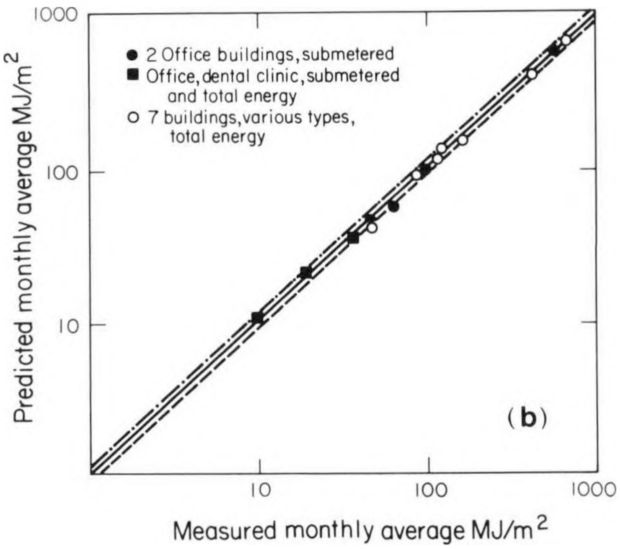




Figure 5. Predicted vs. measured energy consumption from the BECA-V data base: (a) individual residential buildings and group averages with no submetered or site-monitored data; (b) commercial buildings with relatively detailed submetered data (logarithmic scales).
[(a) XBL 832-65; (b) XBL 832-66]

## Planned Activities for FY 1983

In the coming year, we will expand the BECA data bases and begin to compile measured performance data for efficient appliances (BECA-D). New commercial buildings will also receive increased emphasis. Other priorities for the next one to two years include:

- Adding multi-year data for both new and retrofitted buildings, to track the persistence of energy savings and begin identifying the effects of physical degradation, lax operating practices, or shifts in occupant behavior.
- Obtaining more detailed, submetered data on individual buildings, to analyze component contributions to savings and cost-effectiveness and make better comparisons between predicted and actual performance.
- Establishing (for the existing stock and new construction) a more accurate definition of the "base case" against which efficient buildings are compared.
- Seeking measured conservation results for end uses other than space heating (cooling, water heating,‡ lighting and appliances), for buildings in mild climates, and for building types currently underrepresented in the data base (multi-family, mobile homes, several categories of commercial buildings).
- Adding data on more intensive commercial retrofits (including major renovations), and less extensive ("warm room") residential retrofits.
- Incorporating, especially for commercial buildings, the effects of design features or retrofits on peak electricity demand as well as energy use.
- Identifying improved techniques for monitoring or analytically accounting for the net contributions of wood heating systems in low-energy homes.
- Establishing a basis for climate-normalizing HVAC performance in commercial buildings that are shell-dominated or have high ventilation rates.

The BECA data bases will continue to serve as a repository for the quantitative results of DOE-funded buildings research. At the same time, we plan to use informal workshops, conference presentations, and other means to strengthen ties with utility, industry, and professional groups, both as prospective contributors of data and as clients and users of the data

‡ In the future, we will seek joint sponsorship by DOE's solar and buildings conservation programs to establish a new data base, BECA-W, on a full range of water-heating and hot-water-use technologies: heat pumps, solar collectors, heat recovery, demand heaters, high-efficiency storage water heaters, and reduced-flow appliances and plumbing.

bases. While DOE provides the core funding for maintaining and updating the BECA data bases, non-DOE sponsors may support specialized regional or subsector data compilations.

We plan to draw, as much as possible, upon past government-funded and industry-sponsored conservation programs as sources of BECA data. These include the Federal Energy Management Program (FEMP), the Institutional Conservation Program (ICP), HUD-sponsored public housing demonstration projects, and a joint effort with the California Department of General Services to analyze data on state-owned buildings. Among privately owned buildings, we will focus on national retail, restaurant, and motel chains that have already implemented energy management programs. Finally, we plan to collaborate with sponsors of major national energy design competitions (ASHRAE, Owens-Corning, AIA) to obtain follow-up data on the actual performance and cost of award-winning buildings.

## CONSERVATION TECHNOLOGIES DATA BASE AND POTENTIALS

### Accomplishments During FY 1982

For conservation measures already in commercial use, performance and cost data are compiled at the building level through the BECA project. The Conservation Technologies/Potentials project is concerned with new and prospective technologies. Laboratory and field data are obtained from R&D programs at LBL and other laboratories, and from innovative designers, manufacturers, builders, and utilities. The project has generated a detailed data base, by end use, for residential conservation technologies. Future work will extend this work to commercial buildings.

These data were used initially in preparing two major studies of the technical potential for improved residential energy efficiency: an analysis of conservation potential in California homes and appliances as of 1980,[6] and an assessment of the year 2000 conservation potential for all U.S. residential buildings.[4] During the past year, as part of a study sponsored by the Bonneville Power Administration (BPA), we undertook a major update of the data on residential electricity conservation measures, applied to the housing stock and climate of the Pacific Northwest.[7] Finally, we provided technical support to the San Diego Gas and Electric Company, as part of a project to estimate conservation opportunities in its service area.

For policy-making and utility planning, it is important to translate performance and cost data on individual technical measures into aggregate estimates of potential energy savings. To do this, we construct marginal cost curves (which we term "supply curves") for conserved energy. Such curves are fundamentally the same as those for any other commodity and provide a tool for comparing the cost and availability of saved energy with those of new energy supplies.[8]

The development of a supply curve for a given end use, region, and year (Fig. 6; Table 1) begins with the ranking of individual conservation measures in order of cost-effectiveness. This requires detailed information not only on the measure itself, but on the existing and projected characteristics of the building and equipment stock and their "baseline" energy consumption (the starting point for calculating savings). During the past year, we developed a subroutine, called WORK4, for our CPS 2.0 computer program. This subroutine performs the extensive accounting needed to calculate stock-average energy savings,

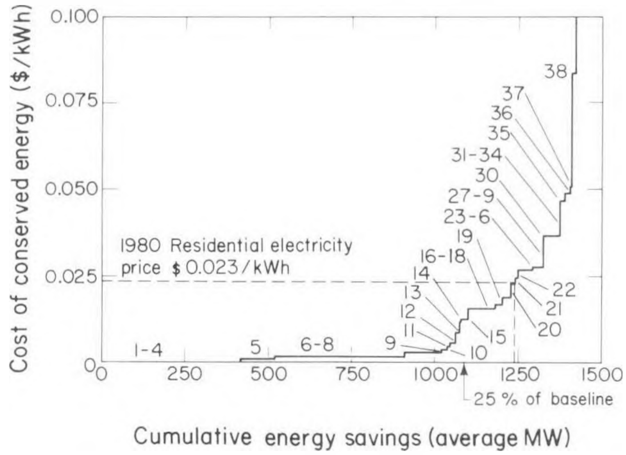



Figure 6. Conservation supply curve showing estimated technical potential for saving electricity in residential appliances, as of the year 2000, for the region served by the Bonneville Power Administration (BPA). Annual savings (horizontal axis) are plotted against cost per unit of energy saved (vertical axis). Each step represents regionwide application of one conservation measure listed in Table 1. Total annual savings potential for measures costing up to $.023/kWh (the 1980 average residential electricity price in the region) is 10.7 TWh (1226 average megawatts), or 28% of the baseline consumption projected for appliances in the year 2000. Savings are calculated (using the ORNL residential model) from a base case that assumes no change in average efficiencies of the 1980 appliance stock or in average additions to it. An "average megawatt" equals 8760 MW-hours. (XBL 832-1220)

