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UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

ENERGY EFFICIENT BUILDINGS PROGRAM

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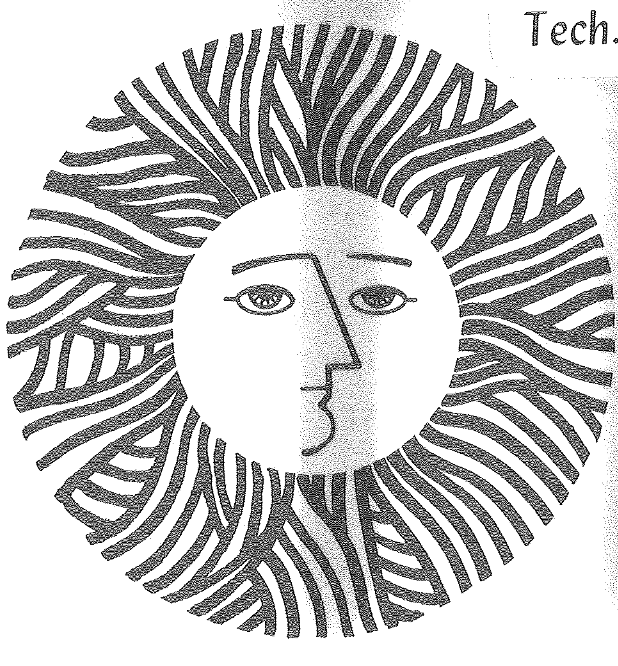

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DISCLAIMER

ENERGY EFFICIENT BUILDINGS PROGRAM
FY 1980

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Berkeley, California 94720

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INTRODUCTION

A. Rosenfeld, C. Hollowell, and S. Berman

About 38% of United States energy resources is consumed by the building sector. In contrast, the energy consumed as gasoline represents only 18% of our energy use. With the scarcity of fuel and the attendant rise in fuel prices, it has been necessary to make radical design changes in automobiles and buildings to enhance their efficiency, at the lowest possible cost, without compromising their previous level of service. For automobiles, Congress mandated a factor-of-two improvement in efficiency and, for buildings, research has shown that present resource energy use can be similarly reduced by 50% through careful retrofitting. In the case of new construction, 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 10% in the case of residences, and to 20% in the case of commercial buildings.

The aim of the Energy Efficient Buildings Program is to conduct 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, we have developed five major research groups whose activities are regularly reported in technical and scientific journals, presented at international conferences, and disseminated in the form of Lawrence Berkeley Laboratory (LBL) reports.

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

Energy Performance of Buildings

Formerly called the "Building Envelopes Program," this group has changed its name to "Energy Performance of Buildings" to more accurately reflect the focus of its work. Essentially, the energy performance of a building is assessed by regarding the building as a system. In this framework, the parameters tested are its air infiltration rates, thermal characteristics of its structural elements, and the behavior of the interface between dissimilar materials. From an analysis of overall performance, we are able to recommend cost-effective solutions for reducing infiltration and thermal losses, either by retrofitting (existing buildings) or improving design features (new construction). This research is conducted in the laboratory and in the field, and tests are made on our research house as well as with computer models.

Building Ventilation and Indoor Air Quality

One of the more obvious means of improving the energy efficiency of a building is to reduce air infiltration/ventilation. Lowering this air-exchange rate, however, can seal in indoor-generated pollutants and allow them to build up to potentially harmful levels. In this program, our goal is to furnish a scientific basis for setting energy-efficient ventilation standards and developing system designs that promote energy efficiency while taking into account the comfort, health, and safety of building occupants. Project activities in support of this goal include (1) development of new methodologies for measuring indoor air quality parameters, (2) laboratory studies of organic and radioactive emissions from building materials, soil, water, and natural gas that may affect indoor air quality and (3) field monitoring of indoor air quality in different types of buildings (e.g., schools, office buildings, residences) under a variety of ventilation conditions. Integrally related to this work is the investigation of prevention and control strategies for indoor air pollution that do not sacrifice energy efficiency. In this connection, we perform laboratory and field tests of various ventilation systems, including those that incorporate air-to-air heat exchangers--devices which can provide the necessary level of ventilation while recovering a substantial portion of the energy that would normally be lost.

Building Energy Analysis Group

The Building Energy Analysis group is responsible for developing, improving, and documenting the computer program, DOE-2, which has been designated as the national program for calculating building energy performance standards. DOE-2 can also be used by architects and engineers as a means of designing buildings to improve their energy efficiency and minimize their life-cycle costs. DOE-2 is systematically updated to incorporate the latest energy-conserving design features (e.g., passive and active solar, thermal storage, natural ventilation, daylighting, and evaporative cooling).

Energy Efficient Windows and Lighting

The Windows and Lighting group is developing a technical basis for understanding the energy-related performance characteristics of windows and lighting systems and, with industry, is working to develop and promote energy-efficient products that are cost-effective to end-users. A primary consideration in the Windows section of our group is to assure that daylight is provided to the building's interior with minimum thermal loss in cool weather and minimum thermal gain in hot weather. To this end, considerable research activity has centered on developing and testing optical coatings for windows as well as evaluating a number of insulating window treatments. Our testing capabilities are being expanded with the addition of an outdoor window testing facility.

The Lighting section is concentrating on developing energy-efficient lighting systems (lamps, ballasts, fixtures, and controls) to provide lighting designers with an array of options for meeting occupant needs. Energy-efficient, high-frequency, solid-state ballasts for fluorescent lights are being field-tested in several buildings. Preliminary results are confirming that installation of these devices can effect a 25% savings over conventional core ballasts.

Building Energy Data, Analysis and Demonstration

The Building Energy Data, Analysis, and Demonstration group compiles and evaluates data on end-uses of energy and on the costs and performance of energy-efficient technical measures, both from direct field measurements and from secondary sources. Using these data, we prepare 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, we create, in effect, a "supply curve of conserved energy," comparable to the supply curves for other market commodities that show the expected levels of production as a function of unit price. The national energy savings that might be effected as a result of our research is discussed in detail in the BEDAD section of the text that follows.

More Energy-Efficient Buildings Research Reported in Other Chapters

Other 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 division's Annual Report.

Specifically, the Energy Analysis chapter, printed separately as LBL-11972, covers 11 studies related to building energy performance standards and labels, appliance energy performance, rating systems for auditors and appraisers, and energy and peak power modeling.

Further, the Solar chapter, LBL-11984 covers the work of the Passive Solar Analysis and Design group.

ENERGY PERFORMANCE OF BUILDINGS*

D. Grimsrud, A. Blomsterber, W. Carroll, P. Condon, D. Dickerhoff, D. Krinkel, M. Modera, A. Rosenfeld, M. Sherman, B. Smith, and R. Sonderegger

INTRODUCTION

The design of an energy-efficient building begins with a tightly built and well-insulated thermal envelope (exterior walls, windows, etc.) and then adds efficient equipment for heating, cooling, hot water, and other energy needs. Formerly called the Building Envelopes Program when our activities focussed on investigations of air infiltration and wall thermal performance, we have now expanded our activity to encompass a broader range of building energy concerns--ergo, our new designation as "Energy Performance of Buildings." Our objective is to provide fundamental information on the energy performance of buildings as a basis for the eventual establishment of energy-conserving guidelines and standards governing the design and construction of new buildings as well as retrofit strategies for existing buildings. Our two primary research areas of air infiltration and wall thermal performance are conducted in the field, in the laboratory, in our research house, and on computer models. A third effort this year has been the development of an instrumented residential energy audit, which will be field-validated in FY 1981.

* This program was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

Air Infiltration

Air infiltration typically accounts for one-third of the annual space heating load of residential buildings in the United States. This energy loss can be reduced in new construction by changes in design and construction techniques, and to some degree in existing structures, by careful repair and maintenance. An important goal of our work in this area, which deals with measuring, modeling, and reducing air infiltration, is to provide design guidelines for architects and engineers, and to develop construction quality standards for air leakage in U.S. buildings. A breakthrough this year was the development of a new model that identifies a single parameter--the "effective leakage area" obtained from fan pressurization--for scaling infiltration rates in different types of buildings. This parameter is a powerful design tool for architects and builders in reducing air infiltration in new construction. In addition, we are demonstrating techniques to reduce air leakage in existing buildings.

Walls

The information currently available on the thermal performance characteristics of building walls is based on theoretical analysis and laboratory tests. Where actual measurements have been made in buildings, the thermal resistance of the walls is often 20% to 30% less than that predicted by laboratory measurements and standard calculations. Ultimately, recommendations for energy conservation standards should be based on accurate measurements of building walls rather than on unverified inferences from laboratory measurements and computer models. Even though a wall may be well designed, differences in construction methods and aging of materials can produce substantial variations in thermal performance. Accordingly, the purpose of our research is to develop techniques for field (or in situ) measurements of the thermal performance of walls. We need to understand what data must be collected to adequately characterize a wall, and how this data can be reduced to uniquely describe the thermal performance of any wall.

Computerized Instrumented Residential Audit (CIRA)

In 1978 Congress passed the National Energy Conservation Policy Act, a part of which, the Residential Conservation Service, required major public utility companies and fuel-oil dealers to provide a house energy audit to customers who request it. States have two options in complying: either they submit a plan for DOE approval, or DOE will mandate its own audit (developed by Oak Ridge National Laboratory (ORNL) and Solar Energy Research Institute (SERI)). In accordance with RCS regulation, this audit is site- and house-specific, considers both conservation and solar measures in its recommendations, and will give the homeowner a cost-benefit analysis of its recommendations.

In addition to the basic ORNL/SERI audit, DOE commissioned LBL to develop a more sophisticated, state-of-the-art residential audit. This audit, the Computerized Instrumented Residential Audit (CIRA) uses a portable microcomputer for evaluating retrofits based on information collected during the audit. In addition, several simple retrofits are completed at the time of the audit, with an expected initial energy savings of 10-15%.

The instrumented audit requires an initial screening of utility bills and weather data to obtain an "energy signature" for the house. Two auditors then make a four-hour visit to the house where they measure air leakage with a blower door that pressurizes or depressurizes the house, and identify leaks, plugging the easy ones as they go and noting the more difficult ones to repair later. They measure furnace efficiency, check water and air temperature settings, insulate the water heater, change the air filter on the furnace, calibrate the thermostat and, with the permission of the homeowner, install a low-flow showerhead and reset the water-heater thermostat.

At the conclusion of the physical inspection, all necessary data are fed to the microcomputer. The auditor then confers with the homeowner on a suitable retrofit package. The computer will scan a master list of possible retrofits stored on a disc that contains conservation measures such as insulation, storm and double-pane windows, insulating shutters, caulking and weatherstripping, furnace retrofits, and active and passive solar systems for space and water heating. Savings and costs of each retrofit are then calculated on a life-cycle basis, and an economically optimal retrofit package is assembled on a minimal total life-cycle cost. The computer will give optimized retrofit packages for several budgets, along with total costs and savings of each package. All cost estimates take into account the possibility that homeowners may wish to do the retrofits themselves. At the conclusion of the visit, the auditor leaves detailed information on the suggested retrofits with the homeowner.[1]

ACCOMPLISHMENTS DURING FY 1980

Air Infiltration

MITU: For model validation work, we have been taking measurements in occupied houses over a relatively long period of time. Because these procedures necessarily inconvenience occupants, we sought and found a solution in the MITU--a mobile infiltration test unit that simulates a house and can be moved to different locations to study the effect of different micro-climates on air infiltration rates (see Figures 1 and 2). The test unit was designed and built to simultaneously monitor air infiltration, surface pressures, and weather data for extended periods of time. By moving the MITU to different locations, we can study the effect of the leakage area and its distribution, and local terrain and shielding on infiltration rates. The data from MITU will be used to test a predictive model of air infiltration discussed below. A complete description of the MITU facility including preliminary results is available.[2]

Data Base: The Infiltration Data Base was developed to provide support for the Air Infiltration Centre, an organization sponsored by the International Energy Agency (IEA). The data base is set up to help researchers perform literature searches and to test predictive models of infiltration. Its four subfiles contain information on infiltration researchers, published articles, test locations, and numerical infiltration data from field measurements. The data base user's manual is a complete tutorial on accessing and using the file.[3]

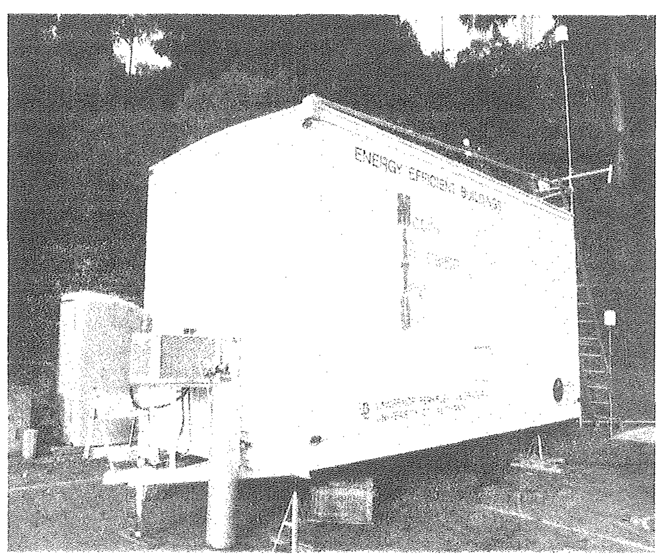

Fig. 1. The Mobile Infiltration Test Unit (MITU). (CBB 8011-13932)

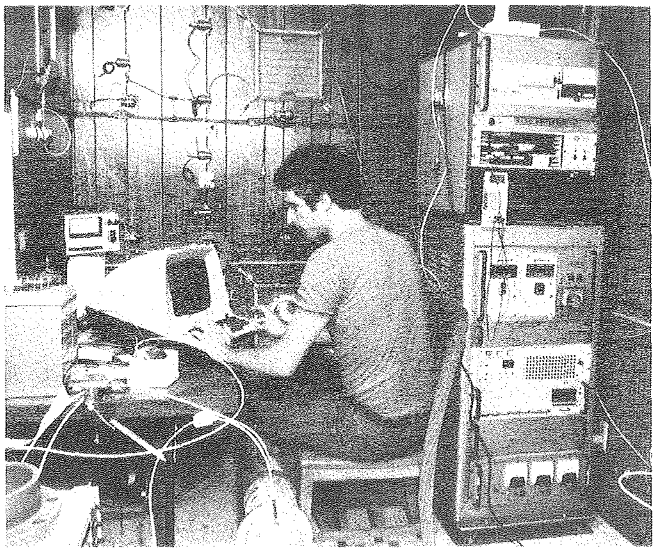

Fig. 2. The MITU interior. (CBB 809-11263)

Models: Unlike conduction losses which can be modeled by means of a single parameter--thermal resistance--infiltration losses have had no equivalent quantity. We have developed a model that uses the effective leakage area for characterizing infiltration losses. Equivalent leakage area is determined from a fan pressurization test of the structure. In addition to this parameter, the model uses the height of the structure, the inside-outside temperature difference, the terrain class, the shielding class, and wind speed to determine infiltration rates. The model can predict the impact of retrofits or other changes in the building envelope on air infiltration using measurable performance changes effected in a few parameters. Figure 3 shows the correlation between predicted and measured infiltration in fifteen houses.[4,5]

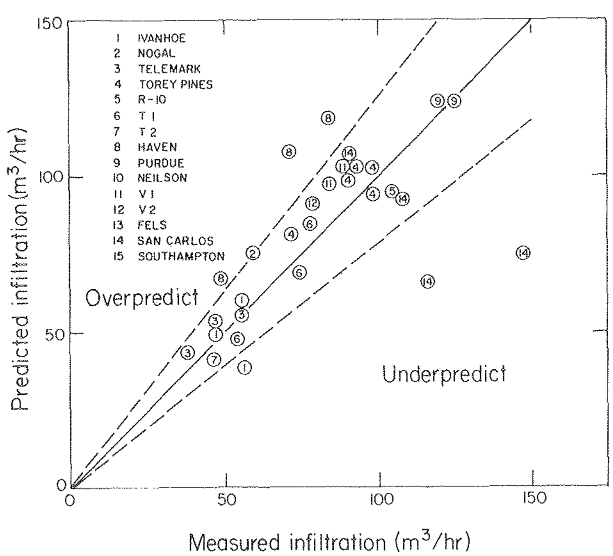

Fig. 3. Predicted vs Measured Infiltration. (XBL 805-907)

AC Pressurization: A technique for examining the low-pressure leakage function of a residence using an oscillating pressure source was developed and tested. The advantage of this method is that it simulates the low-pressure range where natural infiltration occurs, and is independent of weather interactions. We found that even at the low-pressures characteristic of natural infiltration the leakage structure of the house showed flow behavior typical of an inviscid fluid.[6]

Average Infiltration Monitor: The Average Infiltration Monitor (AIM), a portable device capable of taking long-term average infiltration measurements, was designed and prototypes were tested. Essentially a suitcase crammed with sample pumps and injectors that operate unattended over a month-long period, AIM will be used in occupied houses and enable us to monitor long-term average infiltration including the effects of occupant behavior, such as opening windows and doors.[7]

Field Studies: A major part of the program this year has been our work with several state utilities and local builders in setting up air leakage measurements in houses. Houses in Washington and New York state were pressurized for air leakage measurements and later retrofitted to reduce the air leakage. In the Washington houses where the initial retrofits were performed by the Bonneville Power Authority, adding storm windows and doors alone resulted in a 15% reduction in air infiltration. The houses in Rochester, New York were standard tract homes where the builder, Ryan Homes, had added features for greater energy efficiency. Air leakage measurements were also taken in eight houses in Atlanta, Georgia to assess the effect of infiltration on the air conditioning load in a hot-humid climate.[8,9]

Collaborative Activities: Our group was active this year in contributing infiltration-related work to national projects. For the Residential Conservation Service (RCS) Model Audit, we developed a simplified infiltration algorithm, and for the ASHRAE Handbook of Fundamentals, we submitted a revised chapter on infiltration which is to be incorporated in the next edition of the text.

Construction Quality Standard: A preliminary draft of a framework for a construction quality standard for air leakage in residential buildings was prepared and circulated to professional groups for discussion and review.[10] The draft proposes using the newly developed infiltration model to develop a verifiable standard for ventilation in new buildings. Included in the report is a survey of the average infiltration during the heating season of 219 houses throughout North America. The infiltration of these houses averages 0.67 ach with a standard deviation of 0.48 ach.

Walls

The key element in our walls testing project is the Envelope Thermal Test Unit (ETTU).[11,12] Designed to measure the steady-state and dynamic thermal response of building walls, the prototype ETTU and the new passive ETTU-2 are capable of taking field measurements. The work this year has centered around building and debugging these units. The computer program to drive the system heaters and log the data has been written. The data acquisition system that interfaces with the general-purpose microprocessor system has also been completed.[13] Preliminary measurements of steady-state R-values of a test sample using ETTU agreed with ASHRAE Handbook values.

Through working on the ASTM C16-30 (Task Group on Characterization of Wall Performance), plans were made with the Portland Cement Association for conducting runs comparing the performance of ETTU with their guarded hot-box.

Computerized Instrumented Residential Audit (CIRA)

Five essential tasks have been detailed in developing our energy audit:

- software development,
- system documentation,
- auditor's resource package,
- homeowner's information package,
- audit validation.

Earlier this year we assembled and tested field instrumentation and built the prototype microprocessor system for the audit. Software development has consisted of the microprocessor-based algorithms that optimize the mix of conservation, solar, and wind options for a given house. These algorithms include recent advances in building science from other national laboratories, e.g., LASL passive solar methodology, F-chart active solar methodology, BNL boiler and furnace performance data, LBL infiltration modeling, etc.

Fireplace Testing

While no new testing of fireplaces took place in FY'80, data analysis, including economic considerations, was undertaken. Both a technical report on the measurements and analysis and a report for homeowners were published.[14,15]

PLANNED ACTIVITIES FOR FY 1981

Air Infiltration

Continued development and validation of measurement techniques and infiltration modeling will be a major part of the program in the coming year. Both AIM and MITU are scheduled for field measurements around the country. The infiltration model will be extended to include the effects of flues and chimneys, local shielding, and occupant ventilation. The model will be coded for use in the DOE-2 residential package.

Several tasks are planned for developing air leakage design guidelines for architects and engineers. Among these is an examination of the effectiveness and cost-benefits of air leakage retrofits. A popular description of the infiltration model, together with tables of normalized air infiltration values for different regions of the U.S. and component leakage areas are part of the package for designers.

A new undertaking will be to extend the AC pressurization technique to multichamber buildings without using large-capacity fans. We plan to begin measurements with a multi-chamber infiltration system in an apartment complex.

Walls

Four main activities are planned for the coming year:

- Initial field measurements of walls in our research house using ETTU;
- Field survey of thermal performance of typical residential wall construction;
- Activity in ASTM C-16.30 task group on in-situ measurement of wall performance;
- Collaboration with Portland Cement Association in completing development of data reduction techniques for laboratory hot-boxes.

The ETTU work will significantly advance our capabilities for measuring wall performance. Through our contacts with ASTM C-16.30 and the Portland Cement Association, our work will have immediate application to ongoing wall testing programs at the Cold Regions Laboratory of the U.S. Army, Owens-Corning Fiberglas Corp., DCS Corp., the University of New Mexico, and Oak Ridge National Laboratory.

CIRA

Tasks in the coming year involve completing the software development, writing the program documentation, preparing a resource package for both the auditor and the homeowner and, finally, validating the entire audit. Validation will consist of actual field testing and comparisons of projected energy savings with DOE 2.1 computer simulations.

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BUILDING VENTILATION AND INDOOR AIR QUALITY

INTRODUCTION

C. Hollowell

The Building Ventilation and Indoor Air Quality (BVIAQ) program is a major component of Lawrence Berkeley Laboratory's Energy Efficient Buildings Program. Funded by the Department of Energy's (DOE) Office of Buildings and Community Systems and the Office of Health and Environmental Research, The BVIAQ program is part of a coordinated effort to respond to the need for conserving the nation's energy while maintaining the health and comfort of building occupants. The overall objective of the BVIAQ program is to conduct in-depth research and development on existing and proposed ventilation requirements in order to provide recommendations for the establishment of energy-efficient ventilation standards and ventilation designs for residential, institutional, and commercial buildings. LBL is also providing technical and management support to DOE for other related ventilation projects.

BVIAQ program activities for FY 1980 represent a continuation of the following tasks:

1. laboratory studies of indoor combustion emissions, organic contaminants, and radon;
2. field monitoring of indoor air quality in buildings;
3. indoor air quality health-risk assessment studies;
4. demonstration and assessment of residential mechanical ventilation systems incorporating air-to-air heat exchangers;
5. completion of subcontract activities consisting of:
   - assessment of ventilation requirements for odor control in buildings;
   - assessment of hospital ventilation standards;
   - study of automatic variable ventilation control systems based on air quality detection in institutional and commercial buildings.
6. completion and implementation of a ventilation/indoor air quality data base.

A description of the work accomplished and projected by our group is presented by program in the next five articles.

COMBUSTION-GENERATED POLLUTANTS*

G. Traynor, M. Apte, and J. Girman

INTRODUCTION

Field and laboratory measurements carried out thus far have indicated clearly that combustion-generated indoor air pollutants can have a significant impact on human health. We have demonstrated that levels of gaseous air pollutants (CO, CO_2, NO, NO_2 and formaldehyde) and respirable particulate carbon compounds are elevated in indoor environments where gas appliances are used--in the case of CO, NO_2 and formaldehyde, approaching or exceeding existing (and recommended) ambient air-quality standards and, in the case of respirable particulate mass, comparable to those typical of a very smoggy day.[1-4] In energy-efficient structures where the reduction of infiltration tends to inhibit the escape of indoor-generated pollutants, the health risk may be more serious.

* This work was supported by the Assistant Secretary for Environment, Office of Health and Environmental Research, Human Health and Assessments Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

While our previous studies have concentrated on emissions from gas stoves,[1-4] there are many other indoor sources of combustion pollutants. Two important sources are portable kerosene heaters, which have become very popular recently, and side-stream smoke from cigarettes. Our research activity for FY 1980 focussed on these two pollutant sources.

ACCOMPLISHMENTS DURING FY 1980

Kerosene Heater

A portable kerosene heater (convective type) was operated under two ventilation rates in an environmental chamber with a volume of 27 m^3, the size of a small bedroom. The manufacturer's rated output for this heater was 2,300 kcal/hr, but actually it consumed 830 kcal/hr based on a kerosene heat production value of 8800 kcal/l.

The heater was operated at the low ventilation rate of 0.33 air changes per hour (ach) using no mechanical ventilation and at the high ventilation rate of 1.6 ach using mechanical ventilation. Figures 1 and 2 show the respective NO, NO_2, and CO_2 concentrations at low and high ventilation rates. Most striking are the NO_2 levels: At the low ventilation rate, the NO_2 concentration reached 1.24 ppm above background after 30 minutes, while at the high ventilation rate the NO_2 level reached 0.89 ppm over background after the same time period. These values should be compared to recommended and proposed short-term (usually peak one-hour average) outdoor NO_2 standards that range from 0.1 ppm to 0.5 ppm.[5]

High levels of CO_2 were also observed, but only very small amounts of CO and particulates. The workplace standard promulgated by the Occupational Safety and Health Administration (OSHA) for CO_2 is 5000 ppm averaged over eight hours.[6] After 30 minutes of heater use at the low ventilation rate, this value was exceeded and, at high ventilation, this value was approached. CO levels peaked at 2.2 ppm at the low ventilation rate, and particulate emissions were undetectable.