Table 1. Residential electric appliance efficiency measures included in the conservation supply curve (Fig. 6) for the BPA region, as of the year 2000.

| Conservation Measure | Avg. Cost | Avg. Sav. | Life (Yrs.) | CCE ($/kWh) | Measure Sav. (GWh) | Cum. Sav. (TWh) | Cum Sav. (Avg. MW) |
|---|---|---|---|---|---|---|---|
| 1 Television—b & w, solid-state improvement | 0. | 150. | 10 | 0. | 272.7 | 0.3 | 31.1 |
| 2 Television—color, solid-state improve. | 0. | 400. | 10 | 0. | 1883.1 | 2.2 | 246.1 |
| 3 Refrig.—side-by-side, buy eff. mkt. model | 10. | 1100. | 19 | 0.001 | 610.2 | 2.8 | 315.8 |
| 4 Freezer—chest manual, buy eff. mkt. model | 20. | 1000. | 21 | 0.001 | 880.6 | 3.6 | 416.3 |
| 5 Freezer—upright auto., buy eff. mdl./CPES | 40. | 1700. | 21 | 0.002 | 908.7 | 4.6 | 520.0 |
| 6 Refrig.—top/bottom-eff. mkt. model/CPES | 25. | 950. | 19 | 0.002 | 2507.0 | 7.1 | 806.2 |
| 7 Freezer—chest manual, CPES improvements | 5. | 160. | 21 | 0.002 | 123.5 | 7.2 | 820.3 |
| 8 Freezer—upright man., buy eff. mkt. model | 30. | 900. | 21 | 0.002 | 704.6 | 7.9 | 900.8 |
| 9 Refrig.—side-by-side, CPES improvements | 10. | 200. | 19 | 0.003 | 106.1 | 8.0 | 912.9 |
| 10 Refrig.—partial auto., eff. mkt. model/CPES | 35. | 665. | 19 | 0.004 | 954.5 | 9.0 | 1021.9 |
| 11 Freezer—upright man., CPES improvements | 15. | 200. | 21 | 0.005 | 137.3 | 9.1 | 1037.5 |
| 12 Waterbed, comforter cover | 20. | 400 | 10 | 0.006 | 80.4 | 9.2 | 1046.7 |
| 13 Refrig.—single-door, buy eff. mkt. model | 30. | 240. | 19 | 0.009 | 136.1 | 9.3 | 1062.2 |
| 14 Waterbed, insulate sides/bottom | 20. | 200. | 10 | 0.012 | 107.2 | 9.4 | 1074.5 |
| 15 Refrig.—single-door, CPES improvements | 10. | 55. | 19 | 0.013 | 29.7 | 9.4 | 1077.9 |
| 16 Lighting—sf, fluorescent in kitchen | 27. | 115. | 20 | 0.016 | 163.3 | 9.6 | 1096.5 |
| 17 Lighting—mh, fluorescent in kitchen | 27. | 115 | 20 | 0.016 | 23.4 | 9.6 | 1099.2 |
| 18 Lighting—mf, fluorescent in kitchen | 27. | 115. | 20 | 0.016 | 21.9 | 9.7 | 1101.7 |
| 19 Refrig.—top/bottom-1985 improvements | 75. | 300. | 19 | 0.017 | 688.3 | 10.3 | 1180.3 |
| 20 Refrig.—side-by-side, 1985 improvements | 100. | 370 | 19 | 0.019 | 177.7 | 10.5 | 1200.5 |
| 21 Refrig.—partial auto., 1985 improvements | 60. | 180. | 19 | 0.023 | 223.7 | 10.7 | 1226.1 |
| 22 Lighting—sf, fluorescent in bathroom | 30. | 80. | 20 | 0.025 | 113.6 | 10.9 | 1239.1 |
| 23 Refrig.—single-door, 1985 improvements | 50. | 130. | 19 | 0.027 | 63.0 | 10.9 | 1246.2 |
| 24 Lighting—mh, replace high use with SL | 20. | 50. | 20 | 0.027 | 25.4 | 10.9 | 1249.1 |
| 25 Lighting—mf, replace high use with SL | 20. | 50. | 20 | 0.027 | 23.8 | 11.0 | 1251.9 |
| 26 Lighting—sf, replace high use with SL | 40. | 100. | 20 | 0.027 | 355.0 | 11.3 | 1292.4 |
| 27 Lighting—mf, fluorescent outside | 25. | 60. | 20 | 0.028 | 5.7 | 11.3 | 1293.0 |
| 28 Lighting—sf, fluorescent outside | 25. | 60. | 20 | 0.028 | 63.9 | 11.4 | 1300.3 |
| 29 Lighting—mh, fluorescent outside | 25. | 60. | 20 | 0.028 | 9.1 | 11.4 | 1301.4 |
| 30 Cooking—elec. ranges/ovens, CPES improv | 22. | 45. | 18 | 0.036 | 187.7 | 11.6 | 1322.8 |
| 31 Lighting—mf, fluorescent in bathroom | 30. | 55. | 20 | 0.037 | 10.5 | 11.6 | 1324.0 |
| 32 Lighting—mh, fluorescent in bathroom | 30. | 55. | 20 | 0.037 | 11.2 | 11.6 | 1325.3 |
| 33 Lighting—sf, replace med. use with SL | 80. | 115. | 20 | 0.047 | 408.3 | 12.0 | 1371.9 |
| 34 Television—b & w, 1985 improvement | 10. | 25. | 10 | 0.047 | 45.4 | 12.1 | 1377.1 |
| 35 Lighting—mf, replace med. use with SL | 60. | 85. | 20 | 0.047 | 40.4 | 12.1 | 1381.7 |
| 36 Lighting—mh, replace med. use with SL | 40. | 55 | 20 | 0.049 | 27.9 | 12.1 | 1384.9 |
| 37 Clothes dryer, moist./temp. sensor & insul. | 35. | 50. | 18 | 0.051 | 157.1 | 12.3 | 1402.8 |
| 38 Well pump, conservation measure | 100. | 100. | 15 | 0.084 | 37.2 | 12.3 | 1407.1 |
| 39 Clothes washer, improved efficiency | 50. | 30 | 10 | 0.195 | 104.5 | 12.4 | 1419.0 |
| 40 Dishwasher, motor efficiency | 150. | 50. | 10 | 0.352 | 111.3 | 12.5 | 1431.7 |

Note: mh = mobile home; mf = multi-family; sf = single-family.

over several years, from a given measure. The model accounts for additions and removals from the stock, and the measure's interaction with other energy-saving features in the same home.

To construct a supply curve, one must determine the stock-weighted average energy savings per unit, the average cost of saved energy, and the number of units to which the measure can be applied. The supply curve relates the unit cost of conserved energy (vertical axis in Fig. 6) to the cumulative annual energy savings (horizontal axis).

Figure 6 is a supply curve of conserved electricity in the BPA region for the year 2000 for one end use: home appliances. The data base used to generate this supply curve (Table 1) lists cost and performance characteristics for each measure, as well as the regionwide annual energy savings that could be achieved by implementing the measure in all technically feasible cases. (This assumption of 100% penetration allows us to quantify the opportunities addressed by energy conservation policies. Lower, "real-world" penetration rates can be modeled exogenously by the utility.)

A conservation measure, representing one "step" on the supply curve, is cost-effective if its cost of conserved energy is less than the cost of the energy it displaces. One can estimate the economical "reserves" of conserved energy by selecting a comparison price for the energy displaced. There are many ways of choosing this comparison price, depending on the policy or analytical perspective of the user.

In Fig. 6, we choose \$0.023/kWh as a comparison price, representing the 1980 (base year) average residential electricity price in the region. An alternative comparison price might have been the projected long-run avoided cost (i.e., the savings per kWh from avoiding the need to build and operate new thermal generating capacity). This value is estimated by BPA at \$0.15/kWh, which is off-scale in Fig. 6; the most expensive measure we considered (Table 1) costs \$0.084/kWh saved.

For measures cost-effective at today's average electricity price, total potential savings in the year 2000 are over 1200 average MW (10.7 TWh), or 28% of the projected baseline consumption for appliances (the baseline assumes no change in current efficiencies). If we include additional measures with costs of conserved energy up to the long-run avoided cost, the potential year 2000 annual savings increase to 1400 average MW (12.3 TWh), or 32%. Similar end-use supply curves were constructed for residential electric space heating and water heating.

Note that the estimated annual energy savings represent only the *technical potential*, not the predicted level of conservation that will actually take place in response to assumed market conditions, government regulations, or utility-sponsored programs.

In our earlier studies, similar conservation supply curves were prepared for residential gas and electricity use in California and in the United States as a whole. The California study found that as much as 25% of the electricity and 34% of the natural gas used by the existing housing stock could be saved, at an average cost of conserved energy well below current average utility rates.

Our analysis of all U.S. homes included additional measures and a longer time horizon (20 years instead of 10). Even though the conservation measures included only those now on the market and economic at today's average energy prices, we identified technical opportunities to reduce residential energy use by the year 2000 to 30% below today's consumption—despite the projected addition of 40 million new homes. Compared to the year 2000 baseline forecast of the Energy Information Administration, these potential savings would be worth (at today's energy prices) about \$75 billion per year.

## Planned Activities for FY 1983

We are continuing to update the technologies data base, replace engineering estimates with measurements, and to refine the techniques for evaluating conservation potential. We will begin extending the supply-curve analysis to non-residential buildings to include the potential for reducing electrical peak demand as well as energy use. The first subsector covered will probably be restaurants, because of the technical opportunities for improvements in refrigeration and heat recovery (see below, under Primary Data Collection).

As an outgrowth of our analysis of residential electricity conservation for BPA last year, we will compare our technology performance and cost data with the data used to generate technology-cost tradeoff curves for the Oak Ridge residential demand model[9] and determine the need for region-specific updates of these trade-off curves.

## PRIMARY DATA COLLECTION

### Accomplishments During FY 1982

*House-Doctor Demonstration Project*

Over the past 3 years, we conducted a cooperative project with Pacific Gas and Electric Company (PG&E) to determine the energy savings attributable to "house-doctoring."[10] House-doctoring is a term for an extended energy audit that includes installation of simple, cost-effective conservation measures and use of infiltration monitoring equipment to identify and seal major air leaks. We trained six PG&E weatherization specialists in house-doctoring techniques and chose Walnut Creek, California, as the site for a controlled experiment. Three groups of 10 randomly selected homes were included in the experiment. One group received a conventional PG&E (information-only) home energy audit. The second group received an audit plus house-doctor diagnosis and treatment. The third group received this treatment plus additional retrofits (principally wall and ceiling insulation) that were recommended in the course of the audit. (Analysis of post-retrofit data for this group has not been completed.) Results were compared with energy use for a control group of 10 homes and a comparison group consisting of all Walnut Creek homes.

Some results of the project are shown in Fig. 7. The two groups of house-doctored homes showed statistically significant savings of 11.4% in (weather-normalized) annual natural gas use. But these savings were not significantly different from the average for the audit-only group, which also saved 9.4% (see below). The small control group (6 homes) and the comparison group of all Walnut Creek homes both showed 7% savings over the same period.

There are several possible reasons for our failure to find, as expected, a statistically significant improvement in savings for the house-doctored homes. These include the limited sample size (due to budget limitations), the failure to monitor changes in thermostat setting or to submeter other energy uses (especially important in the mild Walnut Creek climate), and the significant variation within groups in pre-retrofit energy consumption. There were also considerable differences in the approach and quality of work by our newly trained house doctors.

But the most significant external influence was a jump in residential gas prices of more than 50% (from \$0.29 to \$0.44/therm) between the pre-audit and post-audit periods. At the same time, electricity prices more than doubled (from \$0.043 to \$0.094/kWh). These energy price increases may have swamped any experimental effect of house-doctoring vs. conventional auditing, by affecting occupant behavior in both the experimental and control/comparison groups. Price changes may also have stimulated "independent" retrofitting by the control group and by other Walnut Creek homeowners.

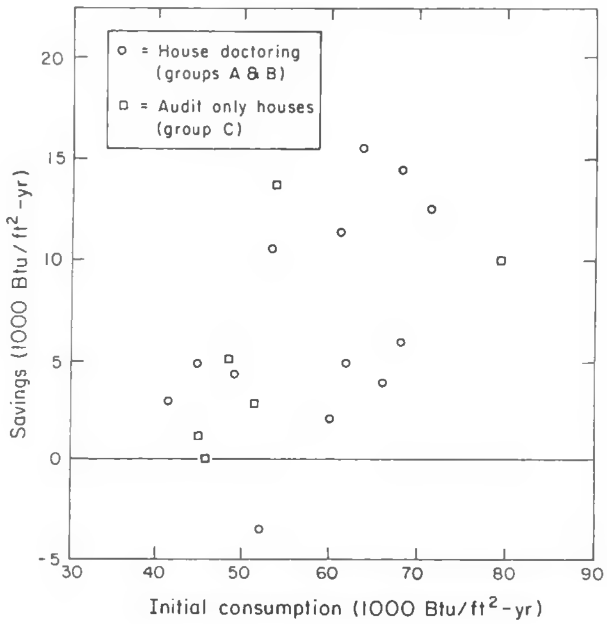



Figure 7. Scatter plot of natural gas savings vs. initial consumption, both normalized by square footage, for 19 homes (13 house-doctored and 6 audit-only) in the PG&E/LBL House Doctor Demonstration Project. Both groups achieved statistically significant savings, but there was no significant increase in savings for the house-doctored group. (XBL 829-1142)

Although the experiment failed to show that house-doctoring can achieve significantly greater savings in total energy use (compared to conventional residential audits), we are reasonably confident of the estimated savings from one aspect of house-doctoring: reduced air infiltration. Reductions in seasonal infiltration were estimated from calibrated blower-door measurements before and after the house doctor visit.

Even before house-doctoring (contrary to our intent), the random sample of homes had considerably lower infiltration rates than the typical California home (an average of 0.53 air changes/hour, compared to about 0.7 to 1.0 ach statewide). In Walnut Creek's mild climate, this meant that infiltration contributed only about 10% of the pre-retrofit annual energy use, so even a large percentage reduction in infiltration would have only a small effect on total energy use. After the house doctor visit, average infiltration was reduced to 0.40 ach, for an annual savings of about $18 (with gas at $0.44/therm) over the typical Walnut Creek heating season.