Sidestream Tobacco Smoke

Particulate emissions contained in the sidestream smoke of one cigarette smoked by a volunteer situated inside the chamber were measured. The volunteer, who was asked to smoke at his usual pace, was a student, and chose to study while he smoked--his typical pattern. The chamber was maintained at a low ventilation rate (0.30 ach) during the entire experiment. The particulates released into the chamber from the sidestream smoke were size-fractionated and weighed using a ten-stage piezoelectric cascade impactor (QCM Cascade Impactor, California Measurements, Inc., Sierra Madre, California). As is evident from Figure 3, very high levels of particulates were measured: during the smoking period, total particulate levels increased 390 $\mu g/m^3$ over background. Ninety-six per cent of this increase is attributable to particulates under 0.4 ± 0.1 µg in diameter--a size range that has a high probability of penetrating the pulmonary region of the lung. The short-term (24-hour average) outdoor air quality standard set by the U.S. Environmental Protection Agency is 260 $\mu g/m^3$; the equivalent California standard is 100 $\mu g/m^3$.

In a similar experiment, this time using an automatic smoking machine, CO, NO, NO_2, and particulates from the non-inhaled fraction of tobacco smoke were measured. (The non-inhaled fraction is different from sidestream smoke in that it does not contain the smoke exhaled by the smoker.) Particulate emissions were essentially the same as in the previous experiment. CO levels in the chamber peaked at 2.7 ppm above background as compared to the outdoor one-hour standard of 35 ppm while NO and NO_2 levels peaked at 0.08 ppm and 0.09 ppm, respectively. NO and NO_2 measurements were made with a Thermo-Electron chemiluminescent analyzer which is subject to a substantial positive interference from hydrogen cyanide; therefore the NO and NO_2 measurements may not be accurate.[7]

Pollutant Emission Rates

Pollutant emission rates from the kerosene heater and sidestream smoke were calculated, and

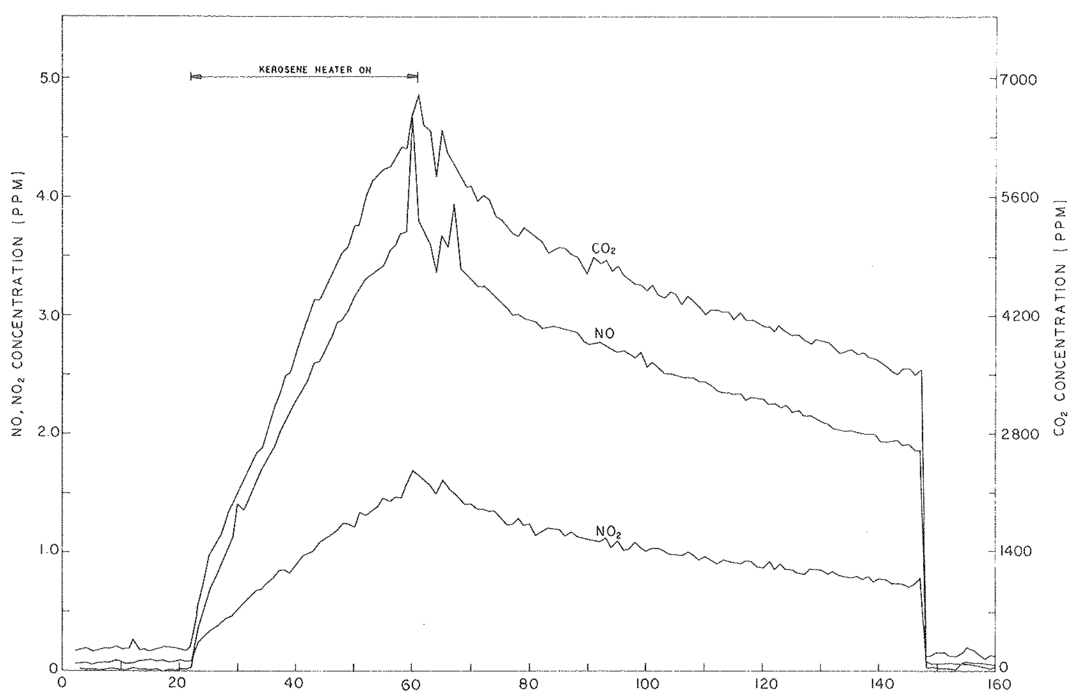

Fig. 1. NO, NO_2 and CO_2 emissions from a portable convective kerosene heater operated for 39 min. CO levels peaked at 2.2 ppm and particulate emissions were negligible. Tests were conducted in a 27 m^3 environmental chamber under a ventilation rate of 0.33 air changes per hour. (XBL 8010-12781)

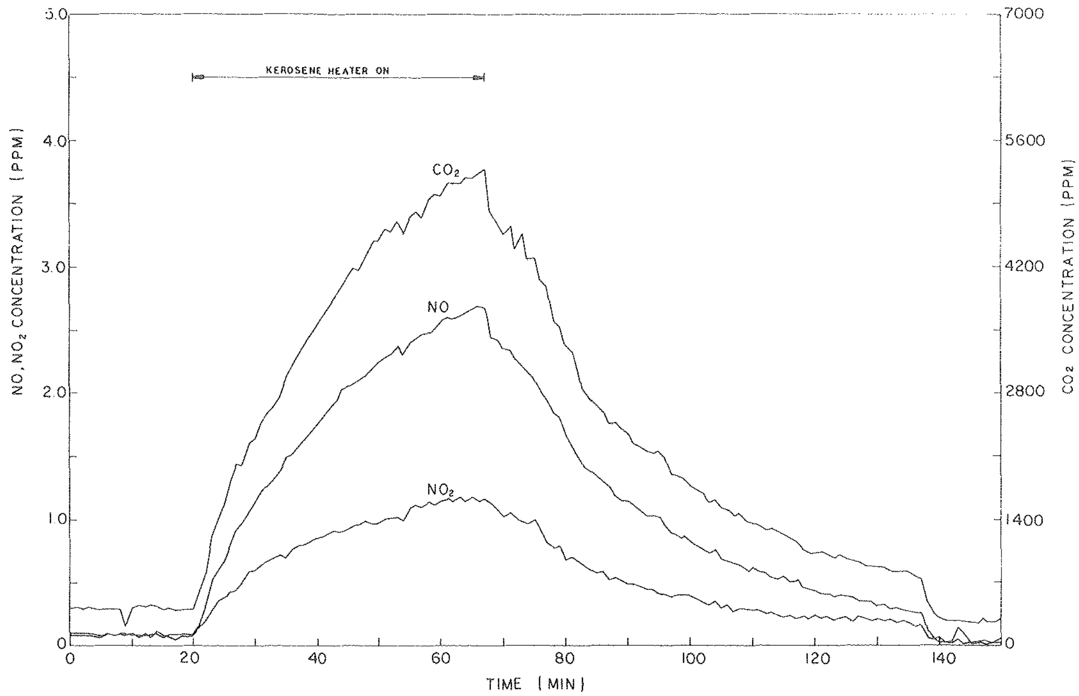

Fig. 2. NO, NO_2 and CO_2 emissions from a portable convective kerosene heater operated for 46 min. CO levels peaked at 1 ppm and particulate emissions were negligible. Tests were conducted in a 27 m^3 environmental chamber under a ventilation rate of 1.60 air changes per hour. (XBL 8012-12888)

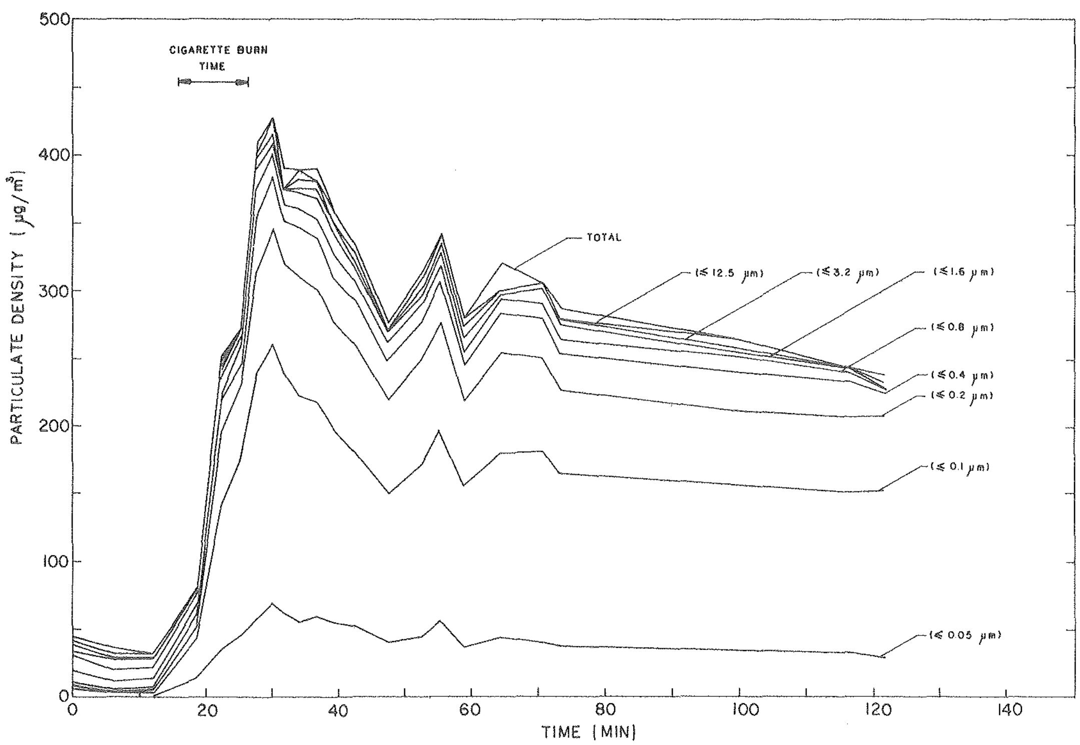

Fig. 3. Size-segregated particulate emissions from one cigarette smoked by a volunteer. The test was conducted in a 27 m^3 chamber under a ventilation rate of 0.30 air changes per hour. (XBL 8012-12887)

the results are summarized in Table 1. Multiplying the pollutant emission rate by the source consumption rate yields the actual mass of pollutant emitted into the room. The kerosene heater we used consumes 830 kcal/hr. One king-size cigarette combusts approximately 600 mg of tobacco in ten minutes. Emission rates combined with source consumption rates are useful for making approximations of pollutant concentrations under conditions other than the ones we tested.

PLANNED ACTIVITIES FOR FY 1981

Our research plans for FY 1981 are to complete the analysis of gas stove-generated pollution data collected at an experimental research house. The data include the pollution profiles of CO, CO_2, NO, and NO_2 throughout the house under various conditions of ventilation and stove use. We intend to add the following activities to our project for 1981: (1) We will use data already collected at a research house as a basis for testing, evaluating, and improving various models of indoor air quality in residences. (Several models published by others were either not tested in residences or yielded inadequate predictions of indoor air pollution levels.[8,9,10]) (2) We intend to further characterize particulate and gaseous emissions from other indoor combustion sources. (3) We will attempt to develop a comprehensive passive-monitoring package to determine one-week average pollution levels in various building types. Such a system would allow us to conduct extensive field studies at minimal cost for instrumentation and personnel. Field studies would have the dual goals of testing a wide variety of building types (using different ventilation schemes) and determining actual site-specific pollutant levels to which occupants are exposed.

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Table 1. Pollutant emission rates.

Pollutant	Kerosene Heater[a] (μg/kcal)	Sidestream Cigarette Smoke[b] (μg/mg)	Conversion Factors[c] 100 $\mu g/m^3$ equivalent (ppm)
CO	d	130[e]	0.086
CO_2	630,000	d	0.055
NO	270	f	0.080
NO_2	210	f	0.052
Particulates	d	18	n/a

[a] Expressed as microgram of pollutant emitted per kilocalorie of kerosene burned.

[b] Expressed as microgram of sidestream pollutant emitted per milligram of tobacco burned.

[c] Calculated at a pressure of 1 atm and a temperature of 20 °C.

[d] Observed concentrations were too close to background levels to calculate an emission rate.

[e] Does not include exhaled fraction.

[f] Subject to positive hydrogen cyanide interference.

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ORGANIC CONTAMINANTS*

R. Miksch, K. Geisling, L. Jenks, H. Schmidt, M. Tashima, and D. Wolosin

INTRODUCTION

The Organic Contaminants Project of the Building Ventilation and Indoor Air Quality Group has been conducting a diversified research effort involving basic research in the laboratory and analysis of field samples. Two main areas of activity have been established, one focusing on formaldehyde and the other on various organics present in indoor air. Formaldehyde can be emitted from common building materials that contain formaldehyde resins, such as plywood, particleboard and foam insulation. Work in this area has included extensive field measurements in energy-efficient and retrofitted homes, assessment of analytical methods used to measure formaldehyde, and the development of primary formaldehyde sources, passive monitors and filter techniques. For other organic contaminants in indoor air, techniques have been developed for collecting and analyzing a wide range of compounds found in buildings. Organic compounds are emitted from such materials as paints and adhesives, household cleaning products, office furnishings, building materials, combustion sources, and people.

ACCOMPLISHMENTS DURING FY 1980

Development of Methods of Analysis

During the past year, extensive effort was devoted to developing a more satisfactory thermal desorption device for analyzing samples collected on the porous polymer Tenax. A new thermal desorption system, designed and built at LBL, was completed in the Fall of 1980. Specific design improvements include a new oven which accommodates smaller sample tubes and does not desorb compounds on the outside of the tube. This change reduces the background and facilitates field sampling. Another improvement was the construction of a new cryogenic trap that is resistively heated and has a "buffer zone" of capillary tubing to handle flashback; this modification enhances chromatographic behavior and eliminates ghost peaks that have been a problem with commercially available devices used previously. The operating parameters of this system are now being optimized. Problems with the breakage of Tenax cartridges and the loss of sample integrity during shipping and handling have been resolved.

Two approaches have been taken to quantify the results of air sampling with Tenax. One method of generating standards involves using an automatic sampling device and a gas chromatograph to load trace quantities of standards directly onto Tenax cartridges. This technique has been tested and appears to be very promising. The other approach involves the use of an electrobalance, which forms the core of a rigorous quantification system based on permeation and diffusion.

Methods of analysis have also been improved for formaldehyde research. Specifically, we have developed a modified pararosaniline technique for more precisly determining formaldehyde in aqueous solution. Unlike earlier methods, this method eliminates the need for a hazardous mercury reagent. The optimization of reagent concentrations, the effect of varying temperature, and potentially interfering compounds were also studied. Comparative data on the analysis of aqueous formaldehyde solutions indicate that the modified pararosaniline method is more sensitive, more reproducible, and easier to use than the widely accepted chromotropic acid method. Results of two of the experiments are presented in Figures 1 and 2. The procedures are described in a report submitted to Analytic Chemistry.[1]

A new gas generation system for low levels of gaseous formaldehyde in air has been developed this year and is now being validated. The system shows promise of providing primary formaldehyde sources; it is based on the catalytic decomposition of trioxane to formaldehyde. Trioxane vapor released from a diffusion tube is passed over a phosphoric-acid-coated carborundum catalyst. The amount of formaldehyde formed may be calculated directly from the weight loss of trioxane, based on initial data showing a 100% conversion of trioxane to formaldehyde.

A passive monitoring system is being developed for the sampling of low levels of formaldehyde in ambient air. The passive monitors are prepared by

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

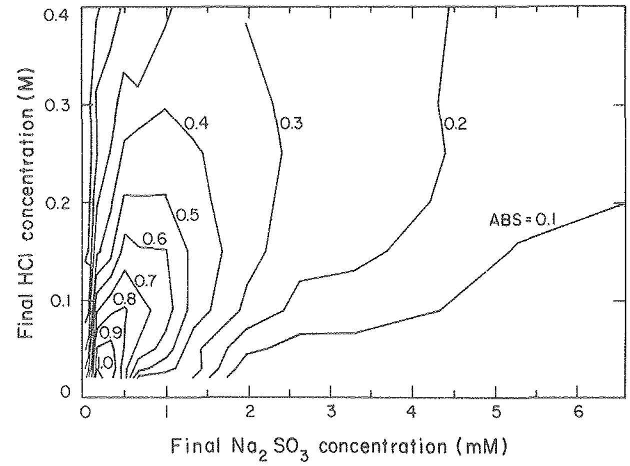

Fig. 1. Net absorbance as a function of the final hydrochloric acid and sodium sulfite concentrations. Hydrochloric acid, sodium sulfite, and pararosaniline are the key reagents in the analysis of aqueous formaldehyde solution by the pararosaniline method. All analyses were performed on a solution of 1.0 μg mL^{-1} (33 μm) formaldehyde. Data shown were obtained by linear interpolation from the data given in Table 1. (XBL 806-1151)

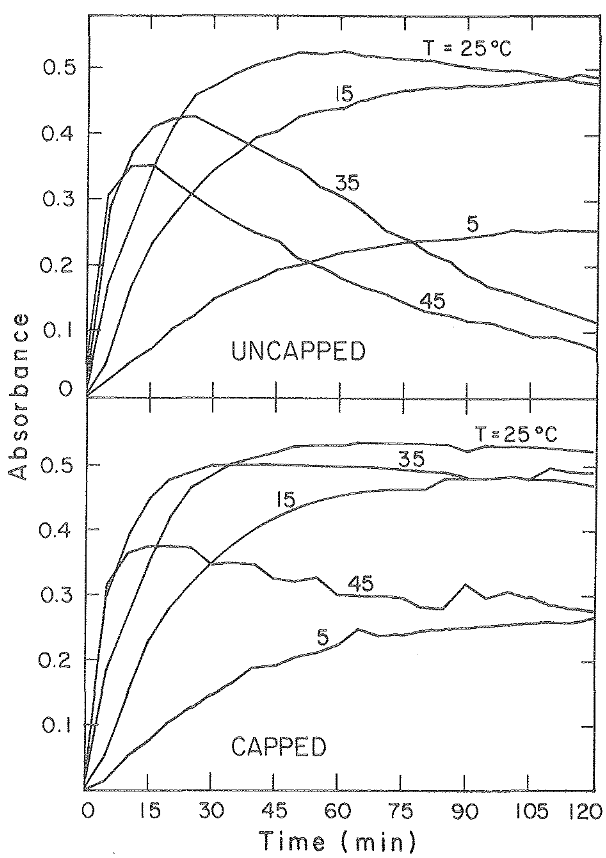

Fig. 2. Net absorbance as a function of development time at various temperatures: a) with cuvettes and b) with cuvettes uncapped. Since the sodium sulfite will equilibrate with the atmosphere while the color of the solution is being developed, the absorbance can be maximized by capping the cuvettes containing the sample solution. The optimized reagent concentrations were used. (XBL 806-1154)

treating glass fiber filters with sodium bisulfite and placing them in glass vials. In the process of establishing a calibration curve for the passive monitors, their collection efficiencies are being tested for reliability and reproducibility.

Field Monitoring of Organic Contaminants

Various field sites were sampled for organic contaminants using Tenax and the unmodified desorption system.[2] Four of these sites were offices at LBL where indoor air quality complaints had been registered; all of these sites were typical modern office settings with partitions, carpeting, and synthetic furniture. In all cases, the organic compounds found indoors were absent or present in substantially lower quantities outdoors. A comparative set of chromatograms is shown in Figure 3. The results of these analyses are presented in Table 1. The most interesting site sampled this year was a new office building in Marin County, where an unusually high number of complaints had been registered with the company nurse following occupation of the building. Although the complaints varied widely, irritation of the respiratory tract and allergic reactions were most commonly cited. The potential health hazard from the organic compounds found in these samples cannot be assessed at this time. No single compound was

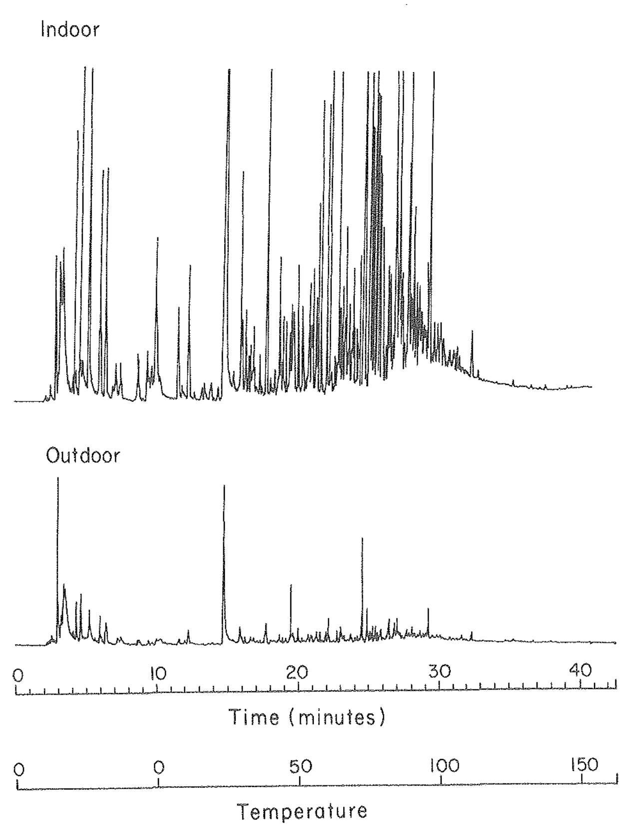

Fig. 3. A comparison of chromatograms of samples taken inside Rm. 3145, Building 90 and outside Building 90. (XBL 808-1727)

Table 1. Organics detected in LBL offices.

	LBL 67C	LBL 90H	LBL 90-3145		OSHA Permissible Exposure Limit (ppm)
Hydrocarbons					
n-hexane	x	x	x		500
n-heptane			x		500
n-octane			x	x	500
n-nonane			x	x	
n-undecane			x	x	
2-methylpentane	x	x			
3-methylpentane		x			
2,5-dimethylheptane			x		
methylcyclopentane	x	x	x		
ethylcyclohexane			x	x	
methylcyclohexane			x	x	500
pentamethylheptane			x	x	
Aromatics					
benzene		x	x		1
xylenes	x				100
toluene		x	x	x	200
Halogenated Hydrocarbons					
trichloroethane	x	x	x	x	350
trichloroethylene	x		x	x	100
tetrachloroethylene			x	x	100
Miscellaneous					
hexanal		x			
methylethylketone	x				200

found to be present in great enough concentration to be singled out as a health hazard by existing criteria. On the other hand, existing criteria were established under conditions of the workplace environment where unusually high exposures to a single compound are routinely encountered.

During the summer, a study was made of organic compounds emitted in trace quantities from common building materials. The materials analyzed included caulking compounds, two rugs, two linoleums, and several mastics and glues. Samples were collected via headspace analysis using a glass vacuum apparatus with liquid nitrogen cold traps. The small-volume liquid samples collected were identified by means of gas-chromatography/mass-spectroscopy. The results of the study are presented in Table 2. The major emissions were aliphatic hydrocarbons, but other emissions included alkyl benzenes, higher aromatics (naphthalenes), ketones, and some phenols and glycols. A few samples contained toluene or methyl ketone; only traces of chlorinated hydrocarbons were found.

In the Fall, the same apparatus was used to qualitatively analyze samples of building materials and office furniture from the office building in Marin County where air samples had been analyzed in September. Many of the compounds emitted by the building materials were found to correspond to those identified in the air samples.

The EEB Mobile Laboratory (described in "Field Monitoring") continues to be used for measuring formaldehyde and total aldehydes in the field. Sites in Minnesota, Wisconsin, Oregon, and New Jersey were studied for two-week periods. Formaldehyde levels at all of the sites were below the level at which significant health effects are expected to occur. Initial analysis of the data indicates that while no obvious correlation exists between ventilation rate and formaldehyde levels at these low concentrations, formaldehyde levels may be related to temperature and relative humidity.

Table 2. Organic contaminants identified in headspace vapor over selected building materials.

Building Material[a]	Description	Major Organic Contaminants[b]	Organic Contaminants of Interest[c]	Remarks
carpet #1	nylon (?) fiber, jute backing	3-phenylcyclohexene, aliphatic hydrocarbons	3-phenylcyclohexene	3-phenylcyclohexene derived from alcohol?
carpet #2	polypropylene fiber, foam backing, self-stick	trimethylcyclohexane, aliphated hydrocarbons	traces of alkylbenzene	
carpet #3	synthetic fiber, thin composition backing	n-octane, n-nonane aliphatic hydrocarbons	none	
carpet #4	nylon fiber, jute backing	3-phenylcyclohexene, decane, dichlorobenzene, styrene, aliphatic hydrocarbons	3-phenylcyclohexene, dichlorobenzene, styrene, small amounts of alkyt-benzenes, traces of napthalene, 1- and 2-methylnapthalene, nonanal, analog of butylated hydroxytoluene (BHT)	3-phenylcyclohexene derived from alcohol? Dichlorobenzene from air deodorizer
carpet #5	acrylic fiber, foam backing	Heavy oxygenated compound, aliphatic hydrocarbons	heavy oxygenated compound, small amounts of phenol, biphenyl, napthalene, 1- and 2-methylnapthalene	Heavy oxygenated compound clearly largest component emitted, unknown.
linoleum #1	vinyl, self-stick	dimethylcyclohexane, n-octane, aliphatic hydrocarbons	none	
linoleum #2	vinyl asbestos, self-stick	octane isomers, nonane	small amounts of toluene, xylene, propyl-benzene, trace of trichloroethylene	
linoleum #3	vinyl	acetone, methyl ethyl ketone (MEK), toluene, butyl acetate, aliphatic hydrocarbon background	acetone, MEK, toluene, butylacetate, small amounts of dimethyl-dioxane, trichloroethylene, benzaldehyde, 2-(2-ethoxy-ethoxy) ethanol (Carbitol)	
linoleum #4	vinyl asbestos	toluene	toluene, small amounts of benzaldehyde, acetophenone, benzylalcohol, butyl benzyl ether, alkylbenzenes	

acoustic ceiling tile	pulp faced by vinyl acrylic latex coating	butyl acetate, aliphatic hydrocarbon background	butyl acetate	water was major emission
acoustical tile/ tileboard cement	mastic	aliphatic hydrocarbons	xylene, ethylbenzene toluene, traces of benzene, napthalene, alkylbenzenes, butylated hydroxytoluene (BHT)	allowed to dry 24 hrs before vapor collected
contact cement	liquid	trimethylcyclohexane, methyl ethyl ketone (MEK), aliphatic hydrocarbons	none	allowed to dry 24 hrs before vapor collected
linoleum cement	mastic	denatured alcohol (ethanol, methanol)	methyl isobutyl ketone (MIBK)	allowed to dry 24 hrs before vapor collected
ceramic tile cement	mastic	hexane, aliphatic hydrocarbons	small amounts of alkylbenzenes, trace of trichloroethane	allowed to dry 24 hrs before vapor collected
caulk #1	"Phenoseal"	butylacetate, 2-(2 ethoxy-ethoxy) ethanol (carbitol)	butylacetate, carbitol small amount of butyl propyl ether	water was major emission, allowed to dry 24 hrs before vapor collection
caulk #2	vinyl acrylic latex caulk	ethylene glycol	ethylene glycol	allowed to dry 24 hrs before vapor collection
caulk #3	butyl caulk	octane, octene, nonane, aliphatic hydrocarbons	octene, small amounts of alkylbenzenes	allowed to dry 24 hrs before vapor collection

[a] Samples were purchased in local hardware stores, obtained from local building sites, or supplied by interested consumers.