Although a number of factors—the mild climate, absence of submetering, small sample size, and concurrent sharp increases in utility rates—complicated the experiment and limited our ability to generalize results, a series of similar experiments were conducted by Princeton University in the colder climate of New York and New Jersey. These showed somewhat larger, cost-effective net savings from house-doctoring vs. control groups.[11]

In addition to some important lessons about the design of small-sample experiments in a mild heating climate, we conclude from this project that house doctors cannot approach all homes in the same way, even within the same community. For homes that are already reasonably airtight, further efforts to find and fix infiltration leaks will generally not pay. Some prescreening, in the first hour of the visit—or even before the site visit, using billing data and phone interviews—might help identify the most cost-effective level of effort and mix of techniques for each home.

### *Infiltration and Indoor Air Quality in New California Homes*

Since 1975, the State of California has required all new homes to meet minimum levels of energy efficiency and has revised and tightened these requirements twice (in 1978 and 1983). At present, there is little information on how well homes built to these standards really perform. There are also unanswered questions about the possible side effects of reduced infiltration on indoor air pollution levels in new California homes.

To begin addressing these questions, we collaborated with the University-wide Energy Research Group on a project sponsored by the California Energy Commission to measure air change rates and monitor indoor air quality in 16 new homes.[12] Limited resources forced us to focus on homes expected to have the poorest indoor air quality: newly built, low-infiltration homes with natural gas appliances. New construction materials and natural gas combustion are major sources of residential indoor air pollution, and tight houses tend to maintain higher concentrations of internally generated pollutants.

Pressurization tests showed that all 16 houses had average heating-season infiltration rates below 0.5 ach; the average was 0.34 ach. Prevailing state standards assumed infiltration rates of about 1.3 ach, while the proposed 1983 revisions require measures assumed to reduce infiltration to about 0.9 ach. We used "passive" monitors to measure concentrations of formaldehyde (typically released by outgassing from new building materials and furniture), nitrogen dioxide (a combustion product), and radon-222 (a decay product of naturally occurring radium in soil, groundwater, and some building materials).

Overall, the results indicated that new houses having low air-change rates do *not* necessarily experience poor indoor air quality, even without mechanical ventilation or other special measures. For example, Fig. 8 shows the weak correlation between infiltration rates and indoor nitrogen dioxide ($NO_2$) concentrations. Nitrogen dioxide levels ranged from 2.6 to 28 parts per billion, with an average of 10.4 ppb. All were well below the EPA limit (for outside air) of 50 ppb. Moreover, for many homes the indoor concentrations of $NO_2$ were lower than the outside concentration. Concentrations of $NO_2$ tended to increase with gas stove use.

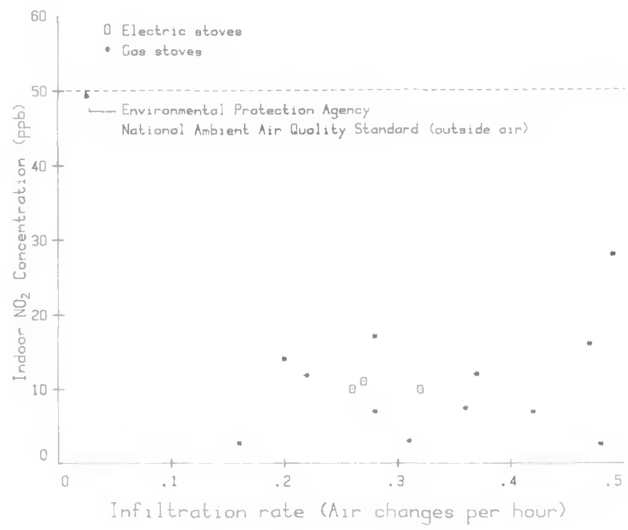



Figure 8. Average indoor concentrations of nitrogen dioxide ($NO_2$) vs. average infiltration rates in 15 new, low-infiltration California homes built to meet or exceed the 1978 state standards. These concentrations, measured over a one-week period, are all below the EPA standard for outside air. (XBL 833-8762)

Measured radon levels ranged from 0.32 to 2.24 picocuries/liter (pCi/l). The strictest indoor standards being considered in the United States or Sweden range from about 2 to 5 pCi/l; two homes were slightly above the low end of this range.

Measured indoor concentrations of formaldehyde (HCHO) varied from 78 to 163 ppb, a range overlapping the low end of the proposed standards. However, these measurements were made using prototypes of the HCHO passive monitors and may have been 15% high compared to conventional measurement procedures. All homes with concentrations over 100 ppb were less than 2 years old, so formaldehyde concentrations might be expected to decline as building materials and furnishings age. Conversely, other building types not tested (such as mobile homes) might have considerably higher HCHO concentrations, especially when new.

Because of the small sample size and the large number of factors affecting both pollutant source strength and indoor concentrations, these results do not necessarily mean that all new, tight homes have acceptable air quality. Localized "pockets" of radon in the soil, poorly vented gas appliances, or building materials and furnishings that release formaldehyde and other organics could create unhealthy air quality in some fraction of new houses. Our data suggest only that indoor air quality problems are not inevitable, even in fairly well sealed, energy-efficient houses.

We conclude that an effective strategy is needed, in California and elsewhere, for identifying and treating "problem" houses—whether or not there are building codes and retrofit programs aimed at reducing infiltration.

## Planned Activities for FY 1983

By establishing early contact with potential sources of data and offering informal suggestions, we hope to improve the quality of data eventually made available for the BECA compilations. In recent months, we have provided comments on experimental design and data collection techniques to:

- members of the DOE-funded Urban Consortium, on superinsulation retrofits and warm-room experiments
- the California Building Industry Association, on performance tests of unoccupied new homes, and
- the evaluation design team for the Hood River Residential Retrofit Demonstration Project, sponsored by the Bonneville Power Administration and Pacific Power and Light.

Beginning early in FY 1984, we will establish a loan pool of reliable, low-cost instrumentation (such as the "Energy Signature Monitor" being developed at LBL) to be made available to organizations with limited technical resources but good opportunities to generate the data needed to fill gaps in our compilations.

## Summer Study on Energy-Efficient Buildings

During 1982, we coordinated the planning for a major, week-long Summer Study held in August 1982 at the University of California campus in Santa Cruz. The Summer Study was organized by the American Council for an Energy-Efficient Economy (ACEEE). Besides LBL, co-sponsors included DOE, the Bonneville Power Administration, Texas Utilities, the Gas Research Institute, Electric Power Research Institute, and the University of California's Energy Research Institute. The Summer Study was judged highly successful by the 240 participants, who represented the building and utility industries, state and local governments, DOE, the national laboratories, and several other research organizations in the U.S. and Europe. Over 150 papers were presented, mainly in small-group sessions, over the course of the week.

This was the second Summer Study organized by ACEEE. At the first one, held in August 1980, participants from industry, government, and research organizations discussed the technical potential for conservation in buildings, as well as government policies and utility/industry practices needed to achieve that potential. BED staff played a major role in editing the proceedings and preparing them for publication.[13]

Whereas the 1980 meeting focused on potential, the 1982 meeting focused on what has been achieved. Its theme, "Documenting the Results of Energy Conservation in the Buildings Sector," was directly relevant to BED's data base effort, and we found a number of leads to new sources of data and possible opportunities for collaboration. Members of the group authored or co-authored eight papers presented at the Summer Study.

During 1983, BED will assist in compiling and editing the 1982 Summer Study proceedings, which will be published by the ACEEE and the American Solar Energy Society. These proceedings will represent a major contribution to quantitative data on energy conservation in U.S. buildings.

## CONCLUSION

The past year has been a developmental period for all our data compilations. We have identified a number of major gaps in the data and will certainly uncover more in the future. Nevertheless, we can offer some tentative conclusions about the data compilation process, conservation results achieved to date, and the remaining potential.

First, some observations on the data compilation process:

- More and better quality data are beginning to become available, but most reported results still must be screened carefully to remove errors and assure comparability. Conservation programs that produce well-documented, empirical measurements of both energy savings and cost-effectiveness are still the exception rather than the rule.
- Data are still more plentiful for residences than for commercial buildings. In the commercial sector, serious measurement and analysis projects are just beginning to deal with complexities related to the diversity in physical characteristics and usage, criteria and methods for climate-normalizing space conditioning energy use in some buildings, and the interpretation of utility billing data where there are multiple buildings on a meter or multiple meters in a building.
- Data compilation is time-consuming. Even for promising "leads," there can be an attrition rate of 80 to 90% before data are finally obtained in a usable form. The lead time for new data can be 2 to 5 years, depending on the nature of the project and the sponsor's resources and commitment to providing high-quality data. This underscores the need for continuity over a multi-year period in maintaining and updating a conservation data base for buildings.
- For meaningful comparisons of energy performance, especially among energy-efficient buildings, new performance parameters for thermal comfort, visual performance, and other amenities must be defined and monitored. For example, when is it important to consider, not just average indoor temperature, but temperature fluctuations, radiant exchanges, and air movement as determinants of occupant comfort in a passive-solar or earth-sheltered home? When an attached sunspace is used intermittently, should it be included in the definition of "conditioned space" for comparison with other buildings? How can reductions in lighting energy use be compared for their effects on visual performance of various tasks, not simply in terms of illumination levels (footcandles)?

As for conservation results and potential, the data suggest that:

- Even after correcting for such obvious factors as building type, type of conservation measure, square footage, indoor temperatures, and climate, conservation projects still show a wide range of results in both performance (savings) and costs. But we still have little understanding of the reasons why some efforts succeed and others fail. It is clearly possible to save a large fraction of the energy used in "conventional" buildings, at very attractive costs of conserved energy—but it is not inevitable. There are both "failures" (higher energy consumption) and extremely sub-optimal projects (where the energy saved costs more per unit than purchased energy). It is especially hard to find data on well-documented failures.
- The most common investments by owners of both residences and commercial buildings are those involving relatively low initial cost, low perceived risk (because they are "familiar"), and short paybacks (1 to 5 years). These investments seldom approach the "societal" life-cycle cost optimum—nor are conservation investments yet treated the same as other public and private investments, including new energy supplies.
- We have no data on extensive, costly retrofit measures (or new design features) that are still attractive in terms of the cost of conserved energy. In some cases, the technology for more extensive, but still economic, retrofits needs further development, but in others it is more a question of making existing technology more widely available and assuring that its performance is adequately monitored and reported.

- Evidence on issues long debated by advocates of specific technologies (active vs. passive solar systems, solar gains vs. increased insulation) is preliminary and still inconclusive. The answers to these questions may never be clear-cut or universally applicable. For example, most of the best-performing low-energy homes monitored in recent Minnesota and Saskatchewan projects had relatively low solar apertures—but one set of large-aperture solar homes also performed well. The same rules of thumb for optimal glazing/insulation trade-offs in cold climates may not apply in milder climates (California), in cold, sunny ones (Colorado), or where effective night insulation has been installed and used conscientiously. In general, we may find that several technical approaches, applied sensibly, can produce roughly equivalent results.
- Major gaps in our data include: results from commercial buildings other than offices and schools, data on multi-family and manufactured housing, information on cooling performance in both dry and humid climates, multi-year savings and cost data for all types of new and retrofitted buildings, data on advanced conservation products and applications outside the United States (to be interpreted with caution, due to institutional and cultural differences), and well-documented, instructive *failures*—perhaps the hardest of all to add to a public data base. Our future efforts will address each of these areas.

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## BUILDING ENERGY SIMULATION GROUP*

*J.J. Hirsch, W.F. Buhl, R.B. Curtis, A.E. Erdem, K.H. Olson, 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, which in its successive public generations has been known as Cal-ERDA, DOE-1.4, DOE-2.0, and, finally, DOE-2.1, has been guided by several objectives:

1. The description of the building by the user should be in quasi-English so that the input can easily be understood by non-computer scientists.
2. 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.
3. The program should permit simulation of commonly available as well as innovative heating, ventilation, and air-conditioning (HVAC) equipment.
4. The computer costs of the program should be minimal.
5. 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[1-3] and other published materials.[4-8]

### ACCOMPLISHMENTS DURING FY 1982

The DOE-2.1B version of the program was completed, and the writing of supplements to the program documentation[9-12] was begun. Additionally, the Engineers Manual[13] for DOE-2.1A was completed. This document describes all the algorithms used within the program to calculate building heat transfer and resultant energy use. LBL was assisted in this effort by the Q-11 Group at Los Alamos National Laboratory (LANL), which was responsible for producing the final DOE-2.1A Reference and Engineers Manuals from LBL-produced drafts. DOE-2.1A is currently available on DEC-10, DEC-VAX, CDC-Cybers, IBM, Data General MU8000, Honeywell level 6, and Cray-N machines.

The BES Group's ongoing research is divided into two parts. The first centers on modeling building-envelope components and systems. The second is the simulation of heating, ventilating, and air-conditioning (HVAC) equipment and their associated control systems. Major new features of DOE-2.1A and DOE-2.1B in these two areas are described below.

#### Building Envelope Heat-Transfer Modeling

The first step in the simulation of a building is modeling the heat transfer through the envelope components. During FY 1982, three major problems in envelope heat transfer were studied: (1) conductive gains through generalized layered walls and Trombe wall systems; (2) daylight transmission through win-

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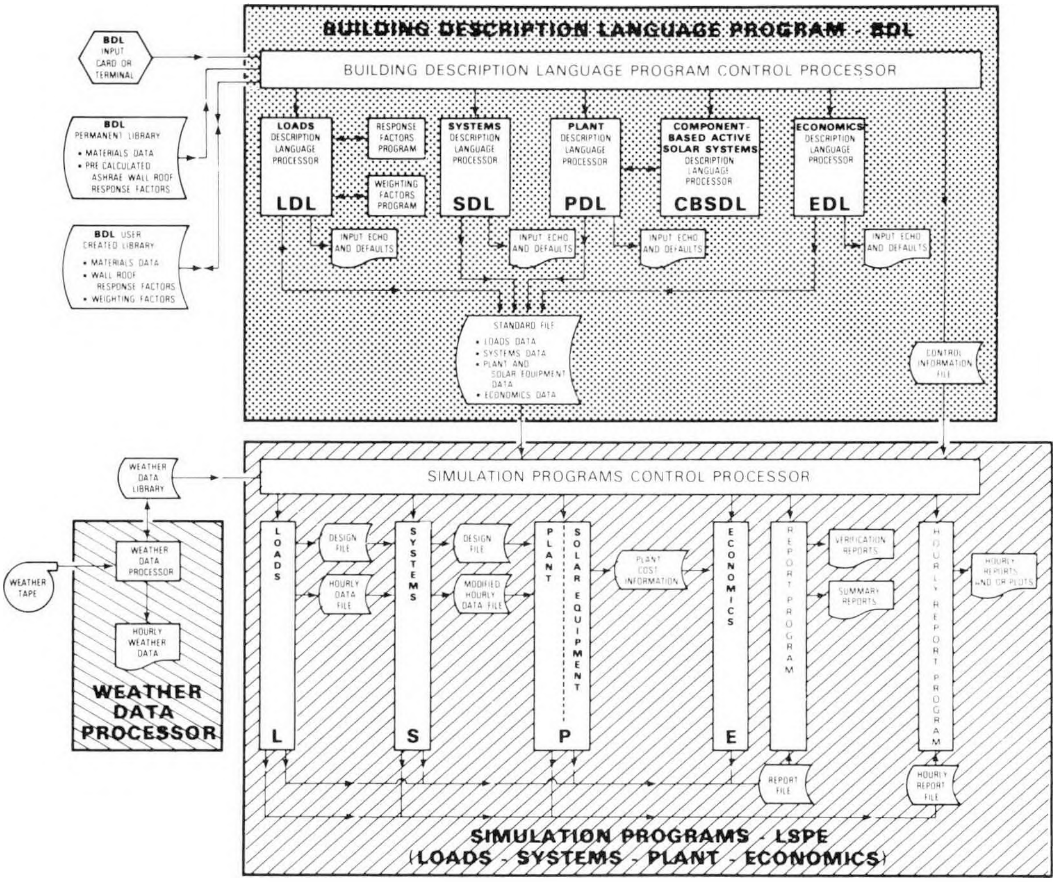