[b] "Major" is defined as one of the five largest peaks. "Aliphatic hydrocarbons" is used in place of a detailed description of the components of petroleum-derived solvent constituents.

[c] Organic contaminants of interest are defined as those compounds that possess functional groups that enhance chemical reactivity. "Trace amounts" applies to compounds that were approaching the limit of detection, while "small amounts" refers to compounds that were clearly present but did not form one of the five largest peaks (see previous footnote).

PLANNED ACTIVITIES FOR FY 1981

Planned activities for FY 1981 include laboratory and field validation of formaldehyde passive monitors, continued field measurement of formaldehyde, and continued optimization of the solid-solvent organic contaminant sampling apparatus.

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RADON: EMANATION STUDIES, INDOOR MEASUREMENTS, AND CONTROL STRATEGIES*

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INTRODUCTION

When energy-conserving features designed to reduce infiltration are effected in buildings, the levels of radon, as well as other indoor air contaminants, can increase. The main objective of this project is to determine the extent to which radon and its daughters are present in indoor air and to study radon sources and source strengths. In addition, an important aspect of our research is to evaluate control strategies in the light of existing data on health risk factors, so that the formulation of national programs promoting energy conservation in buildings can consider the potential health impact of indoor concentrations of radon and its daughters.

Radon 222 is a chemically inert gas, occurring from decay of radium 226 that is naturally present in the earth's crust. Radon can migrate from its site of formation, and the potential for radon gas emissions into the interior space of buildings depends on the presence of radium in the soil under and around the structure or in the materials used to construct the building, as well as on transport of radon from more distant radium deposits that occurs, for example, via underground water supplies.

The indoor daughter levels associated with a given radon source strength depend, at a minimum, on the rate at which indoor air is exchanged for outdoor air, the internal air circulation rate and pattern, and the indoor particulate concentration. As a result, understanding sources and concentrations of indoor radon and its daughters requires study both of sources--which we know vary from one building to another and one geographical region to another--and of radon daughter behavior. Correspondingly, control techniques can be based on either prevention of radon entry into the interior space or on removal of radon or its daughters from indoor air.

The recognition that radon exposure poses a health risk, generally, and that energy-conservation measures may exacerbate present risks to building occupants has made such studies a research priority. The health hazards of radon result from its four short-lived daughters (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) all of which have half-lives of less than 30 minutes and two of which (the polonium isotopes) are alpha emitters. These daughters can be inhaled into the lower respiratory tract, and exposure to high levels over prolonged periods (as was historically the case for uranium miners) can increase the incidence of lung cancer. The risk factors associated with low-level exposures are not directly known; however, if factors derived from the high-exposure data are applied to the lower indoor exposures, the estimated risk appears to be significant.

Our investigations have focussed primarily on the following activities:

1. measuring the rate of radon emanation from commonly-used building materials;
2. monitoring radon and daughter levels in conventional and energy-efficient residential buildings;
3. developing appropriate monitors for detecting radon and radon daughters; and
4. evaluating control techniques and strategies effective in limiting indoor concentrations.

ACCOMPLISHMENTS DURING FY 1980

One major project this year was to examine samples of building materials commonly used in the

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United States, emphasizing concrete, to determine their contribution to radon concentrations observed indoors. Our principal measurement technique employs gamma detection using a heavily shielded sodium iodide system. Measurement of gamma rays from ^{214}Bi and ^{208}Tl from a sample in a sealed container indicates concentrations of the ^{238}U and ^{232}Th decay chains, respectively. Subsequent measurement with the container open, allowing radon (the parent of ^{214}Bi) to escape, yields the radon emanation rate. (In both cases, ^{40}K is measured from its own gamma ray.) An alternative technique, developed by our group[1,2] measures radon emanation directly by sealing the sample in a container for one to three days and then transferring the radon collected to a scintillation cell for counting. This technique is effective even for low emanation rates.

The results of our survey of ordinary concrete from ten U.S. metropolitan areas are shown in Table 1, which gives emanation rates per unit mass and elemental concentrations. The mean rate for the ten sample groups ranges from 0.4 to 1.2 pCi kg^{-1} h^{-1}. As seen in Table 2, a group of concretes containing fly ash also fell within this range, while samples containing phosphate slag fell below. Gypsum, brick and wood were toward the bottom of this range or lower, as were solar rock bed samples with high uranium content and a radon escape-to-production ratio of 4%.[3]

The materials examined appear to contribute only a small portion of the radon levels ordinarily found in U.S. homes. For 0.2 m thick concrete, 1 pCi kg^{-1} h^{-1} corresponds to an emanation rate per unit area of approximately 0.05 pCi m^{-2} s^{-1}, which would contribute 0.1 pCi/l to the indoor radon concentration in a house having an air exchange rate of one per hour and an emanating-surface-to-interior-volume ratio of 0.5 m^2 per m^3.

We have also been engaged in other concrete-related studies. A few measurements of radionuclide concentrations in and radon emanation from concrete components have been performed,[3] but more extensive studies are required to determine the contribution of these components to the radon emanation rate from concrete, since the reactions that take place in the formation of concrete can influence the extent to which radon is free to move through the cured material. We have made a few measurements of components of ordinary concrete, and have also examined a selection of fly-ash samples, supplied by the U.S. Environmental Protection Agency, as a prelude to further study of fly-ash concretes. A more substantial effort has been devoted to developing a technique for measuring diffusion parameters for radon in concrete. (A few samples have already been measured by this technique.[4]) Knowledge of these diffusion parameters is important not only for understanding the emanation of radon originating in the concrete itself, but also for characterizing the transport of radon from other sources through concrete building components. The latter is necessary for us to evaluate the extent to which radon from soil and rock underlying buildings affects indoor concentrations of radon.

Indoor Concentrations of Radon and its Daughters

During FY 1980, we completed a review of available information on indoor radon and daughters.[5] This review, as expected, indicates that the range of indoor radon concentrations is very large. Perhaps more importantly, it emphasizes the fact (established primarily by LBL work) that in U.S. housing the major influence on indoor radon concentrations is the source strength rather than the air exchange rate, a crucial conclusion for formulating strategies for energy conservation and indoor air quality control.

LBL has conducted surveys in both energy-efficient and conventional houses, measuring radon, infiltration rate and, in most cases, radon daughters. Radon and its daughters are measured using grab samples, and the infiltration rate is measured by a tracer gas technique. Occupants are asked to close windows and doors for the night prior to measurements to assure a degree of correspondence between the observed radon concentrations and infiltration rates and thereby yield the radon source strength. These surveys indicate the range of source strengths and concentrations in houses and provide a basis for more intensive research characterizing indoor exposures and the influence of energy-conservation and control measures.

Two of these surveys, one in energy-efficient and one in conventional houses, were conducted largely in FY 1979,[1] with subsequent analysis of results in FY 1980. The "energy-efficient" houses surveyed in the United States and Canada were typically demonstration or research houses, privately-owned residences built to assure low infiltration rates, or passive solar houses with rock-bed heat storage.[6] Measured radon concentrations and infiltration rates in these houses are shown in Figure 1. If the radon source strengths were the same for all these houses, and if the outdoor radon concentrations were low, the points would be on a straight line. Source strengths were found to differ by more than a factor of 10, however, even in this small number of houses.

The second 1979 survey group, 26 conventional houses in the San Francisco Bay Area, was examined in a similar manner.[1] Radon concentrations in these houses ranged from 0.4 to 0.8 pCi/l, typically much lower than those obtained in our energy-efficient sample. Measured infiltration rates ranged from 0.02 to 1.2 air changes per hour (ach) with 80% in the range of 0.1 to 0.6. (These infiltration rates are thought to be lower than typical for these houses because of mild weather conditions at the time of measurement.)

A third group of houses was surveyed during 1980. These were conventional houses in the vicinity of the single energy-efficient house in Maryland that showed the highest radon concentration in our earlier survey. The purposes of this survey were to examine the efficacy of random sampling for characterizing indoor concentrations of an entire community and to determine whether the high radon levels measured in the energy-efficient house

Table 1. Emanation rates and radionuclide concentrations in ordinary concrete.

Origin of Material	No. of Samples	Emanation Rate per Mass ($pCi kg^{-1} h^{-1}$)			Elemental Concentrations (mean)			Average Escape-to-Production Ratio (%)
		Range	Mean	S.D.	U (ppm)	Th (ppm)	K (%)	
Albuquerque, NM	12	0.70-1.95	1.22	0.35	2.5	6.0	1.5	22
Kansas City, MO	12	0.40-0.65	0.53	0.07	1.0	2.0	0.7	25
Philadelphia, PA	7	0.35-0.55	0.42	0.08	0.6	1.5	0.7	17
Salt Lake City, UT	9	0.50-0.75	0.64	0.08	2.0	4.0	0.6	14
San Francisco - Oakland, CA	21	0.65-1.10	0.83	0.12	1.5	3.0	0.6	24
Austin, TX	8	0.60-0.92	0.73	0.12	1.3	1.5	0.8	24
San Antonio, TX	8	0.27-0.72	0.46	0.14	3.0	7.5	1.5	8
Chicago, IL	12	0.25-1.39	0.66	0.36	1.5	2.0	0.5	25
St. Paul - Minneapolis, MN	5	0.54-0.75	0.62	0.09	1.5	4.0	1.5	19
Knoxville, TN	6	0.46-0.78	0.59	0.12	1.0	1.2	0.5	23

Table 2. Emanation rates and radionuclide concentrations in miscellaneous materials.

Material (Origin)	No. of Samples	Emanation Rate per Mass ($pCi kg^{-1} h^{-1}$) (Mean)	Elemental Concentrations (means) U (ppm)	Th (ppm)	K (%)	Average Escape-to-Production Ratio (%)
Fly-ash Concrete (4%) Knoxville, Tenn.	8	1.01	1.5	2.6	0.7	25
Phosphate Slag Concrete (20%) Savannah, Ga.	1	0.23	0.6	2.2	0.6	14
Gypsum four locations in the U.S. and one in Baja Calif.	12	0.61	1.0	0.5	0.2	28
Rock (Solar storage) N. Mex.	9	0.50	4.5	13.0	3.0	4
Red Brick Calif.	6	0.10	3.6	10.4	1.7	1
Adobe Brick N. Mex.	2	0.35	2.5	6.7	1.9	6
Wood Western states	2	0.02	--	--	--	--
Soil San Jose, Calif.	2	2.1	3.2	11.2	1.6	25
Soil Mt. Airy, Md.	2	2.1	3.3	15.1	2.2	25

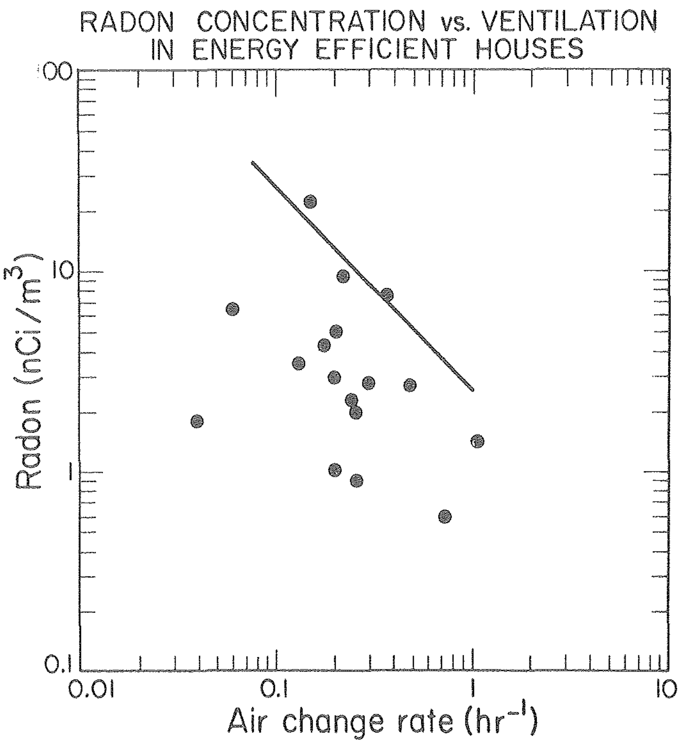

Fig. 1. Radon concentrations and ventilation rates in energy-efficient houses. Results are from grab samples of radon and concurrent ventilation rate measurements. The line indicates results from a house in which the ventilation rate was varied using mechanical ventilation with air-to-air heat exchange. (XBL 801-38A)

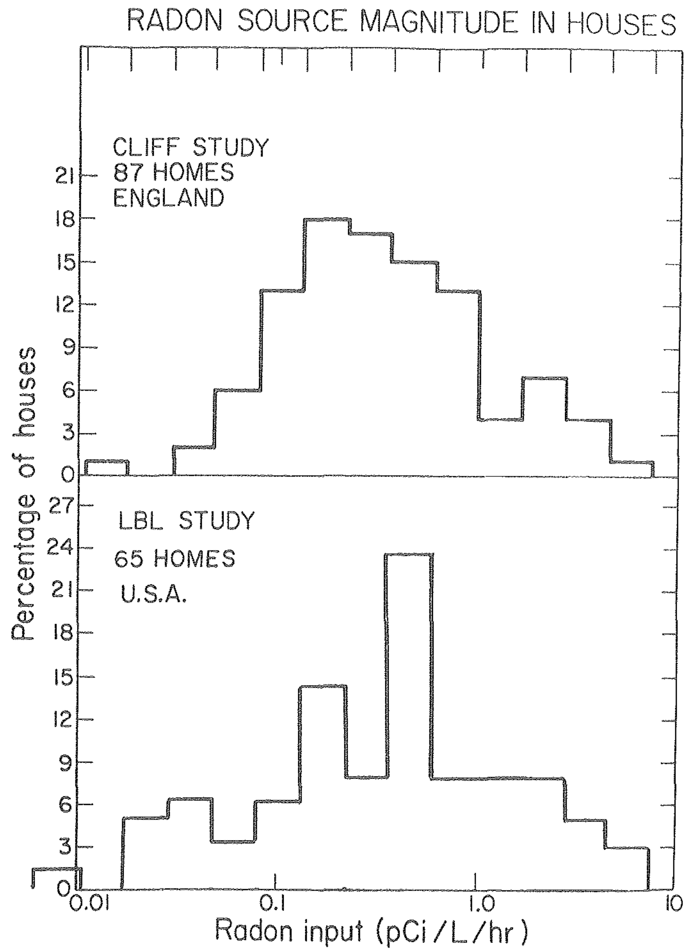

Fig. 2. Frequency distribution of radon source strengths in houses. The radon input per unit interior volume can be calculated from measured values of indoor radon concentration and air exchange rate. The upper distribution shows results obtained in England (Ref. 7). The lower distribution shows results based on measurements in three LBL surveys, including both conventional and energy-efficient houses. (XBL 803-419A)

extend throughout or beyond the community. Preliminary results indicate that the source strengths and indoor radon concentrations in this particular area are, indeed, atypically high.

The combined data from these surveys provide us with a unique view of radon source strengths in U.S. housing. The two surveys of conventional housing in the San Francisco area and in the Maryland area indicate differences in indoor source strength of more than a factor of 100. Moreover, our survey of energy-efficient houses gives source magnitudes within the same range. A preliminary compilation of our data is given in Figure 2, which also shows comparable results from England.[7]

CONTROL TECHNIQUES AND STRATEGIES

Of the available techniques for controlling indoor radon and daughter concentrations, those we investigated are designed to directly affect the airborne concentration rather than reduce the source strength. In particular, we have investigated the effect of mechanical ventilation systems incorporating air-to-air heat exchangers on indoor concentrations of radon. Such systems can control indoor pollutants other than radon and its daughters, are applicable to existing as well as new structures, and avoid much of the energy loss ordinarily associated with mechanical ventilation in heating and cooling seasons.

For our initial tests, we selected the Maryland house mentioned above. Using a mechanical ventilation system with air-to-air heat exchange to vary the air exchange rate, we measured both radon and radon daughter concentrations for a two-week period. The line shown in Figure 1 represents the equilibrium radon concentration. Individual daughter concentrations yielded the potential alpha energy concentrations (PAEC) shown in Figure 3.[8]

These measurements indicate a very complex behavior of individual daughter concentrations (and even PAEC), with an as yet ill-defined dependence on particulate concentrations. This complexity, also observed in our laboratory measurements, cannot as yet be understood in terms of existing models for indoor concentrations of radon and its daughters. Its explanation awaits more comprehensive measurements in controlled conditions and more complete modeling of the behavior of indoor radon daughters and particulates.

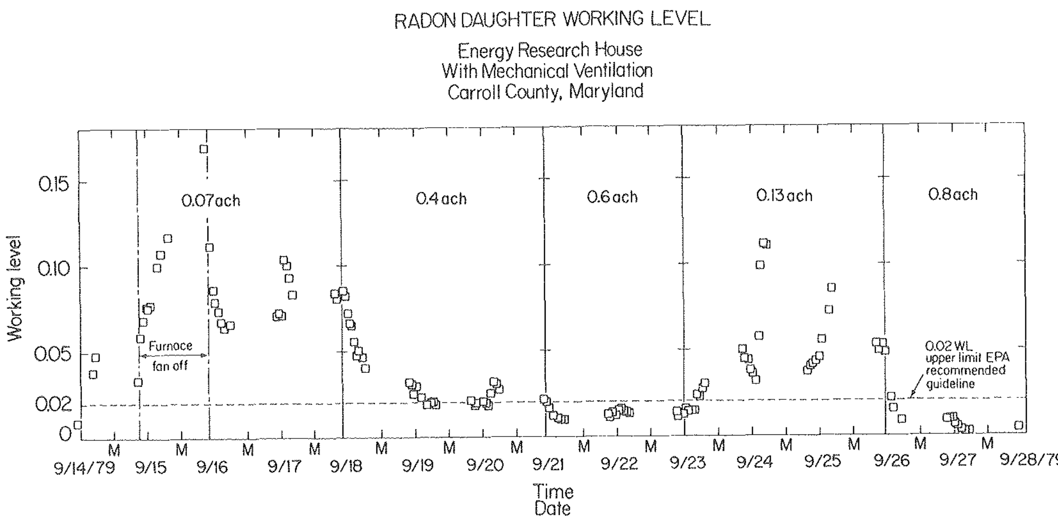

Fig. 3. Variation of potential alpha energy concentration (PAEC) with time. Five ventilation rates were examined using mechanical ventilation with air-to-air exchange during a two-week test period. (The indicated EPA guideline for average PAEC applies to houses on land reclaimed from phosphate mining.) (XBL 7910-4484)

In addition to the energy-efficient Maryland house, we have also begun to study the effectiveness of ventilation with air-to-air heat exchangers for radon control in a number of recently built conventional houses. As discussed in the section, "Mechanical Ventilation with Air-to-Air Heat Exchangers," these houses were selected as having relatively low infiltration rates, i.e., 0.6 ach or less.

We have begun to assess the potential use of mechanical ventilation and other control measures for limiting radon exposures in conventional and energy-efficient houses. As indicated by findings to date, present exposure rates vary substantially among geographic areas and from house to house in the same area. A significant percentage of the population receives exposures in the "occupational" range, that is, in the vicinity of 1 Working Level Month (WLM) per year or higher. National programs implementing ordinary tightening measures--those that reduce existing infiltration rates (typically 0.5 to 1 ach) by about 25%--will not increase this incidence greatly. (Independently of programmatic decisions to employ infiltration-reducing measures, however, it appears that some remedial action is required in cases where radon exposures are found to be high.) On the other hand, in new, very tightly constructed houses where infiltration rates are being reduced to as low as 0.1 ach, ventilation or air-cleaning systems appear to be required to control the levels of indoor-generated pollutants, including radon. Strategies to control radon exposures could have two complementary goals: to assure that virtually no exposures exceed a designated limit, as yet undetermined; and to design buildings to assure an acceptably low average exposure, also to be determined. Development of such limits requires substantial work characterizing indoor daughter concentrations. (See reference 9 for discussion of these issues.)

INSTRUMENTATION DEVELOPMENT

We have devoted substantial efforts to developing and evaluating instrumentation, primarily for measuring airborne radon and daughter concentrations, but also for source monitoring. Particular attention has been given to alpha spectroscopic methods for both field monitoring and laboratory measurement of radon daughter concentrations. We have analyzed two-count procedures used to measure individual daughters, adjusting the timing of the counting intervals to maximize precision.[10] Results of this analysis, shown in Figure 4, compare favorably with other techniques employing total measurement time in the vicinity of 40 minutes. An instrument with parameters chosen on the basis of this analysis yielded the results shown in Figure 3. An automated instrument using a two-count spectroscopic procedure is being fabricated for use in experiments studying radon daughter behavior. In addition, we have analyzed the suitability of rapid single-count spectroscopic methods for field measurements of PAEC. This analysis indicates that a single-count procedure taking a total of 11 minutes yields the PAEC with statistical uncertainty less than 20%, and with methodological error due to assumptions about equilibrium conditions ordinarily less than 20%.

In cooperation with the air-to-air heat exchanger project, we have also designed and fabricated an automatic system, the "Aardvark", for field measurement of indoor radon concentration. The Aardvark uses a continuous radon monitor previously described[1] and measures infiltration rate by means of tracer gas techniques and infrared analysis[12] (see Table 3 for approximate parameters). A more complete system incorporating an automatic spectroscopic daughter monitor of the kind mentioned above is under development for use in a "radon research house."

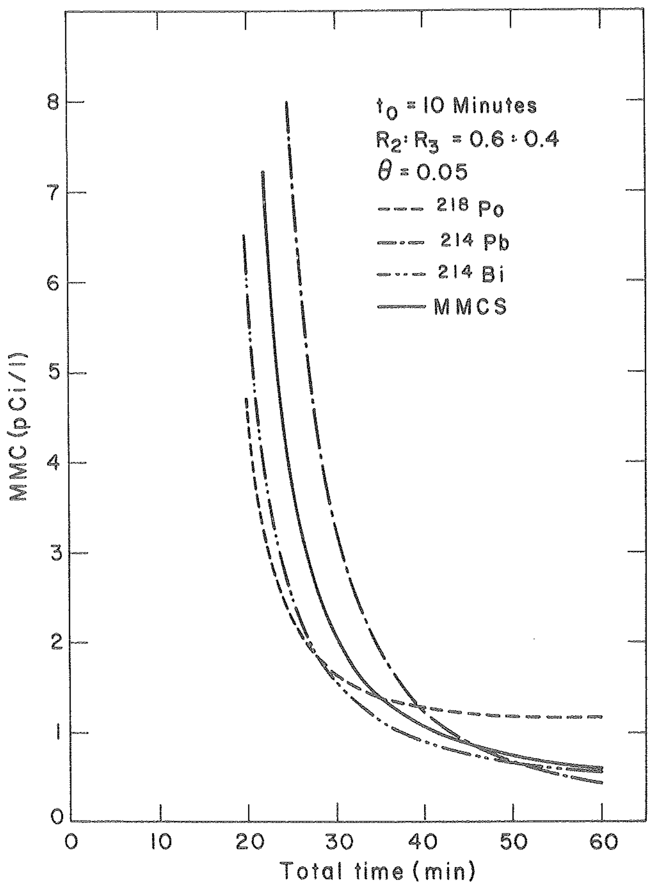

Fig. 4. Minimum measurable concentrations of radon daughters as a function of total measurement for optimized alpha-spectroscopic technique. The solid line (MMCS) is a weighted average of the individual daughter concentrations. (XBL 803-465A)

Table 3. Features of the Aardvark instrumentation system.

Computer controlled

Ventilation
- Tracer gas (SF_6) decay
- Measurement every 1.5 hours
- Automatic analyzer calibration

Radon
- Continuous radon monitor (after Thomas)
- Average measurement every 3 hours
- Precision: 50% uncertainty @ 0.25 pCi/l

Temperature
- Seven points: indoor (2), outdoor (1), heat exchanger airstreams (4)
- Recorded each 1/2 hour

Furnace activity
- Continuously monitored for change in state (on/off)

We have also engaged in testing and refining integrating radon monitors for our field program, including those based on thermoluminescent and track etch detection. The passive environmental radon monitor, PERM,[1] has been modified and tested to determine the effect of various features on its sensitivity and stability. In addition, we have conducted chamber studies to measure the sensitivity of track etch detectors and are examining their usefulness by pairing such detectors with other measurement devices in our field studies.