Figure 1. DOE-2.1A computer program configuration. (XBL 825-601)

dows and the thermal effects of alternative glazing systems; and (3) techniques for providing fast and accurate calculation of heating and cooling loads (or response) of whole spaces.

## Response Factors

Building energy-use analysis programs like DOE-2, which take into account transient heat flow, must simulate the delayed transmission of heat through layered walls. The most popular means of doing this are based on response factors developed by Mitalas and Stephenson.[14,15] Significant improvements in the computational speed of the algorithms generating the response factors were achieved through theoretical developments reported elsewhere.[3] These improvements were implemented into the DOE-2.1B version of the program, resulting in a reduction of up to a factor of 20 in the time required to compute response factors.

The gist of the improvements can be expressed as follows. In the usual computation of the thermal response of a multi-layered wall, each layer is summarized in a matrix. The thermal response of the composite wall is given by the product of the matrices for each layer. A method was found to evaluate the matrix elements of this product as a sum of terms with constant coefficients. This formulation avoids the necessity for making a matrix multiplication many times during the response-factor calculation.

## Trombe Walls

The available building-energy analysis programs, which have concentrated on energy transport by conduction and radiation, are incapable of simulating convective transport because it is so much more difficult to simulate than conduction and radiation. In many buildings, particularly those employing "passive" solar designs, convection can be an important and even a dominant effect.

The BES Group, in collaboration with LANL, has begun to integrate models of certain passive solar elements into the DOE-2 building-energy analysis code.[16] A Trombe wall consists of a south-facing (in the Northern hemisphere) window (usually double- or triple-paned) separated from a massive masonry or concrete wall by an air gap (Fig. 2). The combination acts as a crude solar collector, with the heat capacity of the wall providing heat storage and preventing large temperature swings in the occupied space. Both vented and unvented Trombe walls are modeled. With unvented Trombe walls, heat enters the occupied space through conduction alone. The vented Trombe wall has vents at the bottom and top of the wall that enable warm air to flow directly into the living area by natural convection.

The unvented Trombe wall model, a straightforward extension of the capabilities of DOE-2, was implemented into an experimental version of DOE-2.1A in FY 1981, and in FY 1982, both the vented and unvented models were added to DOE-2.1B.

The vented case was the more difficult to simulate. A force-balance equation is written to obtain the air-flow rate. The buoyancy force of the warm air is balanced by the opposing frictional forces caused by the air flowing through the vents and the air gap.

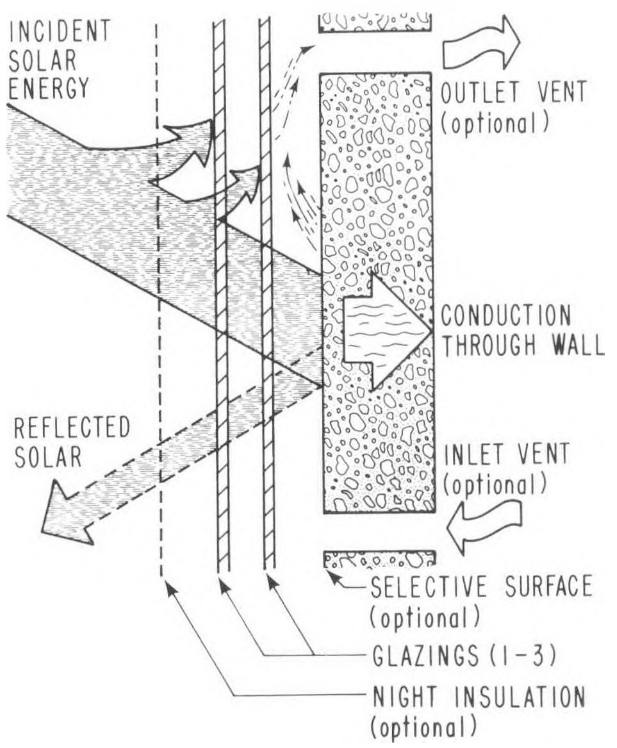


Figure 2. Diagram of heat flows in the DOE-2.1 thermal storage model.[16] (XBL 825-597)

Because the buoyancy of the air depends on its density, which is a strong function of the air temperature, the model must simultaneously do an energy balance on the wall and window surfaces to obtain surface and air temperatures. Because the operations are non-linear, they must be solved numerically, and the model must iterate between the two equations until a stable, simultaneous result is obtained for air flow, air temperature, and surface temperatures.

These problems are typical of the difficulties in modeling convective processes simultaneously with radiative and conductive heat transfer. The experience gained in modeling the Trombe wall will help in developing models for other situations in which convective heat transport is important.

## Daylighting

Lighting accounts for about 20% of total electrical energy consumption 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 which 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 the 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 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 by 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 pre-defined comfort level. Adding the illuminance contributions from all the 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 x 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 minimum (30%) power.

The results of a DOE-2 run of a partly cloudy June day in San Francisco are shown in Figs. 4a and 4b. Fig. 4a 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. 4b gives a net reduction in lighting energy use of 59%.

To verify that the DOE-2 daylighting calculation gives accurate results, program predictions are being checked against illuminance measurements obtained by the Windows and Daylighting Group, using scale models having various window configurations. An offshoot of this cross-check will be the development of a method for DOE-2 to directly use daylight factors from models (or calculated by programs such as LUMEN-II), thus making it possible to simulate virtually any daylighting configuration.

During FY 1982 the initial version of the daylighting model was completed and integrated into the DOE-2.1B version of the program.