A new development this year has been the design and fabrication of a prototype radon "sniffer" to be used in houses for identifying places at which radon enters the structure. In preliminary tests, the prototype performed as designed, and more detailed laboratory and field testing is continuing. If such devices can be used to measure soil gas concentrations, we may be able to determine time correlations between radon source behavior and indoor concentrations.

PLANNED ACTIVITIES FOR FY 1981

The major projects already initiated will continue during 1981. We will conduct laboratory and field (in situ) studies of radon sources, including building materials and soils. Field projects will also use the radon "sniffer" to observe entry of radon into homes.

Monitoring of radon, radon daughters, and infiltration rates in conventional and energy-efficient buildings will be continued, both to determine the range and distribution of source strengths and concentrations and to correlate these parameters with structural and operational features of buildings. Cooperative efforts with organizations such as commercial home builders and utility companies will continue, as will our joint undertakings with the air-to-air heat exchanger project and the combustion pollutants group.

In our instrumentation development and evaluation work, we will continue to give attention to passive and active field radon monitors, field and laboratory radon daughter monitors, and source-monitoring techniques.

Several fundamental topics must be addressed more vigorously than heretofore if we are to characterize indoor radon and its daughters successfully, i.e.:

1. geographic distribution of radon sources and strengths;
2. radon transport into structures;
3. behavior of daughters indoors (including the effect of removal processes);
4. sensitivity of measurement techniques under various environmental conditions.

With additional support from DOE/Environment, we can undertake such studies in FY 1981. The first two of these research areas will receive modest emphasis as part of our program of source studies.

A much more intensive effort will be devoted to studies of radon daughter behavior in a "radon research house." This facility, now being established in an off-campus University of California building, consists of a three-room area that is being refurbished to permit control of infiltration rate over the range typical of U.S. housing. A gas-fired hot-air heating-ventilation system that can accommodate potentially interesting air-cleaning devices is now being installed. The research house is being instrumented for automatic remote measurement of air exchange rate, radon concentration, individual daughter concentrations, temperature, and wind, as well as for measurement of particulate concentration, particle size distribution, and humidity. The instrumentation package will also permit study of air transport between rooms, using tracer-gas techniques.

The studies of radon and daughter behavior in this research house will serve as a basis for indoor radon modeling and for testing or evaluating control techniques. Although some of our effort in FY 1981 will be expended on such modeling and testing, more substantial resources must be devoted to acquiring an adequate understanding of the research areas listed above.

Finally, the radon research house, as well as other LBL facilities, will serve as sites for evaluating field monitoring instrumentation. During FY 1981, LBL will initiate a routine program of interlaboratory comparisons of radon monitoring instrumentation.

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FIELD MONITORING OF INDOOR AIR QUALITY*

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INTRODUCTION

One of the primary considerations involved in setting energy-efficient ventilation standards is their effect on indoor air quality. In support of the various laboratory research projects ongoing in the BVIAQ group, this project conducts on-site measurements of numerous parameters of indoor air quality in a variety of building types, including structures that have been weatherized and otherwise retrofit and new construction specifically designed for energy-efficient performance. By manipulating ventilation rates and measuring such comfort parameters as moisture, odor, and humidity as well as the levels of indoor-generated pollutants (see Table 1), we hope to ascertain what level of ventilation is required to assure a comfortable and safe indoor environment without compromising energy-conservation goals. It is important that any ventilation standards recommended on a wide scale differentiate the needs of various categories of buildings based on structural factors specific to the building, the source strengths of the indoor pollutants encountered, the relative hazards of the pollutants present, and the way the building is used by the occupants. (Schools and hospitals, for example, have different needs from those of residences, and occupant behavior and activity affects the air quality in houses.) Much of our work is accomplished in the Energy Efficient Buildings (EEB) Mobile Laboratory, an instrumented facility that can be stationed at a field site for extended periods of time. The capabilities of the mobile laboratory and the field sampling sites visited this year are described below.

EEB Mobile Laboratory

Since its construction in 1978, the EEB Mobile Laboratory has been used extensively in our field monitoring projects. As shown in Figure 1, the unit is positioned outside a building whose air quality is to be monitored. Air sampling lines are installed at several sites within the structure under study and terminate inside the laboratory where the air monitoring instrumentation is located. As a general practice, we sample the outdoor air in order to determine what fraction of the pollution indoors originates outside. For indoor sampling, we select three sites to account for the spatial distribution of pollutant sources and incomplete mixing of the interior air, both of which can cause variations in the pollutant concentration from one room to another. Air is sampled sequentially from these four locations with a microprocessor-controlled sampling and data logging system.

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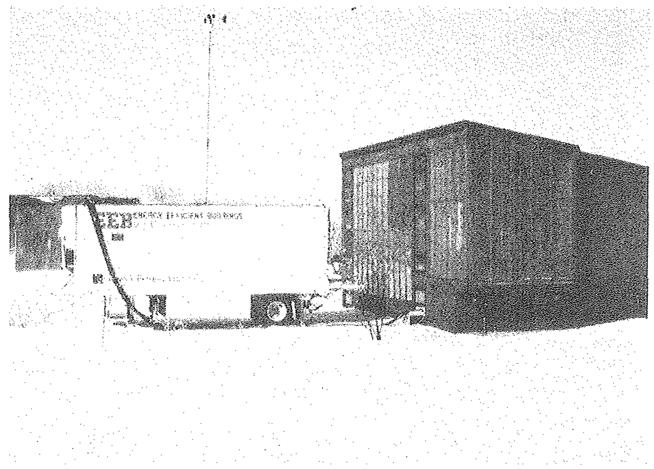
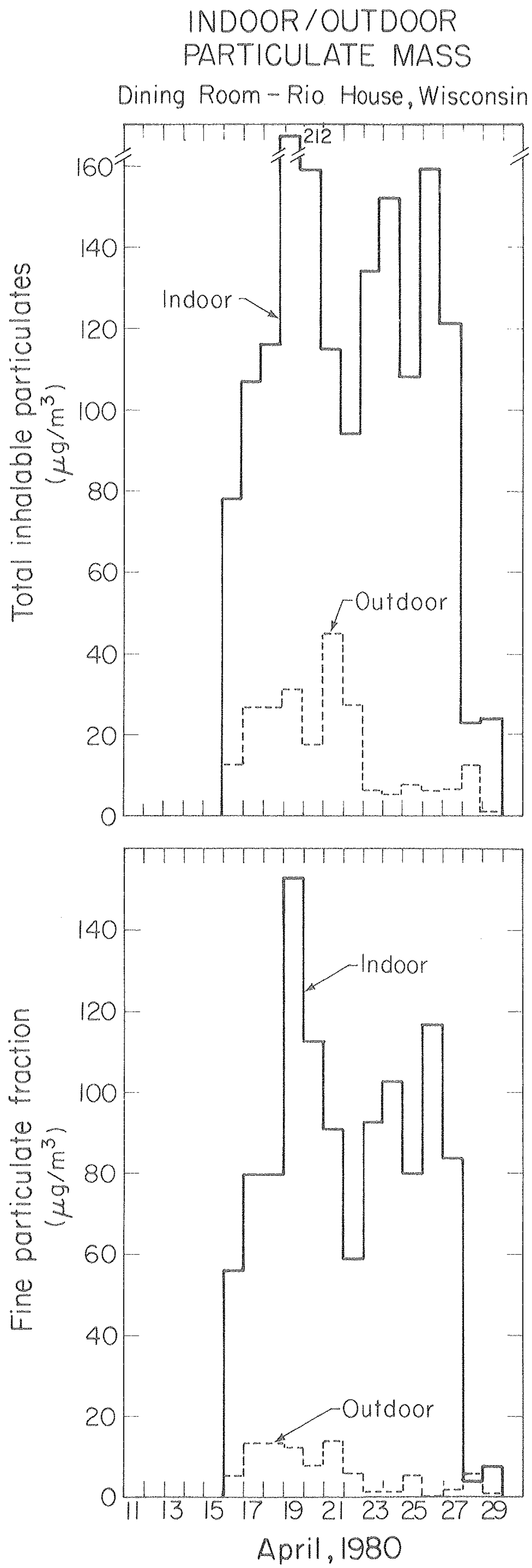


Fig. 1. The EEB Mobile Laboratory. (CBB 806-7077)

The total exposure to occupants is determined not only by the respective pollutant concentrations in the rooms occupied, but also by the time spent in these rooms, for the concentration of any single pollutant may vary widely over the course of time. Figure 2 shows the concentration of nitrogen dioxide over a 24-hour period in the kitchen of a Wisconsin farmhouse. Nitrogen dioxide is a product of combustion; in this house, propane cooking, cigarette smoking and a woodburning stove constituted the combustion sources that we see reflected in the peaks.

Table 1 lists the various parameters that can be measured by the mobile laboratory, and the relevant method or instrumentation it uses. Most of the gaseous pollutants, as well as air exchange rates and comfort and meteorological parameters can be measured on a continuous basis, as indicated. Several of the pollutants, however, because of their physical and chemical properties or low concentrations, must be measured on a time-integrated basis. Often these measurements must be made directly at the sampling site rather than in the mobile laboratory. For example, radon measurements are made in the structure under study for a one-week period using a portable battery-operated device which records the alpha decays from decaying radon atoms.[1] Formaldehyde and total aldehydes are collected over periods up to 24 hours using temperature- and flow-controlled gas bubblers.[2] Other organic contaminants are collected over periods of hours using the porous polymer Tenax-GC as an adsorption medium. This collection system is still under development (see Organics). Inhalable particulates are divided according to size and collected on teflon filters, typically for 24-hour periods.[3] Most of these collection devices were



developed at LBL and all require subsequent laboratory analyses to determine composition and concentrations.

ACCOMPLISHMENTS DURING 1980

During the sampling year, which began in the summer of 1979 and continued into 1980, we used the EEB Mobile Laboratory to monitor the Minimum Energy Dwelling, MED-II, in Mission Viejo, California, the Oakland Gardens Elementary School in Bayside, New York, the Fridley Jr. High School in Fridley, Minnesota, two highly energy-efficient houses in Northfield, Minnesota and in Dundas, Minnesota, and a retrofitted residence in Rio, Wisconsin.

Oakland Gardens Elementary School

Air quality was monitored in two classrooms, a corridor, and outdoors for a period of seven weeks, and odors measurements (sensory perception, odor acceptability and chemical composition) were made by an LBL subcontractor, The Research Corporation of New England (TRC), for a two-week period. Ventilation of the classrooms was controlled by a system that exhausted air through ducts under negative pressure to exhaust fans located on the roof. Outdoor air entered through cracks around the windows. We restricted the exhaust flow by various means in order to monitor indoor air quality under different ventilation conditions. The three rates selected ranged from a high of approximately 14.8 m^3/h (8.8 cfm) per occupant to a low of approximately 4.4 m^3/h (2.9 cfm) per occupant, with one intermediate rate of approximately 8.2 m^3/h (4.9 cfm) per occupant.

In terms of pollutants, the only problems encountered were high levels of particulates in the hallway (but not in the individual classrooms) and an elevation in nitrogen dioxide levels (both indoors and outdoors) close to or slightly exceeding EPA ambient air quality standards. TRC findings showed a decrease in odor acceptability in one of the classrooms at the lowest ventilation rate. The small number of panelists used and the large uncertainty margin inherent in odor measurements make these data difficult to evaluate. We concluded that ventilation rates could be safely reduced to the intermediate level of 8.4 m^3/h (5 cfm) per occupant (one-half the level recommended by ASHRAE) without any adverse effects on health, safety, and comfort of the occupants.

Fridley Jr. High School

The study at Fridley Junior High School was a demonstration project jointly conducted by LBL and its subcontractor, Honeywell Inc. The purpose of this study was to determine the feasibility of operating a variable ventilation control system based on CO_2 levels which serve as an indication of

Fig. 2. Total inhalable particulate mass (<15 μ) and fine particle fraction (<2.5 μ) at a Wisconsin farmhouse. Occupants refrained from cigarette smoking for the final two days of the study. (XBL 808-1592)

Table 1. Instrumentation used in the EEB Mobile Laboratory.

Purpose	Method/Instrument	Manufacturer/Model
Continuous monitoring of the following parameters:		
Gases:		
CO_2	NDIR	Horiba PIR 2000
CO	NDIR	Bendix 8501-5CA
SO_2	UV fluorescence	Thermo Electron 43
NO, NO_x	Chemiluminescence	Thermo Electron 14D
O_3	UV absorption	Dasibi 1003-AH
Indoor temperature & moisture:		
Dry-bulb temperature	Thermistor	Yellow Springs 701
Relative humidity	Lithium chloride hygrometer	Yellow Springs 91 HC
Outdoor meteorology:		
Dry-bulb temperature	Thermistor	MRI 915-2
Relative humidity	Lithium chloride hygrometer	MRI 915-2
Wind speed	Generator	MRI 1074-2
Wind direction	Potentiometer	MRI 1074-2
Solar radiation	Spectral pyranometer	Eppley PSP
Infiltration	Automated controlled-flow measurement or tracer gas decay/IR absorption	LBL/Wilkes
Time-averaged monitoring of the following parameters:		
Gases:		
Radon	Electrostatic collection/ thermoluminescence	LBL
Formaldehyde/total aldehydes	Absorption (gas bubblers)/ colorimetry	LBL
Selected organic compounds	Tenax GC adsorption tubes/ GC analysis	LBL
Inhalable particulates (fine & coarse fractions)	Virtual impaction/ filtration	LBL
Data acquisition:		
	Microprocessor	Intel System 80/20-4
	Multiplexer A/D	Burr Brown Micromux Receiver MM6016 AA Remote MM6401
	Floppy disk drive	ICOM FD3712-56/20-19
	Modem	Vadic VA-317S

occupancy; that is changes in occupancy levels are reflected in fluctuations in carbon dioxide concentration which is monitored by a sensing device that, in turn, regulates the ventilation rate accordingly. Such a control system, because it responds to actual occupancy conditions rather than having an arbitrarily fixed rate, promises significant energy savings. The study was restricted to the music wing of the school which contained a band room, two chorus rooms, and many practice rooms. Outdoor air entered the rooms by natural infiltration and through the ventilation system's CO_2-controlled outside air damper. The operating set point at which the outside air damper began to open was set at 3,000 ppm; at 5,000 ppm, the lowest existing standard for CO_2 concentration, the damper opened fully. During the test period, the occupancy level was low enough that infiltration alone was sufficient to keep the CO_2 levels below 3,000 ppm; thus the energy savings were significant.

Energy Efficient Houses

Table 2 summarizes the indoor air quality data collected at five energy-efficient houses throughout the 1979-80 year. The house in Carroll County, Maryland was an energy-efficient research house which, in addition to other energy-conserving features, had a plastic vapor barrier to minimize infiltration; this house had electric appliances and was occupied by LBL field personnel during the sampling period. The house in Mission Viejo, California was built by a large home building company as a model home incorporating several energy-conserving features. It has natural gas appliances and was occupied by a family of three during the sampling period. Both houses in Minnesota were owner-designed and include many energy-conservation features. Because of the very low air exchange rates achieved in these latter houses, indoor moisture problems arose. To circumvent these and other

Table 2. Indoor air quality measurements in five energy-efficient occupied houses.

	Carroll County, Md.	Mission Viejo, Calif.	Northfield, Minn.		Dundas, Minn.		Rio, Wisc.
			HX off	HX on	HX off	HX on	
Infiltration rate (ach)	0.15[a]	0.4	0.1	0.3	0.1	0.3	0.3
CO (ppm)	1.2	1.4	0.5	0.4	0.7	0.4	2.2
CO_2 (ppm)	598	689	1175	722	1316	478	1125
NO_2 (ppb)	9	41	15	16	19	20	77
NO (ppb)	5	44	5	2	70	5	72
SO_2 (ppb)	3.2	0.9	1.0	1.7	---	---	9.0
O_3 (ppb)	4.3	15.6	1.7	1.7	9.0	9.3	15.0
Particulates--fine ($\mu g/m^3$)	7.8	32.6	6.8	6.8	19.5	8.0	92.4[b] 6.0[c]
Particulates--total ($\mu g/m^3$)	9.9	48.9	14.8	13.8	27.9	14.6	129.6[b] 23.5[c]
Formaldehyde (ppb)	98	214	69	73	80	64	53
Total aldehydes (ppb)	150	227	99	91	122	163	81

[a] All values represent average concentrations during the monitoring period.

[b] Smoking.

[c] No smoking.

possible indoor air quality problems, we recommended the installation of air-to-air heat exchangers in both houses, and air quality measurements were taken with and without the heat exchangers operating (0.3 and 0.1 air changes per hour, respectively). Both houses had electric cooking appliances. The Northfield house was occupied by a family of five and the Dundas house was occupied by a family of two. The Rio, Wisconsin farmhouse had been retrofitted (storm windows, weatherstripping, and a vapor barrier on the interior walls). It was occupied by a family of five, one of whom was a cigarette smoker, and propane cooking appliances were used. The house was heated with a woodburning stove which was located in the basement.

As indicated in the table, the infiltration rates in these houses is considerably less than the national average. No significant carbon monoxide problems were observed in any of the houses. (Such problems are usually associated with unvented or improperly tuned gas appliances or cracks in the heat exchanger surrounding the combustion chamber which can cause combustion gases to enter the ventilation system.) Carbon dioxide levels remained low and were expected to remain low unless a large number of people were present. In the two Minnesota houses where air-to-air heat exchangers had been installed in the basement, it is clear that these devices were effective in reducing the concentrations of pollutants originating in this area. The high levels of nitric oxide in the Dundas house before the heat exchanger was turned on were associated with the operation of a basement oil-burning furnace, and the dramatic reduction effected by the heat exchanger was because its exhaust inlet was adjacent to the furnace.

Very high levels of particulates were measured in the Rio, Wisconsin house. As is evident in Table 2 and in Figure 2 (which shows the levels of total inhalable and fine particulates measured for a two-week period in the dining room of this house) the difference in particulate levels between smoking and non-smoking periods is dramatic. Although this house differed from the others in using propane combustion appliances and a woodburning stove, the data clearly confirm that the significant rise in particulates was attributable to cigarette smoke.

PLANNED ACTIVITIES FOR 1981

In FY 1981, we will conduct intensive field monitoring at additional sites, as described below:

- Detailed indoor air quality measurements will be taken at two houses in Medford, Oregon that are being retrofitted as part of a weatherization program sponsored by the Pacific Power and Light Company, in an energy-efficient earth-sheltered house in Minnesota, and in a house undergoing extensive retrofit as part of the "house doctor" program conducted by Princeton University.
- Air leakage measurements will be taken in approximately six other houses involved in the PP&L weatherization program.
- Heat exchanger performance will be evaluated in several energy-efficient houses in Rochester, New York. Parameters to be tested are: their effectiveness in improving indoor air quality, their performance in cold weather, including potential freeze-up and leakage problems, and their cost-effectiveness in saving energy.

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MECHANICAL VENTILATION SYSTEMS USING AIR-TO-AIR HEAT EXCHANGERS*

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INTRODUCTION

One of the primary means of reducing energy consumption in buildings is to reduce infiltration, the uncontrolled leakage of air into and out of buildings. When the infiltration rate in houses is lowered through various weatherization measures, the levels of indoor-generated air pollutants (e.g., odors, chemical contaminants, moisture, formaldehyde, and radon gas) can build up and degrade indoor air quality. One possible method to resolve the problem without compromising energy efficiency is to use a mechanical ventilation system with an air-to-air heat exchanger. A research program to investigate the pollutant control capability and energy performance of these systems is underway at Lawrence Berkeley Laboratory.

The essential feature of the heat exchanger is that it brings the incoming and exhaust air into close proximity in its "core" where heat is exchanged between the two air streams. Such devices are commercially available in a number of different configurations. Figure 1 illustrates a fully ducted installation in the attic of a house, and Figure 2 depicts the principle of operation.

Three tasks have been delineated to accomplish the goals of this project:

1. Analytical and experimental (laboratory) evaluation of air-to-air heat exchanger performance;
2. Installation and testing of various heat exchanger/ventilation systems in occupied homes;
3. Economic analyses of heat exchanger/ventilation systems in different climate zones of the U.S.

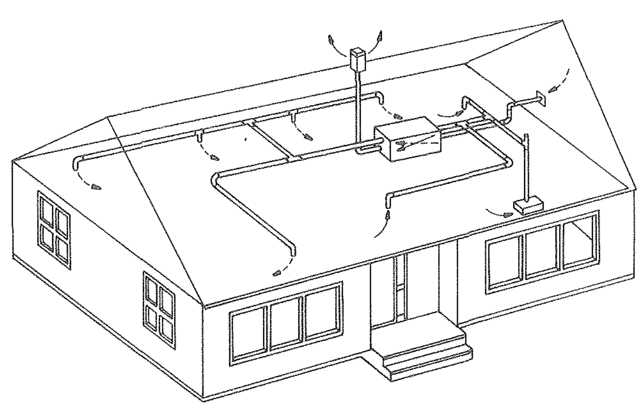

Fig. 1. Attic installation of a residential heat exchanger. (XBL 812-8054)

* The work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

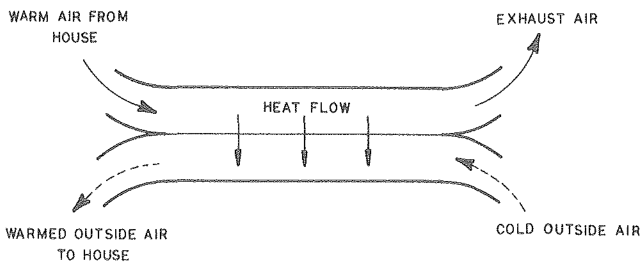

Fig. 2. Principle of thermal transfer in a heat exchanger. (XBL 813-8790)

ACCOMPLISHMENTS DURING FY 1980

Laboratory Testing

The experimental evaluation of air-to-air heat exchangers at our test facility was initiated early in 1980. Five commercially available residential size heat exchangers have been tested for thermal performance versus flow rate. In two of these heat exchangers, the performance of the fan system was also measured using a newly constructed Fan Performance Test System. The results of this testing program are detailed in an LBL report entitled The Performance of Residential Air-to-Air Heat Exchangers: Test Results and Methods.[1] Heat exchanger "effectiveness" is the ratio of actual heat transfer within a heat exchanger to the maximum level that is theoretically possible. Figure 3 is a graph showing the measured effectiveness versus flow rate for these heat exchangers.

Cross-leakage between the airstreams within a heat exchanger can affect both the thermal performance of the unit and its ability to remove indoor contaminants. A cross-leakage test system that uses a tracer gas to measure the rate of leakage between heat exchanger airstreams was constructed during 1980. Cross-leakage tests have been completed for two heat exchangers. One heat exchanger showed very high cross leakage rates (up to 30% of the airstream flow rates) when the airstream pressures were highly imbalanced. The leakage in the second heat exchanger was only a few percent of the airstream flow rates.

Field Testing

A field testing project to evaluate the use of mechanical ventilation with heat recovery for controlling indoor radon and formaldehyde concentrations was conducted by LBL with the National Association of Home Builders Research Foundation Inc., and Geomet Corporation as subcontractors. For this study, two air-to-air heat exchangers were installed in a home built by the Home Builders Association that had elevated indoor concentrations of radon and formaldehyde. Formaldehyde and radon concentrations versus ventilation rate were measured for a two-week period. The natural infiltra-

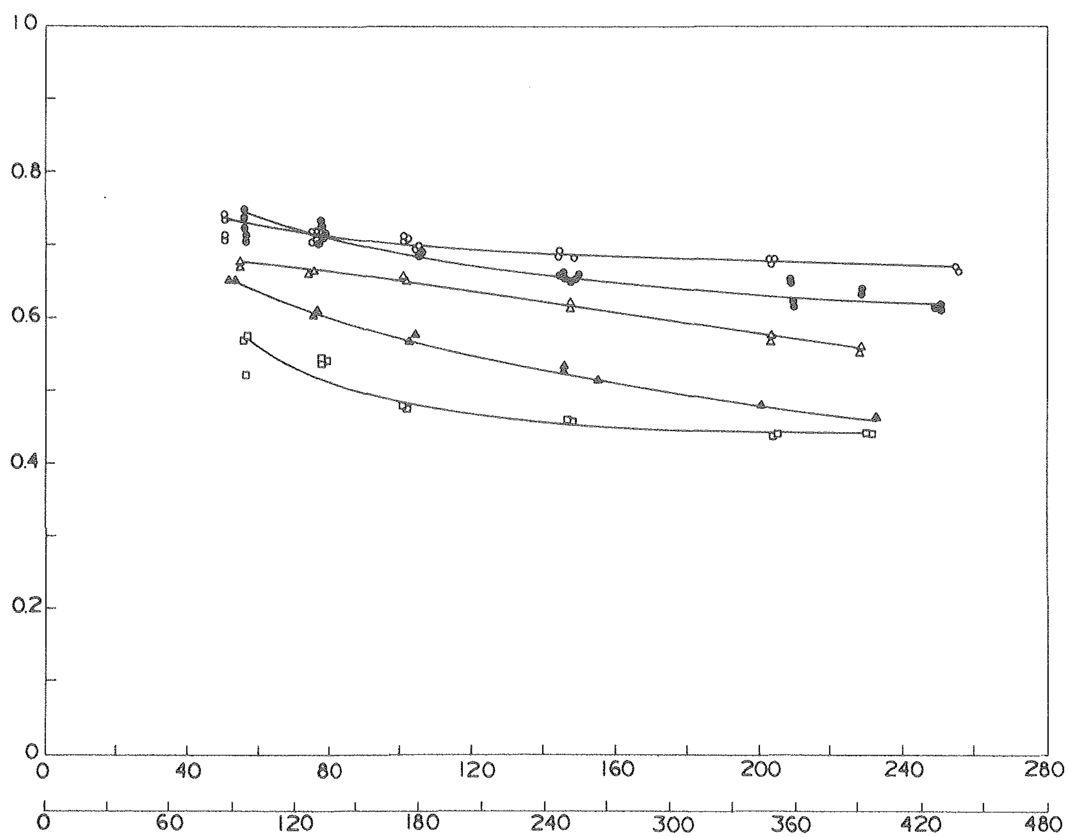

Fig. 3. Effectiveness versus flow rate for five models of residential air-to-air heat exchangers. (XBL 8011-12106)

tion rate of the home with the doors and windows closed was found to vary between 0.1 and 0.25 air changes per hour (ach) depending on outside weather conditions. When the air exchange rate was increased to 0.6 ach by mechanical ventilation, the radon concentrations in the home were reduced from very high levels to a level below EPA guidelines (established for homes built in Florida on land reclaimed from phosphate mining). The findings from this study are detailed in an LBL report entitled The Use of Mechanical Ventilation with Heat Recovery for Controlling Radon and Radon Daughter Concentrations.[2]

Another field study initiated this year is a joint project with the New York State Energy Research and Development Administration, Rochester Gas and Electric Company and the Rochester Institute of Technology. Thus far, approximately 60 homes built by two commercial builders in the Rochester area have been tested for air-tightness using a blower door designed by LBL. We have selected nine of these homes for a study of indoor air quality, and the energy efficiency and pollutant reduction capability of mechanical ventilation systems with heat exchangers. In seven of the homes, a small computer-controlled ventilation monitoring system, called the AARDVARK, will be used. Figure 4 is a photograph of the AARDVARK, which measures average ventilation rate every 1.5 hours and average radon concentration every three hours. The AARDVARK, pictured in Figure 4, also monitors the furnace on and off times; these data will be used to determine the energy consumed by the home heating system. In addition, the system monitors the thermostat setting, the outside temperature, the four temperatures at the inlets and outlets of the heat exchanger, and one other interior temperature. Studies will be conducted in each home for one week without mechanical ventilation and one week with mechanical ventilation. Average daily formaldehyde concentration and average weekly nitrogen dioxide concentration are also being measured in these homes. In the remaining two homes in the study, indoor pollutant levels and ventilation rate will be measured by the EEB Mobile Laboratory (see Field Monitoring).