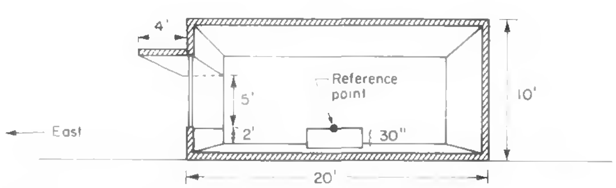


Figure 3. Test model for DOE-2.1 daylighting calculation. (XBL 825-596)

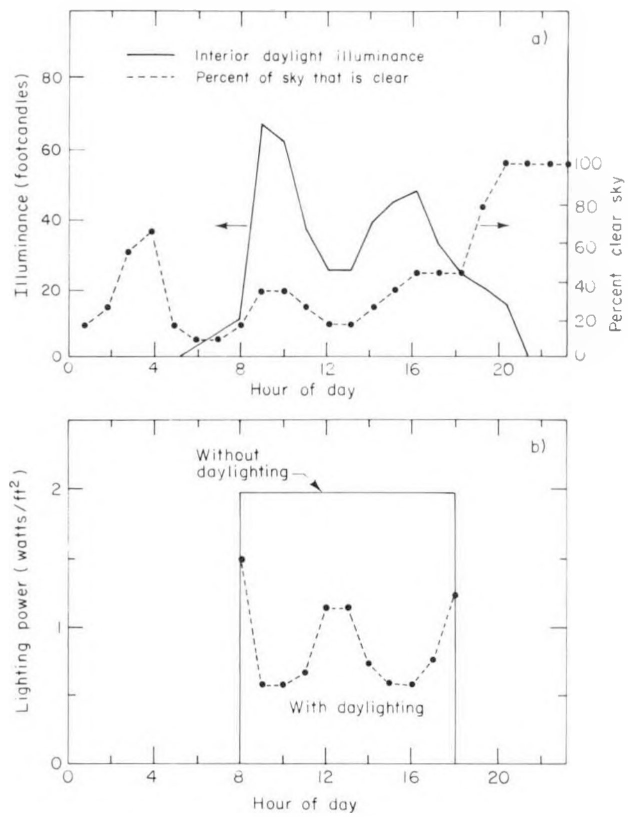


Figure 4. Results of DOE-2.1 daylighting calculation for a partly cloudy June day in San Francisco, for the test module shown in Fig. 3. (a) Daylight illuminance at the reference point and percent of sky that is clear. (b) Power consumption for electric lighting with and without daylighting. (XBL 825-598)

## Custom Weighting Factors and Thermal Balance Loads

Research continues on these two methods to substantially improve the calculation of heating and cooling loads in building spaces. In the "custom weighting factor" (CWF) method, a fast-executing transfer function is used. The second method, called "modified thermal balance," is more time-consuming but more accurate. Ultimately, the user will be able to choose the technique best suited to the application at hand.

The CWF approach calculates the heat gains from lights, solar radiation, people, equipment, and conduction through the envelope for each hour. Part of each gain will appear immediately as a load on the HVAC system; the remainder will be stored as heat in the walls, floor, furniture, and other mass in the building and will be released over time to the room air. The delays involved in this process are accounted for by the weighting factors.

In earlier versions of the program, "ASHRAE weighting factors" were used. These were calculated about 15 years ago by the National Research Council of Canada for buildings of very simple geometry and were adapted by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE).[13] LANL studies showed that the ASHRAE weighting factors lead to inaccurate results for buildings where direct gain is important.

A technique for calculating weighting factors specifically for the space configuration described by a user has been developed[13] and incorporated into DOE-2.1. In this technique, a detailed thermal-balance calculation is made initially to find the cooling-load profile produced by a unit impulse of heat gain from each of the sources listed above. By adding the CWF technique, it is possible to accurately account for the storage of heat in the thermal mass of the building; in particular, it enables direct-gain, passive solar buildings to be modeled with DOE-2.

In FY 1982, several important improvements were made to the weighting-factor calculations to more accurately represent multi-room and multi-story buildings, as well as to allow the modeling of a generalized lighting system. For multi-room and multi-story modeling, two major changes were made: first, several new types of interior zone surfaces with different heat-transfer properties (non-mass air exchange pathway, adiabatic mass walls, and mass partitions) were added; second, a new type of thermal zone MULTIPLIER was added to distinguish between vertically- and horizontally-duplicate thermal zones. In the lighting system model, the heat transfer is assumed to occur through three mechanisms: radiative transfer to surfaces in the zone with later heating of the air (radiation); direct heating of the air in the absence of forced air flow (natural convection); and direct heating of the air via forced flow over the lighting fixture (forced convection). The first two mechanisms have heat-load components from the lighting system into the lighted zone as well as into the plenum above the lighted zone. The third mechanism applies to systems that have the return air passing through the lighting fixture. These improved features were added to the DOE-2.1B version of the program and will be used by ASHRAE to update tables in the *ASHRAE Handbook of Fundamentals*.

The modified thermal balance (MTB) algorithm calculates space heating and cooling loads by considering the radiative coupling between the surfaces of the space. For each wall or window, the thermal-balance equations are written for the inside and outside surfaces. Thermal-balance equations include radiative, conductive, and convective heat transport. (The convective term is still in its simplest form and will be improved later.)

Coupling between the surfaces is achieved through a radiative interchange, in contrast to the CWF method, where the coupling between components of heating/cooling loads are calculated with a time series for each component. In the radiative interchange method, for each surface we lump all other surfaces into a single effective surface and assign a mean radiant temperature to it; then we do radiative interchange with the surface in question and the lumped surface. This calculation is repeated for each surface, and convergence is checked. Then we linearize the Boltzmann equation, which is fourth order, with respect to the surface temperature. Inside and outside surface temperatures are tracked. The heat storage and delayed transport through walls, floors, and furniture are handled with response factors. Solar gains on the outside surfaces are calculated in a similar manner, as in the weighting-factor LOADS program. Solar gain on an inside surface is calculated by computing the amount of solar radiation coming through the windows and hitting the surface.

Several primary approximations in modified thermal balance require further improvement:

- The view factors used in radiative interchange are proportional to the surface areas; more accurate view factors must be calculated.
- The room temperature used in the expressions is constant; this should be able to vary within a given range.
- The convective coupling between the surface and room air is a constant; it should vary with surface and air temperatures.

We believe that the MTB technique may be more accurate in certain situations than the weighting-factor approach. For example, it could model movable insulation being placed over windows at night. The CWF technique does not treat room transfer functions as functions of time, which is necessary when the conductance of the windows varies with time. MTB also computes the inside surface temperature as a function of time. If these temperatures vary widely, the convective, and even the radiative, heat-transfer coefficients can vary enough to cause significant changes in building conditions. Human comfort depends strongly upon the inside surface temperatures, but the weighting-factor approach provides no information in this regard. Further studies will be made of the differences among the CWF, MTB, and full-thermal-balance techniques to determine when accuracy requires the more complex, and therefore more time-consuming, methods.

## HVAC Equipment and Controls

The SYSTEMS and PLANT sub-programs of DOE-2 were originally designed to estimate the energy consumption of the HVAC equipment of large buildings. Many modeling assumptions were based on the philosophy that the most important considerations should be those that have a significant impact upon the energy-consumption values integrated over time. The program made no attempt to simulate the actual performance of the equipment components on an hour-by-hour basis but, rather, predicted overall energy use. This approach was adequate because, in the past, HVAC equipment had been systematically oversized and tightly controlled. For modeling such systems, it was not necessary to consider performance parameters that depended on inside or outside environmental variables.

As DOE-2 gained popularity, the user community wanted to extend its use to small commercial and residential buildings. At the same time, the engineering community, in an effort to conserve energy, was moving away from recommending oversized systems and constant, year-round control points. These shifts prompted us to make substantial changes in the algorithms of both SYSTEMS and PLANT. The new algorithms are more concerned with modeling hourly performance of actual equipment.

In the SYSTEMS simulation, work during FY 1981 and 1982 concentrated in three areas: more accurate equipment sizing, more accurate control system interactions, and the implementation of new HVAC equipment configurations. In the PLANT simulation, work focused on: (1) the development of algorithms to simulate "free" cooling using cooling-tower water and (2) implementation of new electrical generation modes and peak shaving studies.