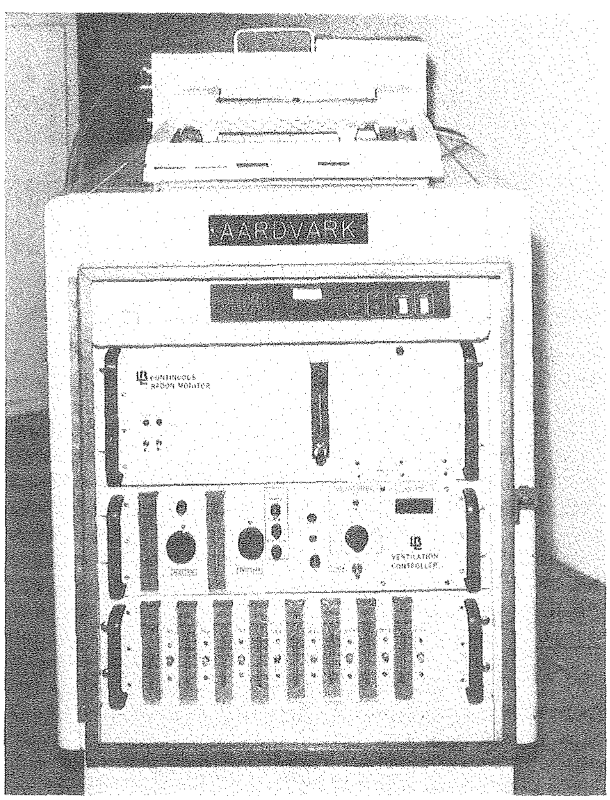

Fig. 4. AARDVARK--automatic infiltration and radon monitor. (BBC 800-12102)

Economic Analyses

An economic analysis of the residential use of mechanical ventilation systems with heat exchangers was made in FY 1980 and is presented in an LBL report entitled Residential Ventilation with Heat Recovery: Improving Indoor Air Quality and Saving Energy.[3] The analysis indicates that these systems can be cost-effective in most geographical areas of the country if the initial cost of the heat exchanger including installation is in the range of approximately $400 to $500. In cold climates, a higher initial cost remains cost-effective.

PLANNED ACTIVITIES FOR FY 1981

In addition to the continuing field program in Rochester N.Y., field studies of installed air-to-air heat exchangers will be undertaken in central Washington state (in a joint project with Bonneville Power Administration) and in Minneapolis, Minnesota. In the Washington project, six occupied homes will receive a one-day "house doctor" retrofit and an additional six will receive two-day "super retrofits" to reduce air infiltration. Heat exchangers will be installed in each of the twelve homes. Indoor air quality measurements will be made prior to the retrofit and after retrofit, with and without the heat exchanger operating. The focus of the Minneapolis study, which involves only one home, is to assess the performance of a heat exchanger in a cold climate. Heat exchanger effectiveness and airstream flow rates will be monitored, and visual inspections will be made for freezing within the heat exchanger core. The data obtained from the field studies and laboratory tests will be used to reassess the economics of employing air-to-air heat exchangers in homes.

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ENERGY-EFFICIENT WINDOWS PROGRAM*

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INTRODUCTION

Approximately 20% of the annual energy consumption in the United States is used for space conditioning of residential and commercial buildings, and about 25% of that figure 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 thermal performance of windows.

An important aim of the Windows and Daylighting Program is to develop a sound technical base for predicting the net energy performance of windows and skylights, including both their 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 development of effective new materials and designs. Of critical importance to our program is that both design professionals and the public recognize, accept, and use this information. To that purpose we have implemented a broadly based program that encompasses research and development projects, field demonstrations, market studies, and information dissemination activities. While most of the program is conducted at LBL, portions are performed under subcontract, with LBL maintaining technical management responsibility.

ACCOMPLISHMENTS DURING FY 1980

Our work is organized into four major areas: (1) Window Performance: Analysis and Testing; (2) Fenestration Systems: Research, Development, and Demonstration; (3) Daylighting; and (4) Program Planning and Support.

Window Performance: Analysis and Testing

Analytical Modeling

The ability to accurately model all aspects of the energy-related performance of windows is a prerequisite to optimizing energy-efficient design strategies and product selection. Analytical models are required at several performance levels: for component materials and assemblies, for isolated window systems, and for windows or skylights studied in the context of a surrounding building. In addition, while some models are needed to predict single performance variables such as conductance, air leakage, or solar transmittance, the primary goal is to create models that predict net energy performance over time.

A number of improvements have been made to our window heat-transfer program, THERM. It can model a window that is composed of an arbitrary number of layers, such as glass panes or plastic films. The effects of plastic substrates that are semi-transparent to long-wave infrared radiation can now be properly modeled. Any layer may have a thin-film coating (heat mirror, solar-control film, optical shutter, anti-reflection coating), and the space between may contain a gas having a low thermal conductance. Extensive parametric studies of heat-transfer rates of windows having transparent heat mirrors and gas fills were performed this year. Figure 1 shows the effects of heat-mirror coating position and emissivity on the overall thermal conductance of single, double, and triple glazing. A significant new result from these studies was the discovery that if a plastic film coated with a heat mirror is mounted in the air space of a double-glazed window, asymmetric mounting of the plastic film provides lower heat-transfer rates than does a film located in the center. The effect is most significant for small air spaces.

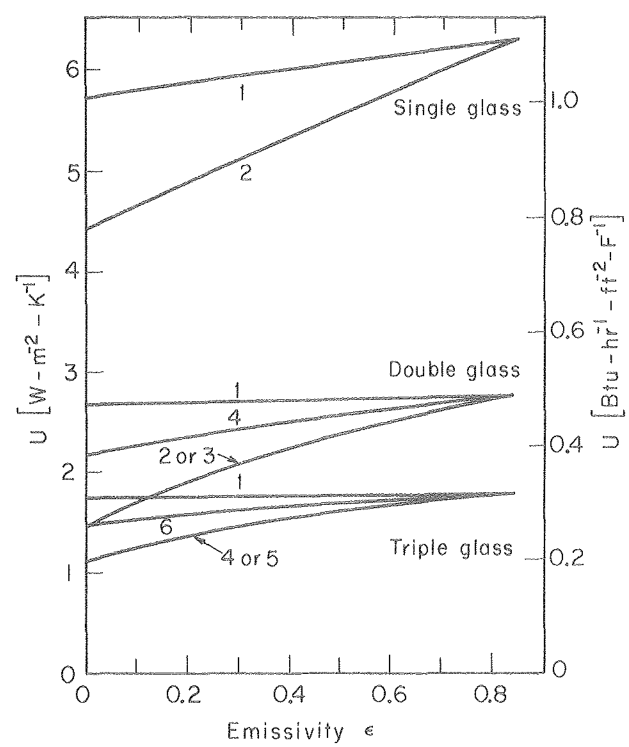


Fig. 1. U-value vs. emissivity for single, double, and triple glazing with low-emissivity coatings on several different surfaces. Surfaces are numbered consecutively starting from the outside surface. (XBL 807-3489)

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

The detailed window model may be coupled with another newly developed program that simulates hour-by-hour weather conditions in a given city and employs a simplified thermal model of the building. With this program, the yearly energy loss or gain attributable to the glazed area can be predicted. This program has been tested with ordinary multiple-pane glass windows and with windows that incorporate heat mirrors.

New algorithms and data were developed this year to expand the capabilities of the DOE-2 Building Energy Analysis program. The public-domain version was modified to allow use of triple glazing with clear or with heat-absorbing glass types. Other energy-conserving windows, such as heat mirrors, solar-control films, and gas fills, are being added to our development version of DOE-2. A standard set of input data has been compiled to test the sensitivity of window energy consumption to climatic factors and building construction. These results will allow us to make specific recommendations about the use of new energy-efficient window designs for residential and commercial buildings in different parts of the country.

A study of the effect of movable insulation on heating loads in a residence in Minneapolis was extended to include results of changes in the standard house operating schedule and the incorporation of new sun-control options for three diverse climates. The trends and patterns observed were similar to the Minnesota case, although the magnitude of the savings was greatly reduced. These results further reinforce the finding that insulating options beyond R5 offer only marginal improvements in most cases. Preliminary studies of fixed and operable shading devices and daylighting strategies in commercial buildings were also undertaken.

Parametric studies of the type described above are important for helping specifiers and producers of products choose from a bewildering array of new products. In September 1980 we published an updated listing of commercially available window-insulating products. The list nearly doubled during a nine-month period and continues to grow. For each product, it includes calculated and measured thermal-performance data in a consistent format to assist building designers in making intelligent decisions regarding window-insulating products.

Performance Testing

In 1977, we established a Building Technology Laboratory in the College of Environmental Design of the University of California, Berkeley, to support our research and development activities, to provide independent testing and evaluation of materials and products submitted by subcontractors, and to permit evaluation of new products being introduced to the market. Testing facilities include a calibrated hotbox (shown in Figure 2), which is now being used to test the thermal performance of windows and associated energy-conserving accessories. A sample of devices now on the market or prototypes of devices soon to be on the market was tested to establish a baseline against which future improvements in window performance can be compared. Sample results are shown in Figure 3.

The heat-loss and heat-gain rates of windows can be improved with the use of thin-film coatings on glazing materials. To fully characterize glazing material performance, we have added capabilities for measuring a range of optical properties of glazing materials and coatings. Infiltration tests on windows are also being made in our laboratory.

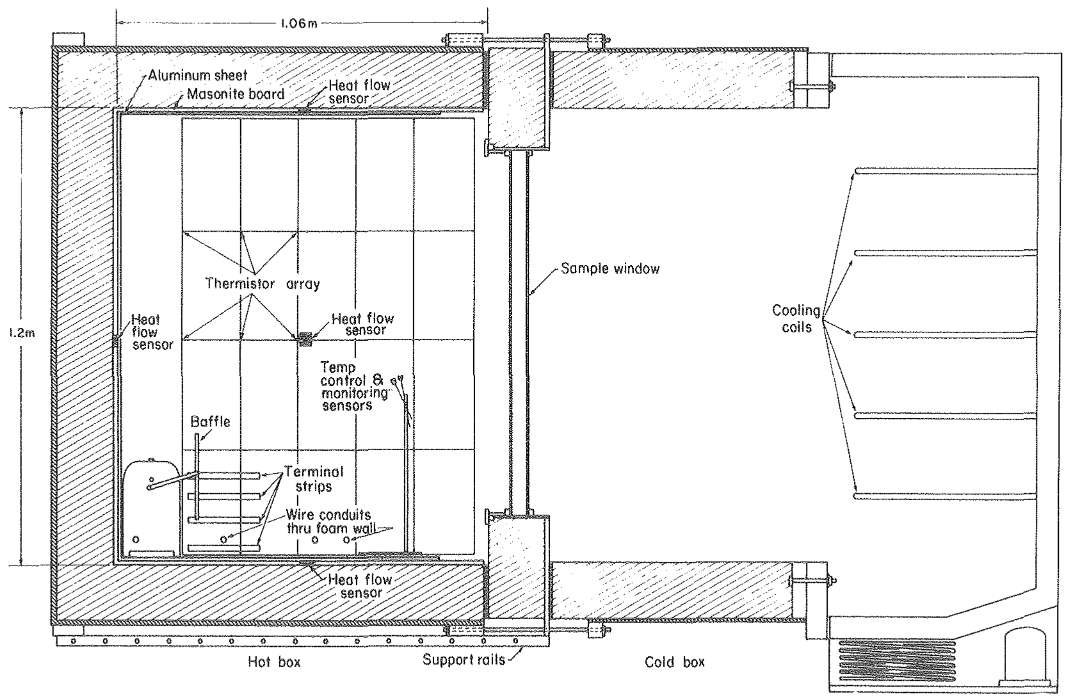
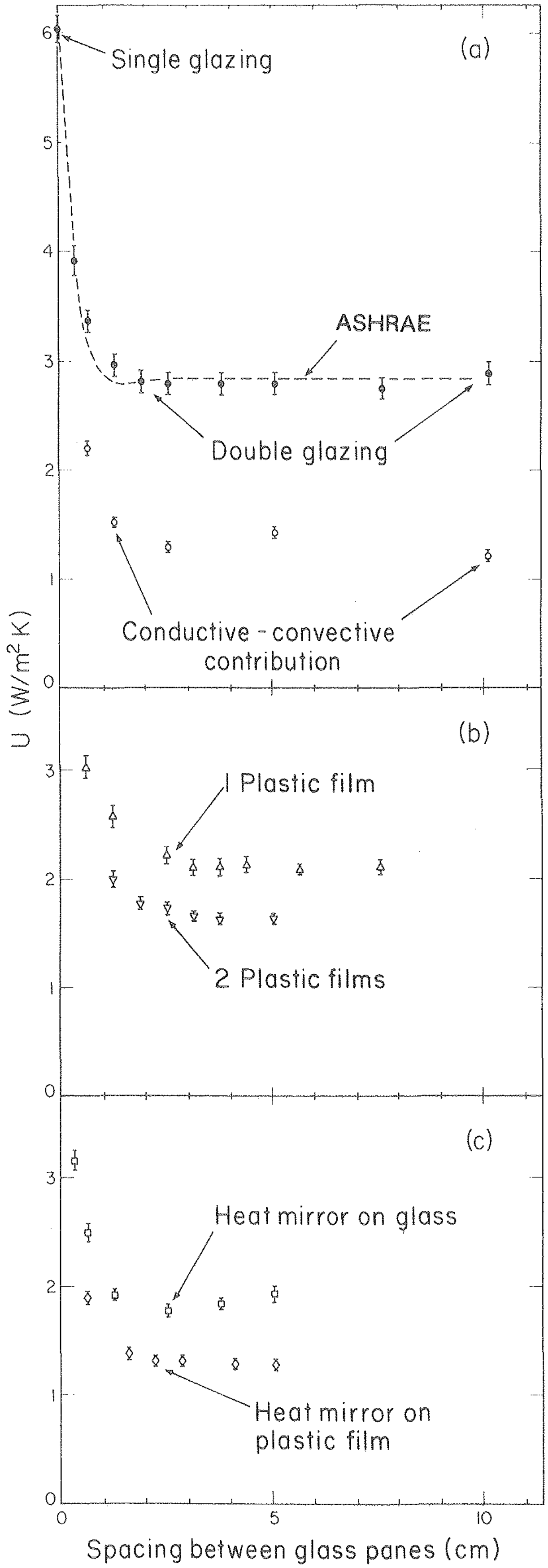


Fig. 2. Section through calibrated hotbox showing hot and cold box chambers and sample window. (XBL 799-2921A)



The single piece of information most relevant to assessing the benefit to be derived from a window or window improvement is its net energy performance under actual conditions of use in buildings. This is a dynamic property, essential for predicting the performance of managed window systems (i.e., windows that have thermal/optical properties that can be manually or automatically changed by building occupants). The laboratory testing facilities described above, 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. Accordingly, in 1980 we continued design studies on our Mobile Window Thermal Test (MoWiTT) facility, being developed to permit the study of combined solar, infiltrative, conductive/convective, and radiative heat transfers through a window as a function of window type and orientation and changing weather conditions throughout the day (see Figure 4). Design, scheduling, and cost estimates for the MoWiTT facility have been completed, and construction is planned for 1981. Development of software for its control and data-acquisition systems is in progress. The thermal properties of each of the four test chambers in the MoWiTT facility can be altered by varying wall insulation level, thermal mass, and air-leakage rate, thus allowing us to simulate a wide range of building conditions. Winter testing will be conducted in a cold, mountainous location and summer testing in a near-desert area. From these experimental results, we will be able to validate or modify our analytical models and to rank the performances of various window-management strategies.

An outgrowth of work on the MoWiTT facility has been the development of a new heat-flow meter concept. Instead of the usual method of measuring the temperature difference across a known thermal resistance using a deposited thermopile, this heat-flow meter uses resistance thermometry to measure the temperature difference (see Figure 5).

This innovation has produced a heat-flow meter that is more sensitive than the commercial variety and one that can be made economically in sizes large enough to cover entire walls. This heat-flow meter will be an integral part of the MoWiTT facility.

Fig. 3. Sample thermal transmittance vs. glass spacing for prototype windows. [a]Ordinary double glazing (solid points) and double glazing with aluminum foil on inside of both glass panes (open circles). [b]Double glazing with one (triangles) or two (inverted triangles) plastic films. [c]Double glazing with heat-mirror coating on plastic film, where the plastic film is mounted on the surface of one glass pane (squares) or suspended between panes (diamonds). (XBL 799-2917A)

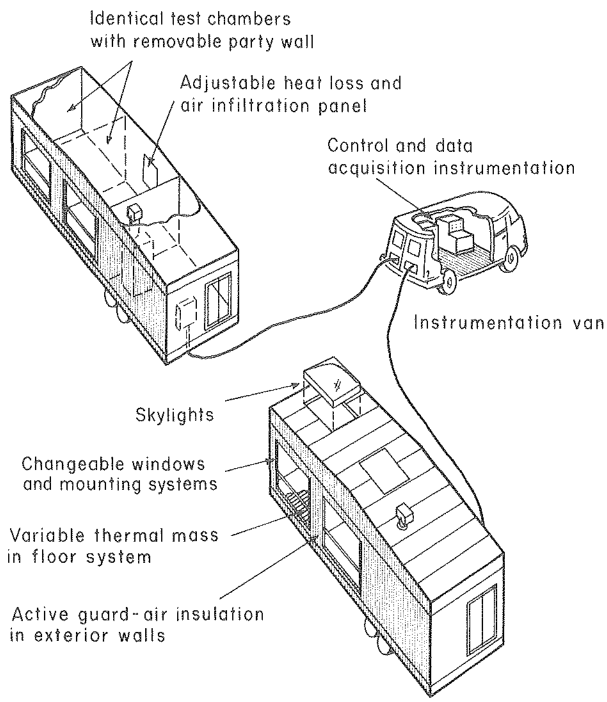


Fig. 4. Schematic view of Mobile Window Thermal Test (MoWiTT) facility. (XBL 811-30)

Fenestration Systems: Research, Development, and Demonstration

To provide real energy savings, window innovations developed by inventors in both the private and public sectors must find their way to the market and then to building installations in significant numbers. The transition from laboratory prototype to local building supply store is not a simple one. A variety of activities are needed to help establish the energy-saving potentials of new and existing window products. Demonstrations and field tests of products frequently lead us back to the laboratory to re-investigate thermal performance characteristics and the properties and durabilities of various materials. Several demonstration projects undertaken this year are described below.

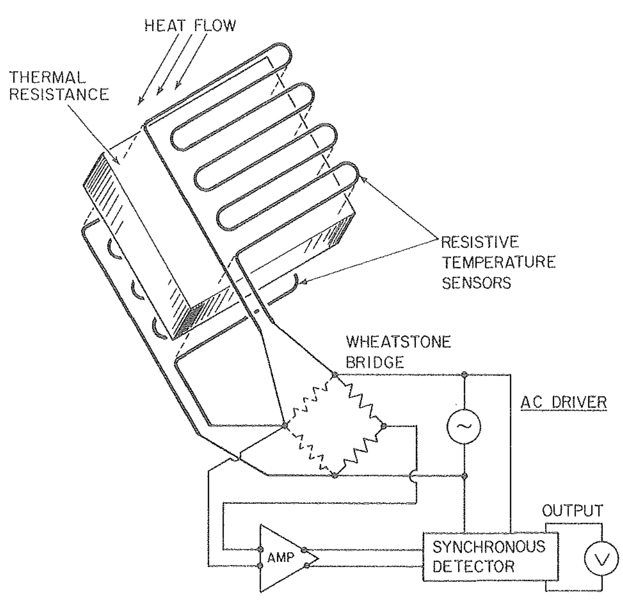


Fig. 5. Schematic view of heat-flow meter design based upon resistance thermometry. (XBL 8011-2627)

Transparent Heat Mirrors

A transparent heat mirror is an optical coating that is applied to a glass or plastic glazing material to transmit the full solar spectrum and reflect long-wave infrared radiation emitted by room temperature surfaces. By reducing the radiative component of thermal losses, the heat-transfer coefficient of a single- or double-glazed window is greatly reduced.

In prior years our program has supported several heat-mirror development projects. Several potential manufacturers are now at the point of introducing heat mirrors on both glass and plastic substrates. The coated-plastic substrate would be incorporated into a window unit either by being glued to glass or by being stretched across the air space in a double-glazed unit, creating an additional air space and, thus, even better insulating values. In 1980 several new computer programs were developed at LBL to provide thermal performance values for many different window configurations that incorporate heat-mirror coatings (see Window Performance: Analysis and Testing section).

For both the manufacturer and the ultimate buyer, the durability of heat-mirror coatings is an essential attribute. Poor resistance to corrosive and abrasive forces characterized many of the coatings first developed and still remains a significant obstacle to widespread and rapid commercialization. In 1980 we examined some of the generic failure mechanisms of coatings by means of sophisticated coating analysis equipment available at LBL, by visual inspections of the coating structure using a scanning electron microscope, and by chemical analysis of corrosion sites. A typical result from the scanning electron microscope is shown in Figure 6.

To prove to the architectural and engineering community that heat-mirror coatings will save energy without creating adverse effects, we conduct and support demonstrations of windows incorporating heat mirrors in new and existing buildings. In 1980 we identified and specified windows incorporating appropriate heat-mirror coatings for several demonstration projects. We expect to expand this type of activity in 1981 and to assist in analyzing and interpreting results.

High-Performance Sun-Control Systems

Although conventional Venetian blinds are reasonably successful in reducing solar heat gain through windows, their performance could be improved considerably. Stevens Institute of Technology, Hoboken (NJ), completed an experimental program to determine the shading coefficients of

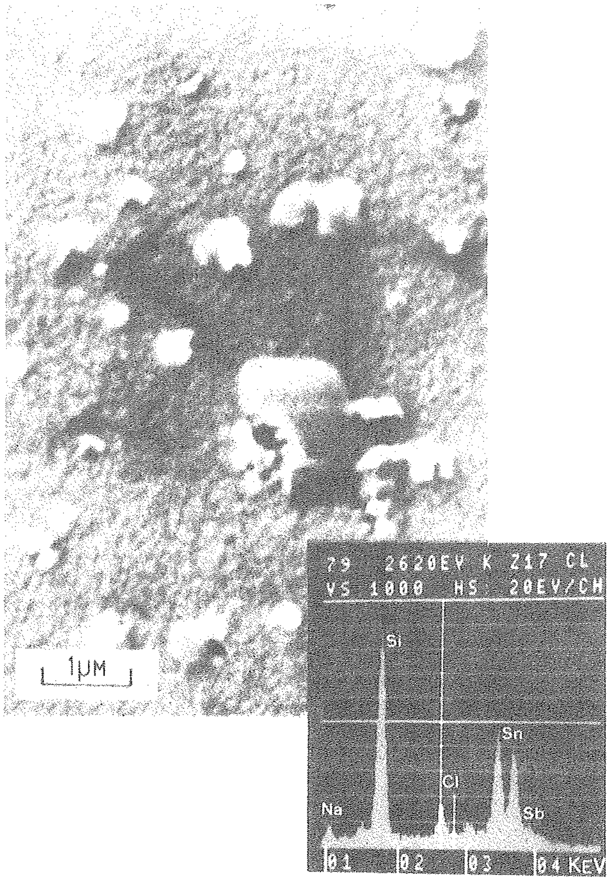


Fig. 6. Scanning electron micrograph of a degraded SnO_2:Sb heat-mirror on window glass. EDAX analysis revealed that surface particles were high in sodium and chlorine. This salt formation can be traced back to diffusive chemical reactions during deposition. (XBB 801-544)

many different types of venetian blinds using an indoor hotbox with an artifical sun. Results of extensive testing were used to generate tables that give the shading coefficients for various combinations of slat tilt, reflectivity, and solar-incidence angle. Although it was expected that some of the blinds with highly reflective surfaces would have shading coefficients as low as 0.2, none having shading coefficients below 0.4 were measured. Newer blinds having experimental coatings are expected to meet the lower value.

Optical Shutter Materials

Thin-film coatings having sun-control properties that can be changed by sunlight, temperature, or an applied voltage represent a long-term development goal of our program. In 1980 we completed an extensive literature search and review of electrochromic materials that might have potential as optical shutters for windows.

Movable Insulation Systems

Movable window insulating systems have attracted much interest, but there is uncertainty surrounding the real savings that can be achieved through their use. One such device, developed by the Insulating Shade Company of Branford (CT), consists of multiple layers of aluminized plastic that separate when the shade is pulled down. The air spaces thereby created are bounded by reflective surfaces, which create a high thermal resistance. Two hundred of the shades were installed in a university dormitory. Building energy consumption was monitored and occupant use patterns studied. Test results demonstrate that, properly managed, movable window insulation reduces building energy consumption. A detailed technical report will be issued on our results.

Selective-Reflectance Coatings

Reflective and/or tinted glass is widely used in many commercial buildings to reduce solar impact and, thus, the energy required for air conditioning. This glazing, however, also reduces the amount of daylight entering interior spaces and thus potentially increases the use of electric lighting. An optical coating that selectively reflects short-wave infrared rays (which account for approximately one-half of the sun's radiation) but transmits visible light could, ideally, reduce cooling loads by 50% without reducing available illumination. Under subcontract, Kinetic Coatings, Inc. of Burlington (MA), has used novel ion-beam sputtering techniques to produce such a coating that is durable and weather-resistant and can be applied to the outside of a window.

Now in the last phase of their subcontract program, Kinetic Coatings has demonstrated that coatings of high quality and good uniformity can be deposited on a thin plastic substrate in a roll-coating process. Coatings tailored to four building applications (residential, new and retrofit; commercial, new and retrofit) were produced and tested in 1980.

As noted earlier, durability of window coatings is a critical issue, for coated plastic glued directly to existing windows must withstand UV exposure, thermal cycling, abrasion, atmospheric pollutants, and cleaning agents. In previous years a wide range of selective-reflectance coatings and protective layers were produced and tested for both optical performance and weatherability. Multilayer metal-dielectric coatings deposited on polyester and polypropylene substrates have shown excellent durability in exposure tests conducted to date.

Because coating durability has been the key uncertainty restricting the development of successful energy-conserving products, we developed a materials science analysis and test capability in 1980. We can now examine the physical structure of coated samples by transmission and scanning electron microscopic techniques, and analyze the chemical composition of film defects by auger spectroscopy and EDAX techniques. Figure 7 shows the type of data generated by this analysis.

Air-Flow Window Systems

Another category of high-performance window systems are those known as air-flow windows. In these systems a stream of air flowing between the

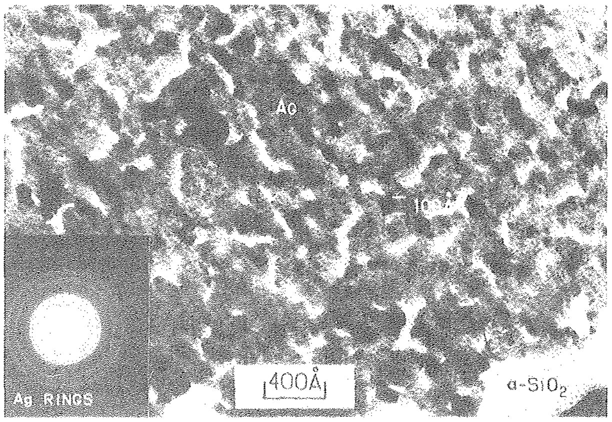


Fig. 7. Transmission electron micrograph (bright field at 100 kv) of an S_iO_2/Ag heat mirror. The polyester substrate was removed for this investigation. Diffraction information reveals very fine silver crystallites along with amorphous SiO_2. (XBB 801-543)

panes of multiple-glazed windows acts as a heat-transfer fluid. Solar gain can be either collected or rejected as required, and daylighting can be fully utilized throughout the year. A design approach that has been used in Europe for many years involves integrating the window into the heating, ventilating, and air-conditioning (HVAC) system and exhausting room air through the glazing cavity. Venetian blinds in the glazing cavity can be adjusted to allow optimum daylight penetration, to control the glare of direct sunlight, and to function as solar absorbers. By means of the air flow, solar gain is either rejected to the outside or distributed through the HVAC system as required (Fig. 8).

Under subcontract, windows from two manufacturers, one domestic and one European, were tested during 1980 in a full-size test building at the University of Utah. Each window was tested separately and in side-by-side comparison with a high-quality conventional window. Performance data were taken during the full range of local weather conditions. These data are presently being analyzed.

Although the first cost for such windows is higher than for conventional windows, the prospect for widespread commercialization is attractive. The window package fits within currently accepted architectural vocabulary, utilizes conventional components having well established reliability, and offers multifunctional control of energy performance.

Another approach being investigated is one developed at the Environmental Research Laboratory (ERL) of the University of Arizona. Their window system, designed primarily for residential application, combines existing commercially available components to achieve control of energy flows, and relies on gravity-induced draft for heating, and on overpressurization of the building by an evaporative cooler for cooling. ERL has completed summer

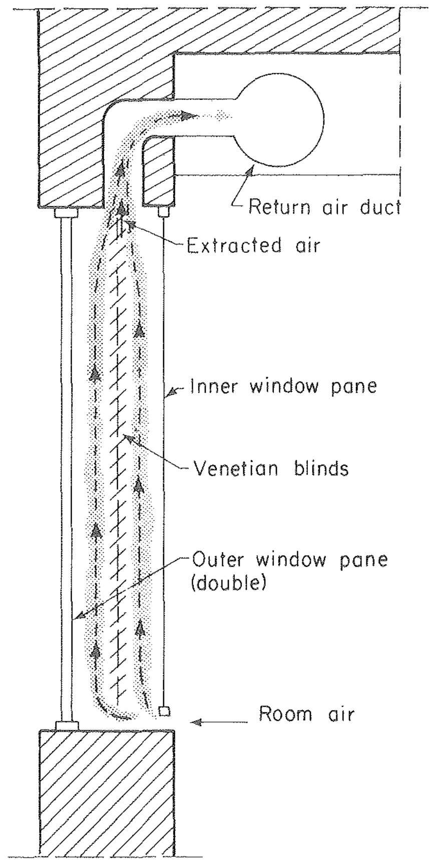


Fig. 8. Schematic cross-sections for air-flow window system. (XBL 7912-13366)

and winter testing and has written computer simulation codes. The computer codes have been validated against the test data. Performance data are being correlated with ASHRAE solar heat-gain tables in order to provide a design tool having widespread applicability.

Preliminary results of performance tests on these air-flow windows are promising. Industry interest has been growing because of the multifunction control options, and it is expected that U.S.-made units will be commercially available in 1981.

Daylighting

Windows and skylights provide daylight in buildings, thus reducing both electric lighting use and peak-power requirements. In addition, because natural lighting has always been valued by architects and building occupants, daylighting studies represent an area where good architectural design and significant energy savings are mutually supportive goals.

Studies of potential annual energy savings from maximum use of daylight in buildings require data on daylight availability (including the frequency and intensity of daylight). No source for such data currently exists for most of the United States. In 1979 the Pacific Gas & Electric Company 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 thirteen pyranometers and photometers was installed to feed readings to a data-acquisition system at fifteen-minute intervals (see Figure 9). Preliminary results from the first year of monitoring suggest strong linear correlations between illumination and insolation -- a finding that encourages us to believe that daylight availability data can be generated from existing measurements of solar radiation. Figure 10 illustrates one technique for analyzing and displaying the data. Daylight illumination on a vertical east-facing surface is shown as a set of contour lines for all hours of the day throughout the year. A generalized method for developing illumination availability data from insolation is now being developed based upon data collected in 1979 and 1980.

Accurate and efficient daylighting design methods must be conveyed to building designers if they are to successfully incorporate daylighting designs in buildings. Several approaches are in progress as part of the overall LBL program in this area: Under subcontract, Renssallear Polytechnic Institute in New York began development in 1979 of a computer program to predict daylight illumination in interior spaces. A working version of the program that can compute illumination for non-rectangular geometries and can treat several types of window-shading devices was completed in 1980. Additional modeling capabilities are now being added. A team at the University of Washington has developed a graphic design method that employs transparent overlays for daylight predictions. This method, meant to be used by architects at an early stage in the design process, was tested before an audience of professional designers in 1980. Several parallel modeling efforts were completed at LBL. A technique for predicting daylight illumination from clear and overcast skies was completed in 1979, and, while relatively accurate, it requires repetitive calculations. In 1980 this model was adapted for use with a programmable hand calculator.

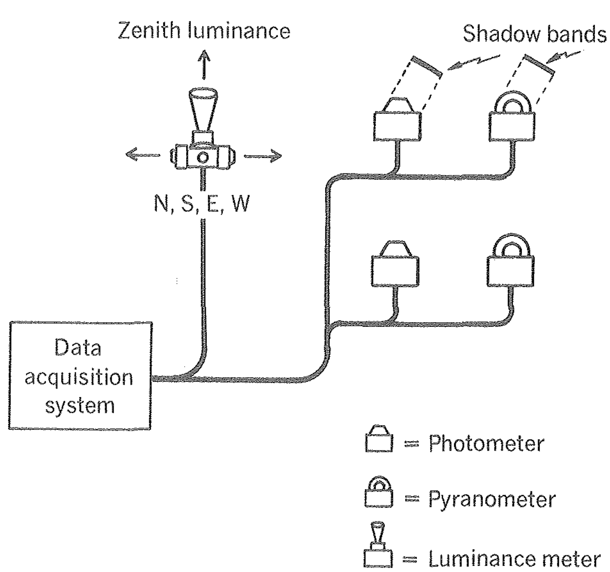


Fig. 9. Schematic of photometric and radiosensor array on rooftop for determining insolation/illumination correlations.
(XBL 796-10182)

An effort to incorporate daylighting analysis capabilities into a building energy analysis program (DOE-2) continued in 1980. Although the ultimate goal is to incorporate a daylighting algorithm within DOE-2, a simplified approach was developed and completed in 1980. The program calculates the average hourly effect that daylight will have on building lighting schedules. Results are presented in the form of extensive tables that become input parameters for DOE-2.

The 24-foot-diameter artificial sky dome, 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. We are now installing improved lighting controls in the dome in order to simulate 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 will be able to predict daylighting illumination patterns in real buildings. The artificial sky already has been used for research and teaching purposes, as well as by architects working on daylighting features for new office buildings (Fig. 11).

To test the combined effects of sky and direct sun, without collimation or horizon errors, four scale models, 3 feet by 5 feet each, were fabricated and mounted on the roof of our building. These test cells incorporate a tilting base so that the sun's incident angle can be varied over a wide range.

Although direct energy savings from daylighting are the main interest of building owners, significant potential savings might also accrue from savings on peak-power demands. For example, a computer simulation study of energy/peak power relationships in a 31-story office building was undertaken in 1980 for two climate conditions. Preliminary results indicate that savings on the cost of time-of-day utility pricing as well as peak-demand charges can equal or exceed the direct energy savings from daylighting in some buildings. This finding suggests that the economic benefits to building owners of employing daylighting strategies can be even greater than those predicted from an analysis of direct energy savings. Such peak-power reductions, if properly utilized by utilities, might also assist their own management efforts.

Because direct sunlight is the only natural light source having sufficient intensity and collimation to illuminate interior spaces deep in a building, various design approaches have been studied to exploit beam daylighting in buildings. During the past four years we have examined the feasibility of mounting reflective and refractive devices in windows to take advantage of direct sunlight. Limited computer simulation and model studies have been conducted; however, additional study

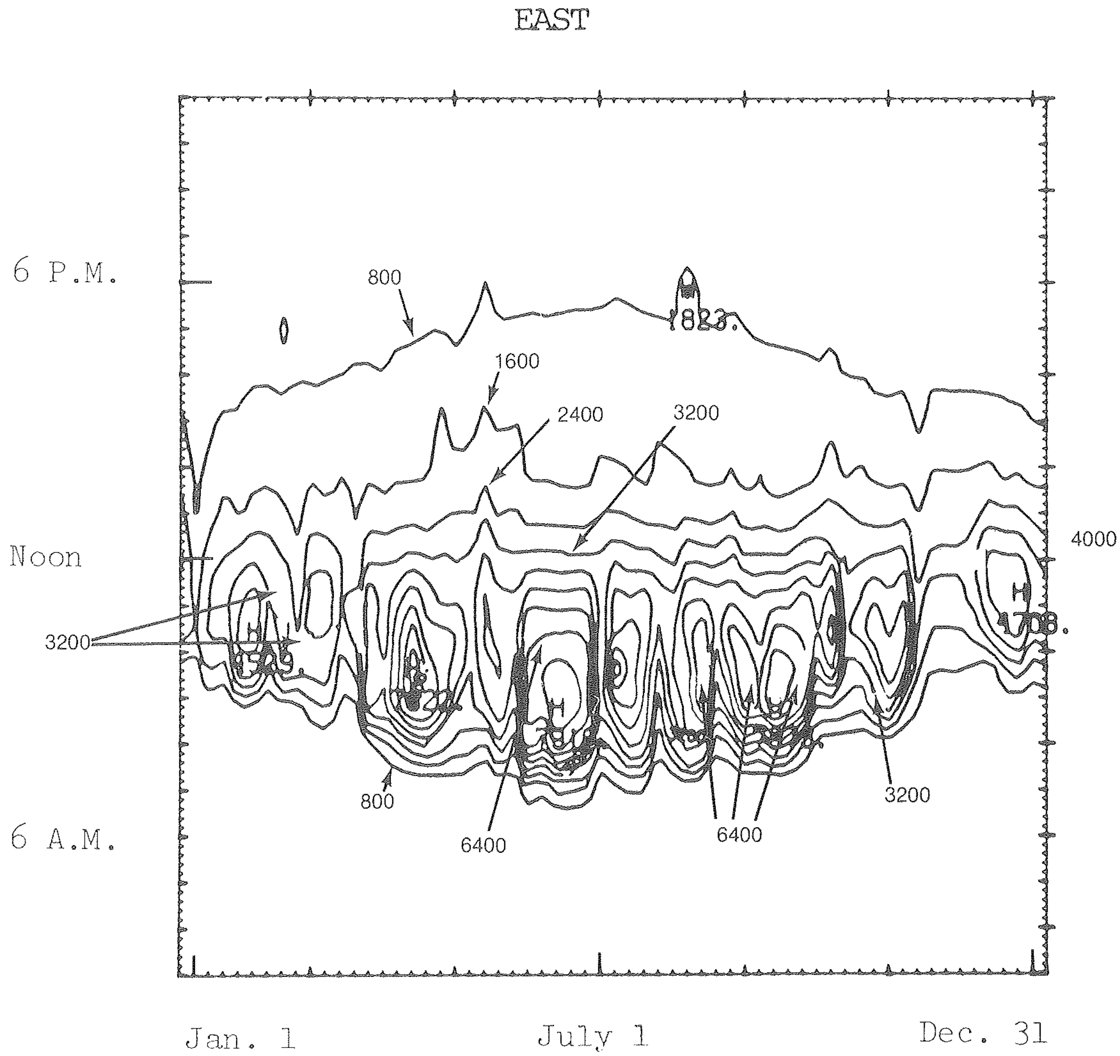


Fig. 10. Vertical illuminance on an east-facing surface as measured during 1979 at the PG&E building in San Francisco. Interval between contour lines is 800 footcandles. (XBL 813-8789)

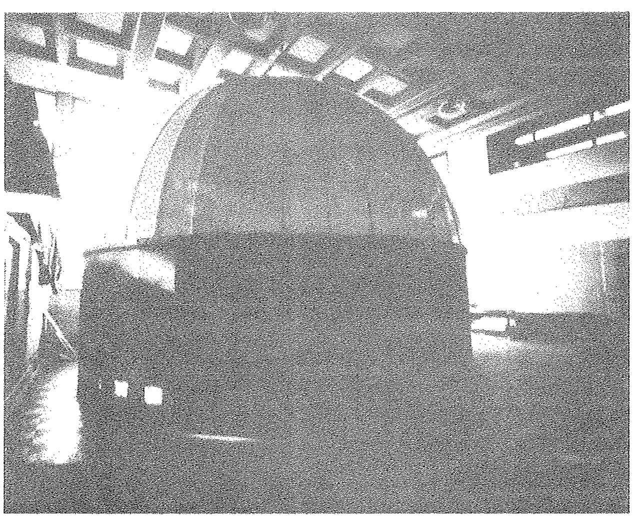


Fig. 11. Exterior view of 24-foot-diameter hemispherical sky simulator for daylighting studies. (CBB 803-2837)

is needed if we are to validate their technical feasibility and cost-effectiveness.

Out of our belief that daylighting techniques would be more widely used by architects and builders if technically accurate information was more accessible to them, we have collaborated with the U.C. College of Environmental Design to develop a comprehensive educational program on daylighting. A draft of our Daylighting Resource Package, aimed at educators and building designers and prepared in collaboration with the Illuminating Engineering Society, several universities, and daylighting experts throughout the country, has been produced. The first draft was discussed in June 1980 at a week-long workshop in Berkeley attended by 35 university educators and 15 other experts and observers. During the next two years, the resource package will be refined, expanded, and disseminated widely.

Program Planning and Support

An early draft of a program plan for the Windows and Daylighting program was completed and, after revision, will be circulated for public comment and review. In addition to identifying the research and development required to achieve the full energy-conservation potential of windows and skylights, the plan will help define the links between this program and related DOE Conservation and Solar programs. Technical and non-technical information on energy-conserving window designs derived from this research program will be transmitted to architects, engineers, manufacturers, inventors, suppliers, code officials, and researchers via a new publication, Windows for Energy-Efficient Buildings. This brochure reports on the latest developments, patents, new materials and products, legislation, etc., of concern and interest to this audience. The first issue was published in 1979 and a second in 1980. Circulation now exceeds 6000. In the process of generating material for this publication, extensive product files, patent files, bibliographies, and related informational resources have been compiled and readied for putting into computer data bases. This capability will enable us to make fast and extensive searches.

Another important aspect of our program is to participate in national and international research programs. In 1980, LBL staff represented DOE at an International Energy Agency (IEA) meeting in Delft, Holland, on the Energy Performance of Windows. The participating countries agreed to share research results and to embark on collaborative research efforts.

PLANNED ACTIVITIES FOR FY 1981

Window Performance: Analysis and Performance Testing

Additional modifications will be made to the window computer model THERM to permit calculation of heating and cooling loads resulting from new materials systems and window designs for both residential and commercial buildings. An intercomparison between THERM (a sophisticated window model coupled with a simplified building algorithm) and DOE-2 (a sophisticated building model with relatively simple window algorithms) will be completed. We will begin analyzing results from extensive parametric modeling of the performance of various window-insulating and shading devices, with the complementary goals of developing more detailed insights into subtleties of performance and creating procedures to simplify and communicate results to architects and engineers.

Studies of window system performance in the calibrated hotbox will be continued. Window system prototypes incorporating new state-of-the-art coatings and glazing materials will be tested. The primary performance-testing effort will focus on the final design and construction of the first unit of the MoWiTT facility so that it may be calibrated in the field in late 1981.

Fenestration Systems: Research, Development, and Demonstration

It is expected that the first commercially available windows incorporating heat mirrors and other selective-reflectance coatings will reach the market in 1981. We will continue to test and model the net performance of these products in an effort to develop guidelines for their optimal utilization. Data from several demonstration projects will be reviewed and analyzed. Coating durability, a central problem area, will be investigated in our materials science program, a limited effort will be undertaken to identify new heat-mirror materials having improved coating properties, and thin-film/substrate interactions will be studied. Additional tests of candidate materials for optical shutters will also be conducted.

Test data collected in 1980 on the performance characteristics of air-flow windows will be analyzed, and performance characteristics will be compared to those of other heat-collecting window designs.

Daylighting

A complete summary of daylighting availability data based upon analysis of three full years of data from our San Francisco site will be completed in 1981. A recommended correlation between radiation and illumination data will be developed.

The simulation capability of our artificial sky will be completed in 1981, and improvements will be made in modeling variable ground reflectances. Plans will be completed to add a sun simulator, although construction will not begin until 1982. As the facility's capabilities are improved, we plan to perform an extensive series of tests comparing results from the indoor simulator, from outdoor tests, and from the computer modeling studies as a means of defining the inherent limitations and constraints of all model-testing studies.

In the area of daylighting computations, the large computer model will be completed and used for parametric modeling studies of various fenestration and building designs. The simplified method for adding daylighting capabilities to DOE-2 will be replaced with a more powerful and flexible model that operates within the hourly calculations of DOE-2. A working version will be completed in 1981, and plans for improving the modeling capabilities will be completed in 1982.

Initial studies of the energy savings attributable to daylighting will be expanded to include the effects of daylighting and lighting controls on a building's peak-power loads. An analysis of prior work on glare from windows and its impact on the potential savings from daylighting will also be undertaken.

A second draft of the Daylighting Resource Package will be completed and distributed for review and comment. Work on a daylighting directory and bibliographic data bases will continue.

Program Planning and Support

A draft of the program plan for Windows and Daylighting will be circulated for public review and comment. Development of bibliographic and product data bases will be continued. Another issue of Windows for Energy-Efficient Buildings, this one centered on daylighting, will be published. We will continue collaborative studies of window performance with other international research groups.

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See publications list at the end of this chapter.

ENERGY-EFFICIENT LIGHTING PROGRAM*

S. Berman, R. Clear, J. Klems, F. Rubinstein, S. Selkowitz, and R. Verderber

INTRODUCTION

The Lawrence Berkeley Laboratory has managed the National Lighting Program for the Department of Energy for the past four years. The goal of this program is to bring about a 50% reduction in our nation's energy consumption for lighting by the mid-1990s. We plan to achieve this goal by accelerating the introduction of cost-effective energy-efficient lighting products, designs, and procedures that will enhance the comfortable performance of visual tasks as well as productivity.

Compared to other energy-efficient retrofit potentials, improved lighting will have a more rapid market penetration because the replacement rate of lighting sources and systems is high. We estimate that if energy-efficient lighting products begin to enter the market during the next couple of years, the nation's annual energy consumption for lighting can be reduced by more than 200 billion kilowatt-hours by 1995. This energy savings is equivalent to 381 million barrels of oil annually, or more than 1 million barrels of oil equivalent per day--an amount greater than could be produced by the proposed synfuel program.

The energy-efficient lighting program focuses on two major tasks. The first is the development, testing, and demonstration of energy-efficient light sources and equipment including (1) solid-state fluorescent ballasts; (2) switching and lighting controls; and (3) energy-efficient light bulbs. The second area concerns the science of illumination and illuminating systems, including (1) the physics of light sources and equipment; (2) visibility, illumination, and performance; and (3) health and environmental effects of illumination.

Each of the above projects, with accomplishments realized in 1980 and the activities planned for 1981, is described below.

* This work was supported by the Assistant Secretary for Conservation and Solar Energy, Office of Buildings and Community Systems, Consumer Products Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

ACCOMPLISHMENTS DURING FY 1980

Solid-State Fluorescent Ballasts

This project has been concerned with operating fluorescent (low-pressure gas-discharge) lamps at high frequency to improve their efficiency. In the first stage of the program, we evaluated electronic ballast designs in a controlled laboratory environment. Our results showed that electronically ballasted lighting systems were 20% to 25% more efficient than standard systems and improved regulation, eliminated flicker, and could dim gas-discharge lamps.[1] In the next stage, we examined the performance of these electronically ballasted systems in a real environment (the Pacific Gas and Electric Company headquarters in San Francisco) where more than 700 ballasts had been installed on two floors. Although the results of this demonstration identified several reparable design flaws, they clearly indicated that electronic ballasts are a viable energy-efficient alternative to core-coil ballasts, as evidenced by the fact that, after three years, the electronic ballasts are still in operation in the PG&E building. The positive results that have emerged from these studies[2,3,4] have served as a basis for the advanced circuit designs that represent the final stage of commercialization.

In 1980 the electronic ballast systems were assessed for total performance; that is, we considered all of the improved attributes of the electronically ballasted system -- the tighter system control brought about by improved voltage regulation, the regulation of light output, and the ability to dim lamps, in addition to the 25% "intrinsic" improvement in system efficiency. Among our findings, now being compiled for publication as an LBL report,[4] we demonstrated that total energy savings can be as high as 40-70%.

Another significant accomplishment during 1980 was the demonstration of electronic ballasts in the Veteran's Administration Hospital in Long Beach, California. This demonstration was designed to determine whether the radio frequency interference (RFI) radiated and/or conducted by electronic ballasts adversely affected any of the sensitive examining or monitoring equipment in a hospital. We replaced standard ballasts with electronic ballasts near a CAT scanner, diagnostic equipment, and in a coronary ward. We monitored the equipment both before and after the replacement. The data are now in the final stages of analysis,[5] but a preliminary review shows that the electronically ballasted system is as safe regarding RFI as is a standard core-coil ballasted system.