For equipment controlled by a zone thermostat, a linear relationship is assumed to describe the interaction of the thermostat, space temperature, and equipment output. As Fig. 5 shows, there are generally five regions of interest for thermostat-equipment interaction: upper and lower bound regions within which maximum cooling and heating, respectively, are supplied; heating- and cooling-action band regions within which proportional control of equipment output is effected; and a dead-band region within which the equipment action is constant and usually equal to that at the bottom of the cooling-action band. The space temperature and resultant thermostat reaction can change significantly during the basic one-hour time step used in DOE-2. Additionally, the heating- and cooling-action bands may each be composed of multiple regions within which different pieces of equipment function. Thus, the seemingly simple problem of modeling temperature-controlling equipment can become a complex set of interacting equations and boundary conditions. Improvements were made and incorporated into DOE-2.1A and DOE-2.1B to closely model these complex control strategies. Similar improvements were designed and implemented to model the control of space humidity.

During FY 1982, several additional capabilities were added to the HVAC SYSTEMS program. Among these are nighttime ventilation cooling (or alternative night fan controls), outside temperature activation of heating and cooling, warm-up cycle for variable flow systems, electric (or gas/oil) humidifiers, air-side false loading of chillers (by the closing of outside air dampers), and plenum heaters.

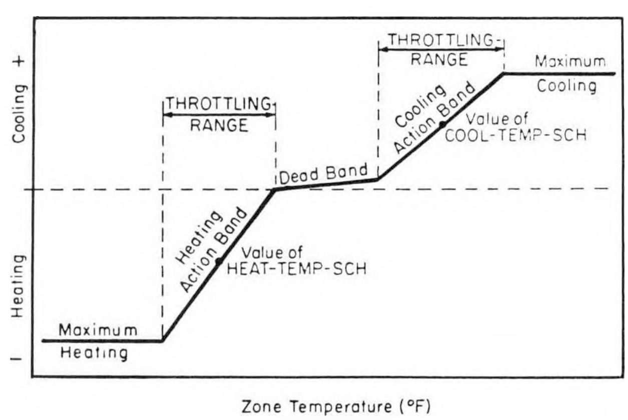


Figure 5. Five possible regions of thermostatic action. (XBL 825-600)

### New HVAC Configurations and Performance Curves

During FY 1982, work began on developing models for simulating new HVAC configurations, powered induction systems, and dual fan/dual duct systems. The powered induction system is an advancement on variable air volume systems that more effectively utilize waste heat from the building core and lighting system to condition the exterior thermal zones. This is done by introducing this warm air into the external zone with a small fan contained in the terminal box. This fan can be placed in series or parallel with the primary system airflow. The dual fan/dual duct system operates under the same principle, except that a central fan rather than individual zone fans introduces warm recirculated air into the exterior zones.

Another area of interest is collecting HVAC equipment performance data and producing empirical correlations for simulation models. This will be important in future work because of the lack of high-quality data. Results of this work are also valuable to other groups interested in HVAC equipment simulation.

### Direct Cooling

Two methods of providing "free" cooling from a central-plant cooling tower were researched and implemented in DOE-2.1A. The motivation is to find an inexpensive retrofit of existing chiller-cooling tower arrangements that will reduce cooling costs. The two "free" cooling concepts take advantage of periods during which the outdoor wet-bulb temperature is low enough (between 35°F and 50°F) to produce cooling-tower exit water that is cold enough to cool the building without using a chiller.

The first method, known as the strainer cycle, injects the cooling-tower water directly into the building chilled-water loop through a strainer that removes harmful impurities. Thus, the water-chiller equipment is entirely bypassed.

The second method, known as the thermocycle, uses the water-chiller equipment as a passive heat-exchanger. The cooling-tower water passes into the chiller-condenser section and cools the refrigerant. A small auxiliary pump, added during the retrofit, sprays the refrigerant onto the evaporator coils, thus cooling the water circulating in the chilled-water loop.

### Generation Strategies and Peak Shaving

Because of changes in the attitudes of utilities and state regulators toward small power producers, requirements that electrical generators in buildings only track the building's electrical demands have been loosened. A modification was incorporated into DOE-2.1B to model alternative strategies. This feature is currently limited to two strategies: generation to track building demands and generation at full capacity. Work was begun to upgrade the models of electrical generation equipment and to model the generation as driven by heating demands (a third strategy). Work was also begun on adding a generalized energy cost program to allow an integrated analysis of energy use, generation, and cost.

This follows earlier work over the past several years in which DOE-2 has been modified to model generalized equipment management based on time-of-day, season, and type as well as magnitude of load. These changes enable the study of strategies to reduce peak electrical demand by using on-site generation facilities. Our first study examined the use of emergency generators for this purpose in high-rise office buildings.[17]

### Advanced Control Simulation

Work began in FY 1982 on developing a major new feature for DOE-2. It will enable the simulation of innovative designs by allowing users to write specific algorithms that can be incorporated into the hourly simulation without modifying the program. These functions are written in a FORTRAN-like manner and entered into the BDL building description. They may include algebraic expressions and conditional decisions. With this capability, individual researchers will be able to entirely replace current DOE-2 algorithms or simply augment current algorithms with new features; researchers working on individual parts of the building simulation will be able to study their new components or controls without building an entire simulation program.

## PLANNED ACTIVITIES FOR FY 1983

Future plans for the program lead in two directions. On the one hand, 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 the program to supplement its capabilities. These include: (1) expanded output report capability, (2) an improved window and daylighting simulation in collaboration with the Windows and Daylighting Group, (3) an expanded user-library capability, (4) further research into the thermal balance LOADS program alternative, (5) completion of the functional values specification, and (6) the addition of new HVAC equipment and controls. We will also continue to carry out building energy performance studies.

The second direction for FY 1983 activity is exploratory. We will probe the development of a building energy-use analysis program that can be easily adapted to new developments in the building and conservation sciences.

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## PUBLICATIONS LIST

The publications list through 1982 for the Energy Efficient Buildings Program is organized as follows:

*Energy Efficient Buildings* (EEB)—general reports not specific to any sub-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 modelling and programming. (GR stands for Group Report, and represents an internal document).
*Building Energy Performance Standards* (BEPS)—reports specific to the proposed Federal Building Energy Performance Standards.
*Energy Conservation Inspection Service* (ECIS)—contains reports concerning the ECIS program.
*Energy Performance of Buildings*—reports specific to the energy performance of building envelopes.
*Hospitals*—reports related to the Hospitals Program.
*Schools*—reports specific to the Schools Program.
*Ventilation*—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 of the report. A longer version of this list including abstracts is also available.

## ENERGY EFFICIENT BUILDINGS (EEB)

### 1976

EEB 76-1, LBL-3274, *Projecting an Energy Efficient California*. D.B. Goldstein and A.H. Rosenfeld, 1976.

EEB 76-2, LBL-4438, *Conservation and Peak Power—Cost and Demand*. D.B. Goldstein and A.H. Rosenfeld, 1976.

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EEB 77-1, LBL-4411, *Efficient Use of Energy in Buildings*. A report of the 1975 Berkeley Summer Study, E. Dean and A.H. Rosenfeld, Editors, special issue of *Energy and Buildings*, 1977.

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EEB 77-3, *Notes on Residential Fuel Use*. A.H. Rosenfeld, chapter 3a.

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EEB 77-5, *Energy Cost of Buildings*. R.A. Herendeen and A.H. Rosenfeld, chapter 8.

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EEB 77-10, *Electric Load Leveling by Chilled Water Storage*. A.H. Rosenfeld and F.S. Dubin.

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