High-Pressure Sodium (HPS) Ballasts

A project to develop electronic ballasts for high-pressure sodium lamps was begun in 1980. Three subcontracts were initiated for the development of circuits to operate 150-watt, 200-watt, and 400-watt HPS lamps at high frequency. In the initial phase, we assessed the performance of the subcontractors' electronic ballast systems in a controlled laboratory environment and compared their performance with that of the same HPS lamp operated with a high-quality core-coil ballast.[6] The results, presented in Table 1, show that both 120- and 277-voltage input electronic ballasts can be designed, and that electronic ballasts can improve the efficiency of both the ballast and the lamp by as much as 15%. In addition, efficient electronic ballasts can be designed to have high power factors. For HPS lamps used in an area that has rotating machinery, the percent flicker was improved to the extent that stroboscopic effects from lamps operated at high frequency were eliminated.

Besides the improvement in intrinsic efficiency, approximately 15%, the electronically ballasted HPS lamps also save energy because of the constant wattage that the electronic ballast supplies to the lamp throughout its life. The total energy savings amounts to approximately 26%. Standard ballasts supply excess power to the lamps due to the reduction of the arc impedance that occurs as the sodium migrates. The average excess, both of light and of energy consumed, is approximately 20% to 30%. Furthermore, as an HPS lamp ages, the voltage applied must be increased to keep the lamp from being extinguished. For testing purposes, we simulated this characteristic by heating the lamp and plotting lamp power versus lamp voltage for both core-coil and electronically ballasted lamps (see Figure 1). This evidence again supports our assertion that the real energy savings from electronic ballasts can be greater than that gained by the intrinsic efficiency of the system, and that the 26% savings should be considered in determining payback or life-cycle costs on the design change.

Switching and Lighting Controls

Strategies and Techniques

The primary goal of the lighting-control project is to evaluate the energy savings realizable by employing different lighting-control strategies. Given this information and the cost of an automatic control system, one can calculate the expected payback, or return, on investing in such strategies.[7]

To evaluate all the desired strategies (daylighting, tuning, scheduling, and load shedding) and techniques (local and group controls; step and continuous dimming), two demonstration sites were required. We selected General Electric and Honeywell as subcontractors, and requested that they install their prototype systems on one floor of the World Trade Center office building in New York (G.E.) and in the Pacific Gas and Electric building in San Francisco (Honeywell). Both of these installations became functional in 1980, and

Table 1. Performance testing of high-pressure sodium (HPS) solid-state ballasts.

	150-Watt hps		200-Watt hps		400-Watt hps	
	Core-Coil	Electronic	Core-Coil	Electronic	Core-Coil	Electronic
Input						
voltage (volts)	120	120	277	277	240	277
power (watts)	189	187	282	230	447	438
power factor	0.48	0.93	1.00	0.95	0.97	0.78
Output						
voltage (volts)	54.4	52.5	116	93	96	96
power (watts)	149	154	215	198	376	324
light (lux)	3500	3840	9440	9160	18,330	19,070
Efficiency						
ballast	0.788	0.824 (+4%)[a]	0.76	0.86 (+12%)	0.84	0.74 (-14%)
lamp (lux/w)	23.5	24.9 (+6%)	43.9	46.3 (+5%)	48.8	58.8 (+17%)
system (lux/w)	18.5	20.5 (+10%)	33.5	39.8 (+16%)	41.0	43.5 (+6%)

[a] Figures in parentheses indicate the percentage change in efficiency from core-coil to electronic ballast system.

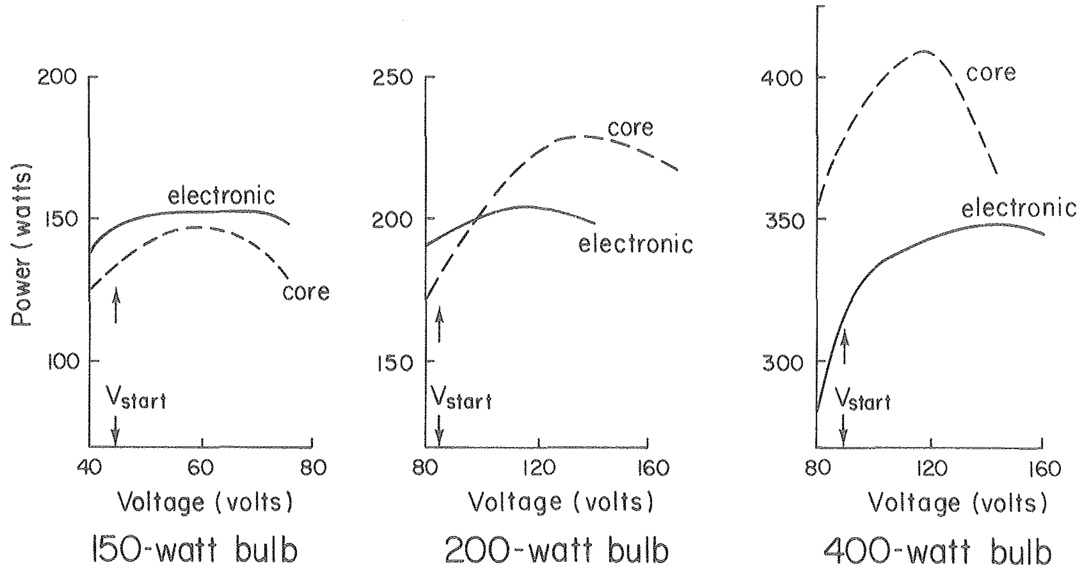

Fig. 1. Comparison of power voltage curves for core-coil and electronically ballasted high-pressure sodium lamps (150-watt, 200-watt, and 400-watt). Electronically ballasted lamps maintained constant wattage outputs that were consistently closer to design levels. (XBL 8011-2625A)

were tested in place prior to initiating performance experiments. Near the end of the year, data were obtained which confirmed our estimates of the energy savings that can be realized through automatic controls.

The General Electric system used a microprocessor to control the switching of each fixture; that is, to turn it on or off separately. Figure 2 shows the power usage for one day's operation using this tuning and scheduling strategy. The tuning (de-lamping) turns off fixtures in aisles and in work areas where a full light level is not required. The scheduling strategy lowers light levels to 1/6 in the evening for the cleaning crews, who do not require the high light levels used in the daytime.

The initial daily energy use was 2256 kWh. Tuning reduced the daily use to 1561 kWh. The scheduling strategy reduced the daily usage to 1020 kWh. At an energy cost of $0.10 per kWh (the cost of electric energy in New York City), the savings is $123.60 per day, or more than $32,136 per year for a single floor.

The Honeywell system used a computer to control the light level of a large group of lamps, each of which can be dimmed continously over a large range of light levels. Figure 3 plots the power usage for a single day at the PG&E building in San Francisco. A photocell senses the light level of the outer zones of the building and, when specified light levels are exceeded because of the contribution of daylight, the light supplied is electrically reduced to maintain the prescribed level of illumination.

For the day these data were obtained, the energy use in the offices in the outer zone decreased from 201 kWh to 147 kWh, or 27%. At a cost of $0.05 per kWh (the cost of electric energy in the San Francisco area), the savings could be more than $702 per year.

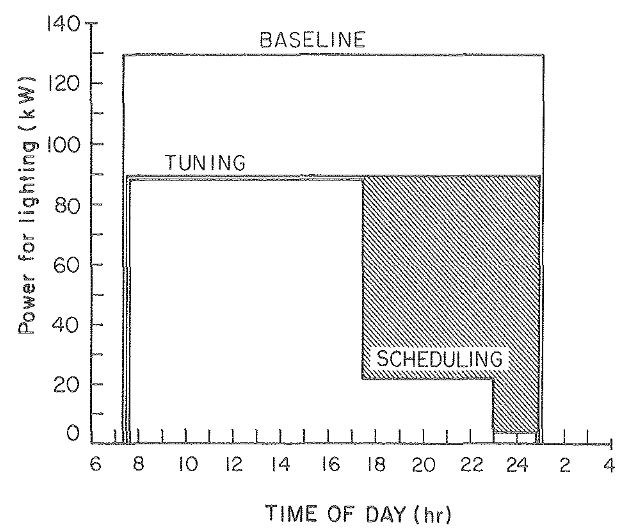

Fig. 2. Results of two approaches to reducing electrical energy consumption on one floor of the World Trade Center, New York. The tuning technique, which adjusts the light level of fixtures to the needs of the task in each area, decreased the baseline or normal energy use by 40 kilowatts per hour. Usage was further reduced at night by the scheduling technique, which lowered light levels to 1/6 daytime use. (XBL 8011-2351)

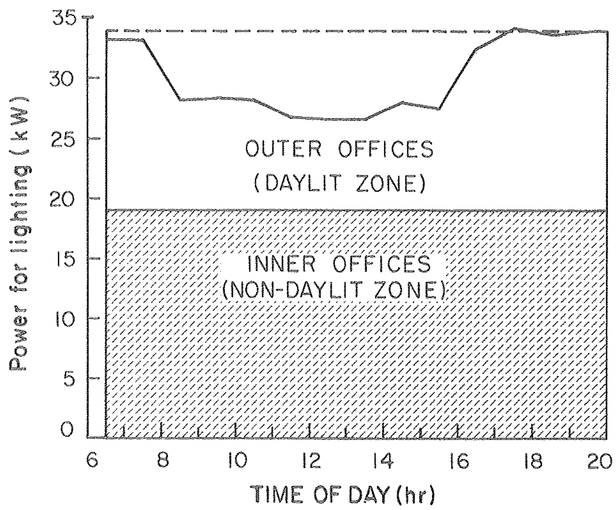

Fig. 3. The daylighting strategy used to reduce electrical consumption in the PG&E building, San Francisco reduced the energy consumption for perimeter offices by 27% but had no effect on the lighting energy required for interior offices (shaded area). (XBL 8011-2350)

Energy Efficient Light Bulbs (EELB)

The objective of our EELB project is to develop energy-efficient light sources that can be used in incandescent sockets (Edison sockets), and that will approach efficacies of 40 to 50 lumens per watt (as compared with the 17 lumens per watt characteristic of a 100-watt incandesecent bulb).[8,9] The national energy consumption for incandescent light is about 180 billion kWh annually. The potential savings associated with replacing 50% of the incandescent lamps (17 lumens/watt) with energy-efficient lamps (45 lumens/watt) is approximately 60 billion kWh, which is equivalent to more than 100 million barrels of oil—the amount needed annually to generate this electrical energy.

Near the end of FY 1980 we signed contracts to have four companies develop their EELBs. Among the objectives we specified for each contractor was the identification of any major technical barriers to production.

Physics, Visibility, and Health

Physics and Engineering Lighting Laboratory

In 1976, a small laboratory facility, designed primarily to measure the relative performances of electronic ballasts and the relative light outputs of light sources, was set up in conjunction with the Windows Laboratory at the College of Environmental Design in Wurster Hall on the University of California campus at Berkeley. Since then, our program has expanded to include involvement in standards committees, e.g., American National Standards Institute (ANSI), which requested LBL staff to propose specifications and testing procedures for high-frequency lighting systems, as well as to perform life testing for new energy-efficient lighting products. In addition to the above activities, we required greater in-house technical competence when we began the EELB program. The laboratory is now responsible for in-depth analysis of the generation of visible light from low-and high-pressure gas discharge, including plasma effects at high frequencies and radio frequency interference (RFI). Because of these added responsibilities, a larger Physics and Engineering Lighting Laboratory was designed in FY 1980 and is now located in Building 46 on the LBL site. The new laboratory includes an area for testing lighting systems (maintained at 25 ± 1°C in order to obtain absolute measures of light output under controlled conditions), as well as a general laboratory area and a lamp-life testing area. The necessary equipment—high-frequency wattmeters, a seven-foot integrating sphere, a spectral-radiometer, and standard certified NBS light sources—has been purchased to provide absolute measurements of light output from light sources as well as to measure the spectral distribution of the visible radiation.

The first project for the new laboratory, undertaken in 1980, was a fundamental study of the H_g isotope mixture in a discharge in order to determine the effect of optimizing the isotope mixture for the generation of the 253.7 nanometer line. Lamps generally use the isotope mixture of naturally occurring H_g. We expect that the efficacy of the low-pressure gas discharge can be increased 5% to 10% by enriching the natural mixture with H_g 196. This improvement will substantially increase the total light output of compact fluorescent lamps.

Visibility and Productivity Laboratory

The connection between visibility in commercial/industrial buildings, as determined by lighting codes and/or design practices, and the productivity of the work force has become an important issue because of the rapidly escalating price and scarcity of electricity and the coincident loss of much of the nation's competitive position in person-hours per dollar of value added. Target light levels used under existing standards allow for a broad comfort/safety margin—a reasonable practice when energy prices and availability were not in question. Disagreement about how much visibility is needed to assure efficient operation and comfort has, in fact, resulted in several different standards, and resolving these differences to arrive at a "best" standard is hampered by lack of information about the relationship between visibility and worker productivity. A review of field studies in this area shows contradictory results.

Because statistically validated data on the relationship between productivity and visibility are critical to determining cost-effective lighting levels, LBL and the University of California School of Optometry developed a joint program in 1980 to examine, in a laboratory setting, the effects of physical lighting parameters such as intensity, spectrum, distribution, and polarization on performance and productivity, using subjects whose visual capabilities are known (e.g., age, corrected or uncorrected 20-20 vision, etc.). To date, the group has published a critical review of the basis for the Equivalent Sphere Illumination concept of quantifying the quality of illumination.[10] In addition, a paper has been presented at the national Illuminating Engineering Society Conference at Dallas, Texas on the cost-effectiveness of visibility design procedures.[11]

PLANNED ACTIVITIES FOR FY 1981

Solid-State Fluorescent Ballasts

In the next phase of this project, we will examine some advanced electronic ballast designs from which we anticipate further improvements in efficiency. We will also evaluate the reliability of these ballasts when voltage surges occur, as they do commonly in real situations.

Switching and Lighting Controls

Further studies are needed to optimize lighting layout designs. One aim is to provide daylighting designers with a way to determine the best position for the sensing photocells. We will obtain this information for areas facing north, south, east, and west, in different parts of the country, and for different types of building spaces. By the end of the next fiscal year, we expect to have developed design techniques that more effectively use natural illumination.

Energy-Efficient Light Bulbs (EELB)

Four viable energy-efficient light bulbs--the compact fluorescent lamp, the coated filament lamp, the magnetic-arc spreading fluorescent lamp, and the electrodeless fluorescent lamp--will be studied in FY1981. While all these designs are more efficient than an incandescent lamp, each has limitations that hinder commercialization. In the first phase of this program, each participating manufacturer will deliver ten laboratory prototypes to LBL for our evaluation of any design or performance shortcomings.

Although the compact fluorescent lamp requires no major changes, its application is currently limited to lower output lamps (less than 1500 lumens). We will study highly efficient phosphors and electronic ballasts, and gas fill with optimized Hg isotope mixtures to achieve light outputs of up to 2200 lumens (equivalent to a 150-watt 3-way lamp).

The coated filament lamp has not been assessed for life, efficacy, or quality control. In addition to determining the ultimate obtainable efficacy of this lamp, we will seek to determine how uniform a coating is required for reliable performance and whether that degree of uniformity can be manufactured commercially.

The electrodeless fluorescent lamp operates at 13 MHz and emits RFI, which can disturb radio and television receivers or computers and other sensitive electronic devices. Our task here is to develop a low-cost electronic ballast system for this lamp and to determine ways of minimizing RFI.

Health Effects Related to Environmental Artificial Lighting

Artificial lighting is now ubiquitous in the living/working environment. Although assertions of potentially harmful effects of artificial lighting on both health and performance have been circulated (especially in the lay community--e.g., Health and Light by John Ott and The Zapping of America by Paul Brodeur), no hard data exist in this area. We are initiating a new project to address the questions of reduced performance and health effects from artificial lights. We will begin by addressing three questions:

1. Are there populations whose eyes are sensitive to artificial lighting, especially in association with other environmental factors?
2. Do certain artificial lighting sources induce fatigue and increase the "work error" rate?
3. Do certain artificial lighting sources act as physiological "stressors" for certain individuals?

Until now, there has been a lack of coherence in the various protocols used by qualified investigators spanning the disciplines of engineering, biochemistry, psychometry, behavioral sciences, and neurophysiology, all of which are involved in any reasonably complete investigation of the human effects of artificial light. To address the potential long-term health effects from artificial lighting, as well as to identify potential environmental hazards of new products before they are introduced into the market, LBL is collaborating with the faculty of the University of California's School of Medicine in San Francisco where test facilities are currently being developed. We hope, in this collaborative effort, to verify, statistically, any aspects of artificial lighting that present hazards to fundamental biochemical and neurophysiological mechanisms.

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DOE-2.1 BUILDING ENERGY ANALYSIS GROUP*

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INTRODUCTION

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-2.0A, and, finally, DOE-2.1, has been guided by several objectives: (1) that the description of the building by the user be in quasi-English so that the input can be read and understood easily by non-computer scientists; (2) that, when available, the calculations be based upon well-established algorithms, i.e., the calculational procedures used should be acceptable to the engineering community; (3) that it permit simulation of commonly available heating, ventilation, and air-conditioning (HVAC) equipment; (4) that the computer costs of the program be minimal; and (5) that the predicted energy use of a building be acceptably close to measured values.

These objectives require compromises to be made. Higher accuracy, for example, can be purchased only at the cost of more detailed and time-consuming algorithms and more complex demands upon the user for data about the building being modeled. Considerable experience and user feedback has culminated in a program which has received much acceptance, and DOE-2.1 has been named by the Department of Energy as the standard evaluation technique (SET) of the Congressionally mandated Building Energy Performance Standards (BEPS).

Details of the development and structure of the DOE-2.1 program are available in past Annual Reports[1,2] and other published materials.[3-8]

ACCOMPLISHMENTS DURING FY 1980

The major accomplishment of FY 80 was the completion of the DOE-2.1 edition of the program, including its accompanying documentation.[9-12] LBL was assisted in this work by the WX-4 Group at Los Alamos Scientific Laboratory (LASL), which was responsible for developing and testing the active solar simulator (known as CBS, for the Component Based Simulator) and for producing the DOE-2.1 Reference Manual. In addition, the DOE-2.1 User Coordination Office at LBL, charged with coordinating user services at commercial computer service bureaus, universities, and national laboratories, has published the first of a periodic journal, entitled "DOE-2 USER NEWS", which serves to keep the user community informed about the latest developments and uses of the program. We have also carried out the first of several training sessions designed to train trainers of DOE-2.1 users.

Among the additions and improvements that distinguish DOE-2.1 from its predecessor (DOE-2.0A) are its ability to create and to store custom weighting factors, its restructured simulation of the HVAC systems, and its integration of the active solar simulator.

Custom Weighting Factors and Thermal Balance Loads

DOE-2.1 has been substantially improved over DOE-2.0A by adding two new techniques to calculate

* This work was funded by the Office of Buildings and Community Systems, Architectural and Engineering Systems Branch, Buildings Division, U.S. Department of Energy under Contract No. W-7405-ENG-48.

heating and cooling loads. The development of both techniques was stimulated by the inadequacy of the technique used in DOE-2.0A to predict energy use in buildings with high thermal mass where solar heat gain is an important component of the loads. In the "Custom Weighting Factor" method, which is now documented and available in DOE-2.1, a fast-executing transfer function approach is used. The second new method, called "Modified Thermal Balance" and now being tested, is a more accurate, but also a more time-consuming, technique. The user will ultimately be able to choose the technique best suited to the application at hand.

Custom Weighting Factors

In this approach the heat gain from lights, solar radiation, people, equipment, and conduction through the envelope are calculated for each hour. Part of each of these gains will appear immediately as a load on the HVAC system; the rest will be stored as heat in the walls, the floor, the furniture, and other mass in the building and will be released over time to the room air. The time delays involved in this process are accounted for by the weighting factors. Mathematically, the cooling load in hour t in Btu/hr due to the i^{th} source (Q_t^i) is given by:

$$Q_t^i = V_0 q_t^i + V_1 q_{t-1}^i + V_2 q_{t-2}^i + W_1 Q_{t-1}^i + W_2 Q_{t-2}^i,$$

where

q_{t-j}^i = the heat gain in hour t-j (Btu/hr)

Q_{t-j}^i = the cooling load in hour t-j (Btu/hr)

V_j, W_j = the weighting factors

i = the index for the source of heat gain (lights, solar, etc.)

The net load for a particular hour is the sum of the Q_t^i over all of the sources. A similar transfer function relationship relates the cooling loads to the actual space temperatures and the heat extraction rates for that hour and previous hours.

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] Studies by Los Alamos Scientific Laboratory (LASL) showed that the ASHRAE weighting factors lead to inaccurate results for buildings where direct gain is important. Figure 1 shows temperature measurements for the LASL direct-gain test cell as well as the predictions yielded by using the ASHRAE weighting factors. There is a 7°F space temperature difference at the peaks between the predicted and the measured data.

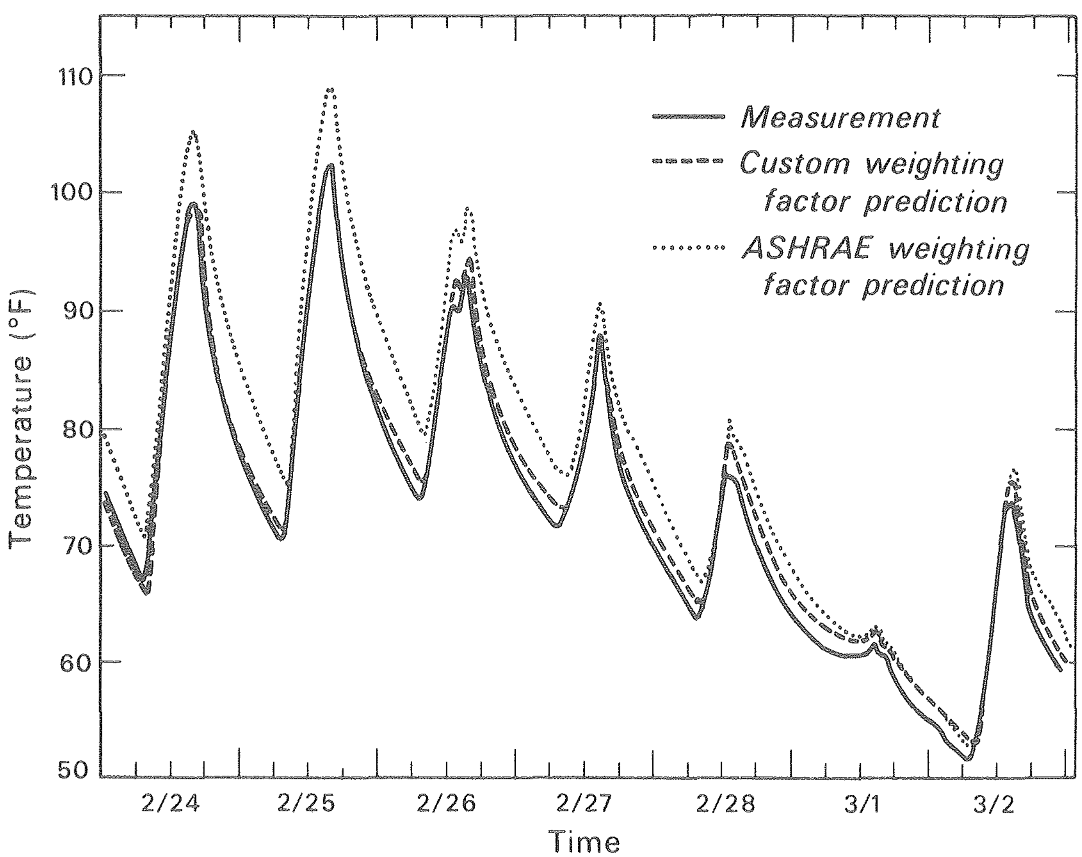

Fig. 1. LASL test cell measurement comparison with DOE-2.1 predictions.
(XBL 812-270)

A technique for calculating weighting factors specifically for the space configuration under consideration was developed[14] 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. Equation (1) is applied to these profiles, and the weighting factors are extracted by solving the resulting equations simultaneously. When these "Custom Weighting Factors" are applied to the LASL test cell (Figure 1), the agreement with measured data is vastly improved.

Modified Thermal Balance (MTB)

The Modified Thermal Balance technique does not treat the various heat gains separately. Instead, the heat balance equations at the inside surfaces of the space are solved simultaneously each hour. For calculating cooling loads, the room air temperature is held fixed, and, similarly to the weighting factor approach, the actual variation of the space temperatures is treated through transfer functions. It is felt that the MTB technique may be more accurate in certain situations than the weighting factor approach. For example, it would allow moveable insulation to be placed over windows at night. The weighting factor technique does not permit the room transfer functions to be functions of time, as is necessary when the conductance of the windows varies with time. The MTB approach 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 the building conditions. Human comfort strongly depends upon the inside surface temperatures, and, yet, the weighting factor approach provides no information in this regard. Further studies will be made of the differences among the weighting factor, the MTB, and the full thermal balance techniques to determine what situations require the more complex, and therefore more time-consuming, techniques, if sufficient accuracy is to be maintained.

Restructured HVAC Systems

The SYSTEMS and PLANT sub-programs of DOE-2.0A were 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 performance of the equipment components on an hour-by-hour basis but, rather, to predict overall energy use. This philosophy was supported by the fact that, in the past, the larger HVAC equipment was systematically oversized and tightly controlled. For modeling such systems, it was not necessary to take into account performance parameters that depend on inside or outside environmental variables.

As DOE-2.0A gained popularity, the user community wanted to extend the use of the program 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 tend to be more concerned with modeling hourly performance of actual equipment than rather merely estimating the integrated daily or annual energy consumption. This new philosophy permitted the introduction of several new equipment simulations into DOE-2.1.

In the SYSTEMS program the most significant changes address the details of the air moisture levels and the cooling coil simulation. The DOE-2.0A program assumed that the sensible capacity of the equipment was constant throughout the entire simulation period. It also assumed that the air moisture level exiting from the cooling coil was a constant fraction of the saturation level at the exit temperature. The newest version of DOE-2.1 more realistically calculates the capacity of each piece of equipment on an hourly basis. This approach allows a strong coupling between the envelope and the equipment by solving simultaneously the equations describing the action of the equipment and the equations describing the space temperature swings within the hourly time step. In addition, we developed a moisture exchange model for cooling coils that simulates the condensation that takes place on the coil surface by calculating the time-dependent surface temperature and the degree of air "contact" with the surface, based upon free-stream conditions of flow rate, and drybulb and wetbulb temperatures. Such a calculation yields an hourly steady-state simulation of the moisture condensation on the coil surfaces in association with the latent space gains due to people, equipment, infiltration and ventilation.

With these new capabilities for performance simulation, it became possible to extend the number of types of equipment simulations to include those appropriate for residential and small commercial buildings. These additional system types include direct expansion, air-cooled cooling systems, as well as water- and air-source heat pumps. Specifically, the new equipment for SYSTEMS includes: packaged rooftop units for single-zone, multizone, and variable air volume applications; packaged terminal air conditioners for window-mounted or through-the-wall applications; central forced air furnace and split-system direct-expansion cooling for residential applications. The residential simulation also permits the evaluation of the efficacy of using operable windows in place of mechanical cooling. The original simulations for chilled and hot water equipment were also upgraded to allow more accurate tracking of hourly performance. (See Table 1.)

Simulation algorithms for the PLANT program were also redesigned to track more accurately the performance of the equipment and to be consistent with the algorithms in SYSTEMS. The treatment of the chilled and hot water supply loops has been modified in DOE-2.1 to take into account the variation of loop temperature. Similarly, the temperature of the condenser water is now allowed to vary. The cooling tower simulation was upgraded as experimental performance data became available. New performance parameters for the chillers were introduced to permit more exact simulation, and an

Table 1. Equipment simulations in DOE-2.1

Systems	Plant
Single Zone	Steam Boiler (fossil fuel)
Packaged Single Zone*	Steam Boiler (electric)
Multizone	Hot Water Boiler (fossil fuel)*
Packaged Multizone*	Hot Water Boiler (electric)*
Dual Duct Fan	Furnace (fossil fuel)*
Ceiling Induction	Furnace (electric)*
Unit Heater	Domestic Hot Water Heater (fossil fuel)*
Unit Ventilator	Domestic Hot Water Heater (electric)*
Floor Panel Heating	Open Centrifugal Chiller
Two-Pipe Fan Coil	Open Reciprocal Chiller
Four-Pipe Fan Coil	Hermetic Centrifugal Chiller
Two-Pipe Induction	Hermetic Reciprocal Chiller*
Four-Pipe Induction	Single-Stage Absorption Chiller
Variable Air Volume	Two-Stage Absorption Chiller
Packaged Variable Air Volume*	Solar-Assisted Absorption Chiller*
Reheat Fan	Double-Bundle Chiller
Unitary Heat Pump	Cooling Tower
Heating and Ventilating	Ceramic Cooling Tower
Ceiling Bypass	Steam Turbine Generator
Residential*	Gas Tubine Generator
Packaged Terminal Air-Conditioner*	Diesel Generator
	Hot Water Storage Tank
	Cold Water Storage Tank

* New equipment in DOE-2.1

improved optimization algorithm was developed to allow efficient operation of a multiple chiller plant.

Like the new additions in SYSTEMS, new PLANT equipment was introduced in DOE-2.1 for smaller installations. These include: electric and fossil fuel hot water boilers, electric and fossil fuel domestic hot water heaters, open and hermetic reciprocal chillers, and electric and fossil fuel furnaces.

Component Based Systems (CBS)

A major addition to the program is an active solar system simulator, called "CBS" for Component Based Systems. This code was adapted and expanded by the WX-4 group at LASL from the TRANSYS program developed at the University of Wisconsin, and was integrated into the PLANT portion of DOE-2.1 with the assistance of our group at LBL. This program offers the user four pre-assembled solar systems (both liquid and air systems for commercial and residential buildings) that are modified for specific applications through the use of keywords, like the rest of DOE-2.1. In addition, the user can assemble his or her own system by connecting together individual components: collectors, pipes or ducts, heat exchangers, hot water storage tanks or rock beds, pumps or fans, and their associated controls. Through either approach the user can simulate the collection of solar energy to satisfy space heating and/or cooling loads or process loads.

In an example used to introduce this program to the user[3] a solar system was simulated to provide a solar assist to the domestic hot water heater in a small commercial building in Sacramento, California. The domestic hot water heater had a heating capacity of 12,800 Btu/hr and a demand schedule for weekdays as given in Figure 2. The demand schedule during weekends and holidays was assumed to be the same as the demand at night during the week. The natural gas consumed annually by the heater dropped from 131.9 therms without solar assist to 76.0 therms with solar assist, an annual savings of 42%. On the other hand the fuel consumption of 131.9 therms produced 72 therms of hot water for an efficiency of 55%, while the fuel consumption of 76.0 therms produced only 31 therms of hot water for a conversion efficiency of only 41%. These values illustrate an important problem that is involved with making

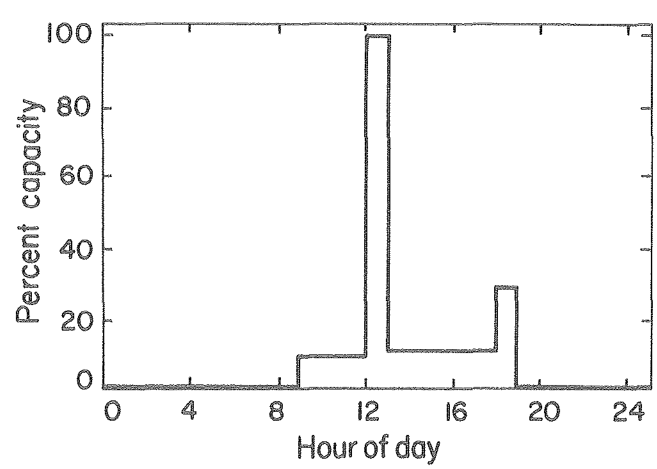

Fig. 2. Domestic hot water hourly profile. (XBL 816-972)

solar retrofits to non-solar systems. Unless the back-up equipment to the solar system is altered to perform at higher efficiency at lower loads, an overall reduction in energy conversion efficiency can occur.

PLANNED ACTIVITIES FOR FY 1981

Future plans for the program lead in two separate 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 be made to the existing program to supplement its capabilities. These include: (1) expanded output report capability; (2) a daylighting simulation in collaboration with the Windows and Lighting Group at LBL; (3) an expanded user-library capability; (4) the thermal balance LOAD program alternative; (5) improved economic calculations; (5) expanded energy cost alternatives; (6) simulation of evaporative coolers; (7) improved infiltration algorithm; (8) simulation of thermal storage devices; and (9) metric input and output options. The program will also be converted so that it will run on IBM, Honeywell, UNIVAC, and Digital Equipment Corporation computers.

The other direction for FY 81 activity is exploratory; i.e., 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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BUILDING ENERGY DATA COMPILATION, ANALYSIS, AND DEMONSTRATION*

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INTRODUCTION

The Building Energy Data Compilation, Analysis and Demonstration group is responsible for compiling, analyzing, and demonstrating the research of the Energy-Efficient Buildings program and integrating it with building science research nationally and internationally. We organize our research by technology (windows, thermal storage, and infiltration) or professional specialty (indoor air quality, building performance modelling, etc.); but we and our clients tend to organize our questions by building type (homes, schools, etc.) or operation requirements (design and retrofit) which, of course cut across all of our research fields. Accordingly, the BEDAD group in addition to responding to questions from utilities, planners, governmental groups, and even our own research directors, reformulates and publishes some of our findings in an aggregated form, which is more useful to building industry and policy professionals.

ACCOMPLISHMENTS DURING FY 1980

During the past year, BEDAD continued to develop and refine a technology data base on the cost and performance of conservation measures in new and retrofitted houses and residential appliances, and began to compile data on commercial buildings and equipment. Using these data, along with the results of DOE-2 runs and other analyses made in support of BEPS (Building Energy Performance Standards), we completed a major study of technical and economic potentials for conservation and solar use in California residences. A similar study of conservation and solar potentials in all U.S. buildings (residential and commercial) between now and the year 2000 was also conducted and preliminary results have been reviewed. Both studies have generated a great deal of interest among utilities, government agencies, and the building industry, and were used extensively as background material for a Summer Study on Energy Efficient Buildings, sponsored last August in Santa Cruz by the American Council for an Energy Efficient Economy, the Solar Energy Research Institute, (SERI) and DOE. Finally, in 1980 we initiated with the Pacific Gas and Electric Company a joint project to (1) demonstrate "house doctor" audit/retrofit techniques, (2) train an initial core group of utility and private industry house doctors, and (3) measure resultant energy savings and cost-effectiveness in a sample of 26 northern California homes. Results to date from each of these projects are summarized below.

*This work is supported mainly by the Assistant Secretary for conservation and Solar Energy, Office of Buildings and Community Systems, Buildings Division, U. S. Department of Energy under Contract No. W-7405-ENG-48, and by the Solar Energy Research Institute. We also thank the California Policy Seminar for partial support.

Reports

Building Energy Use Compilation and Analysis (BECA). BECA is a series of publications providing an international comparison and critical review of building standards and the energy use of typical buildings as well as cost-effective, low-energy buildings. Its findings are published as a review consisting of three parts which are to be updated and republished regularly. Part A, Single-Family Residences, was submitted to Energy and Buildings, in January 1981; Part B, Retrofitting of Residences, is in progress, as is Part C, Commercial Buildings.

BECA-A: Single-Family Residences

In BECA-A, the potential for energy conservation in space heating of new residential buildings is characterized using results from computer analysis and from a survey of low-energy houses. Simulations of the energy requirements of a prototypical house in the United States at different levels of conservation have shown that minimum life-cycle cost can be achieved with much higher levels of conservation than those presently employed. Measurements taken in actual houses indicate that very low energy requirements for space heating--comparable to those now used for domestic water heating--can be achieved in new houses by adding insulation, reducing infiltration, and using solar-design principles. We conclude that building standards should be made more stringent to hasten the adoption of cost-effective conservation measures.

Figure 1, taken from BECA-A, plots ten cost-effective low-energy homes comparing them with proposed standards and with current building practice.

BECA-B: Residential Retrofit

Parallel to our work on energy use in new homes, we have begun to compile and evaluate data on the characteristics, energy performance, and associated costs of retrofits to existing structures. The data collected thus far are summarized in Figure 2, which shows the percentage of energy saved as a function of contractor cost. The entries shown on Figure 2 range from individual values for single homes to averages for a large number of retrofitted homes (nearly one million, in the case of the Canadian "CHIP" homes). All but two of the data points are derived from actual metering of homes, and soon all points will be based on meter readings or utility billing records.

The exponential decay curve drawn on Figure 2 is our estimate of the "frontier" curve for space heating requirements after retrofit vs. the cost of the retrofit. The curve starts down with an initial slope of 8% fuel savings per $100 invested (cost of conserved fuel oil at 10¢/gal) and passes

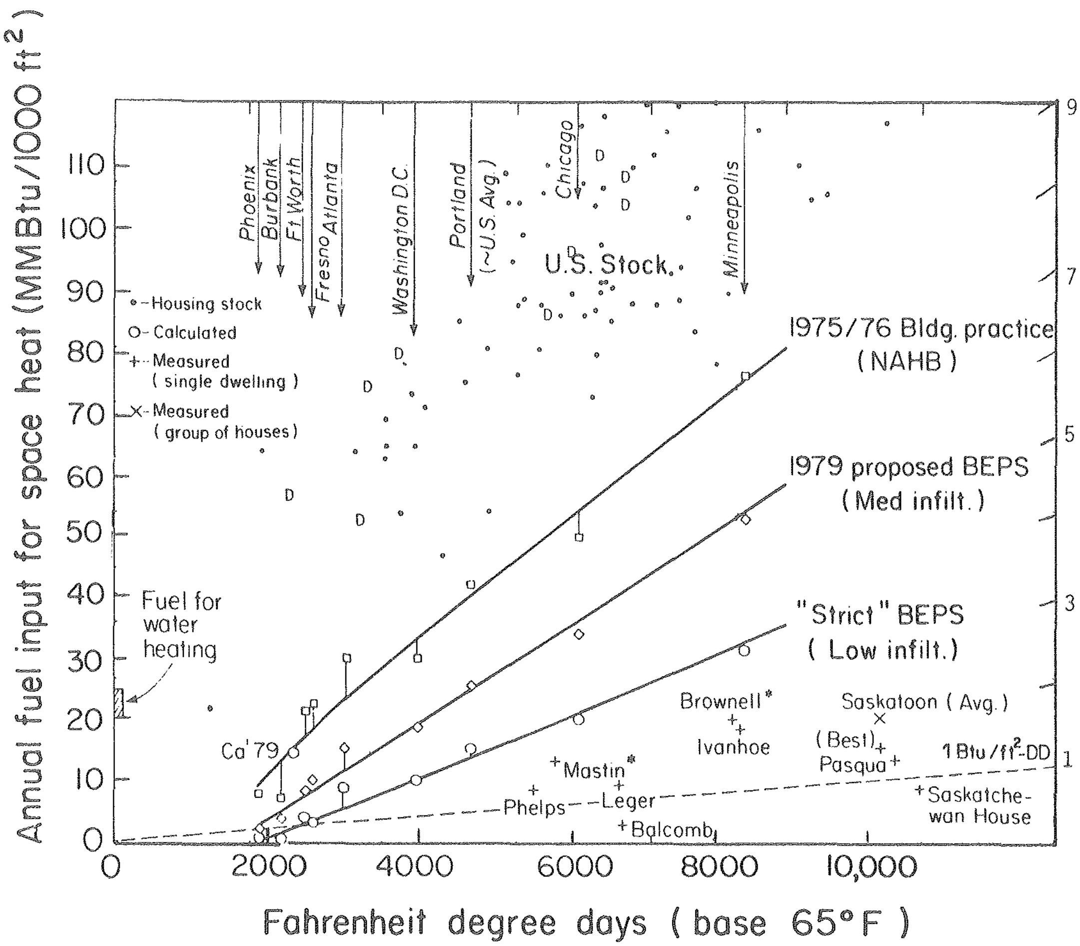


Fig. 1. Annual fuel input for space heating of single-family U.S. homes. Black dots are actual gas sendout to residential customers for space heat for calendar year 1978. The 1979 proposed BEPS (Building Energy Performance Standards) leaves infiltration at current practice levels of 0.6 air changes/hour (ach); strict BEPS reduces infiltration to 0.2 ach but restores 0.4 ach with mechanical ventilation through a heat exchanger. Approximate extra costs for conservation above 1975/76 practice; BEPS, $1,000; tight BEPS, $1,500; better-than-BEPS houses, several hundred to several thousand dollars.[3] (XBL 809-1904E)

close to 50% savings for $2500 (40¢/gal). Even 40¢/gal is considerably cheaper than the price of $1.20/gal, the cost of fuel in New England during the winter of 1980-81, or the tailblock rate for natural gas in northern California of 60¢/therm or the equivalent of 80¢/gal.

In the course of 1981, we plan to continue adding to and refining the data on residential retrofits, especially as new information sources become available from demonstration projects (like our "House Doctor" demonstration, described below) and the nationwide Residential Conservation Service programs. These data will be published as Part B of the "BECA" series, and then regularly updated in future years.

BECA-C: Commercial Buildings

We plan to issue our first edition of BECA-C in April 1981. Figures 3 and 4 display some of the data compiled and estimated for commercial buildings to date. In Figure 3, long-range trends in the energy efficiency potential for newly built office structures in the U.S. are compared with trends in the efficiency potential for new passenger cars over the same 40-year time-frame. What is perhaps most striking about both sides of Figure 3 is the sudden improvement in efficiency of both new automobiles and new commercial buildings beginning in the mid-1970's. We anticipate that efficiency levels for both autos and office buildings will continue to improve over the next decade in response to rising energy costs, the spread of technical innovations, competition from imported cars, and direct incentives or government regulations.

Figure 4 presents several examples of possible retrofits in office, commercial, and university buildings at costs of conserved energy ranging from $.20 to $1.22 per MBtu and indicates similar opportunities for improving the operation and maintenance of non-residential buildings.

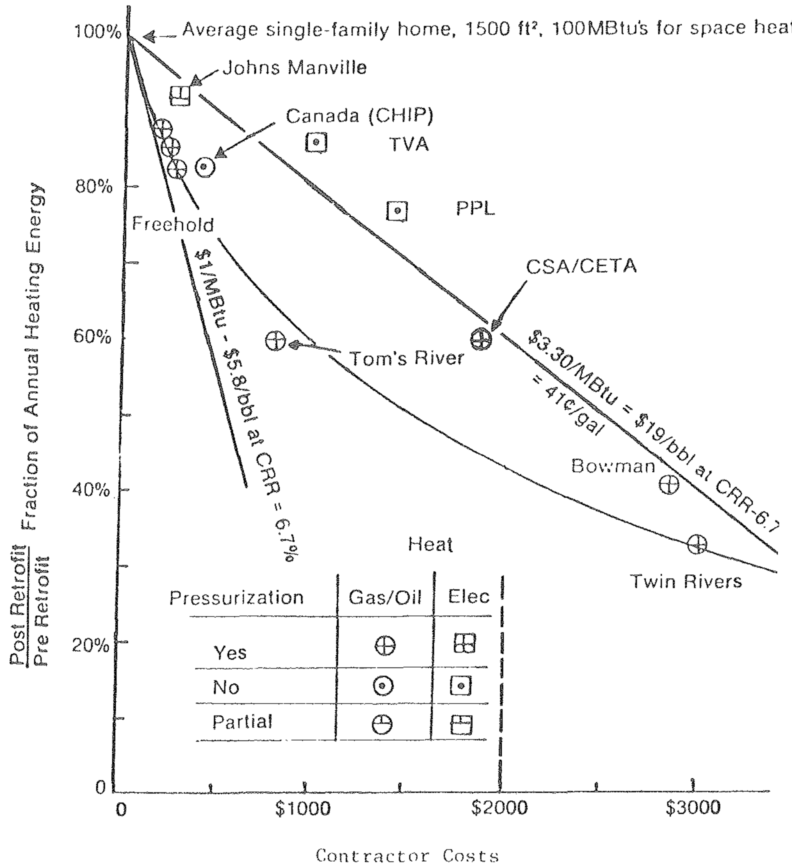


Fig. 2. "Frontier" curve for measured single-family home retrofits. The upper and lower edges of the wedge represent costs of conserved energy of $3.30/MBtu and $1/MBtu, respectively. All points represent measured data except for the CHIP (Canadian Home Insulation Program) sample of 700,000 homes. (XBL 813-8793)

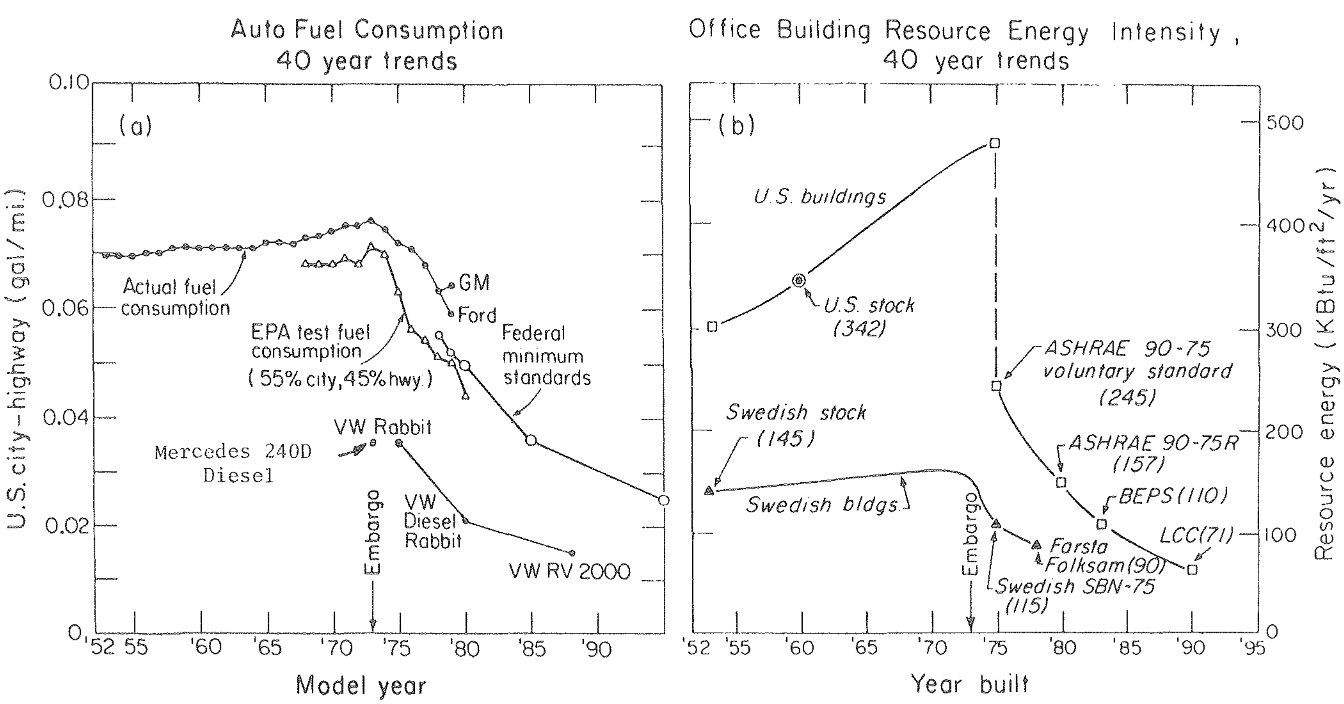


Fig. 3. Horsepower Race: Forty-year trends in energy use for automobiles vs. office buildings (measurements vs. calculations).4,5 (XBL 809-1847A)

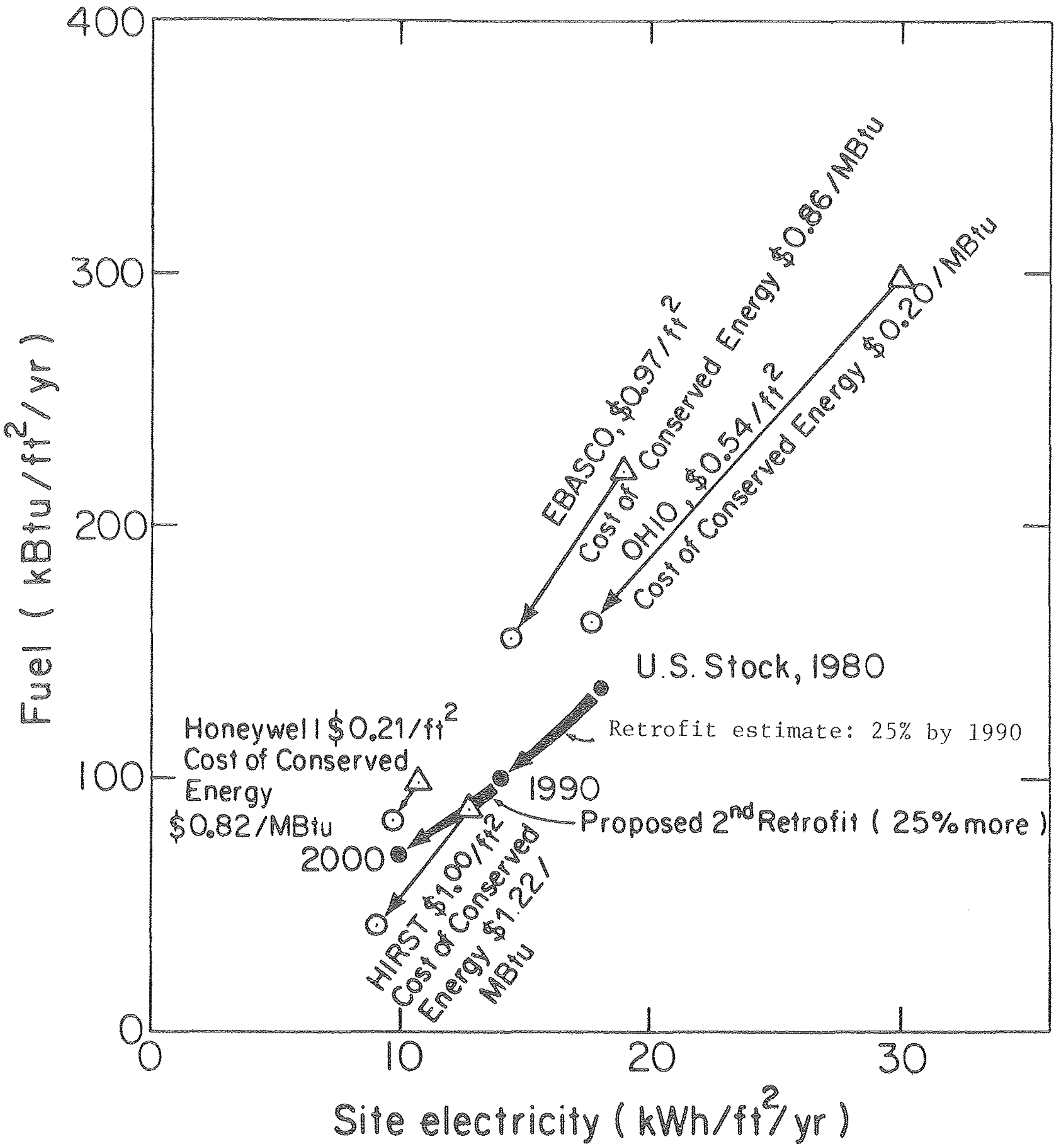


Fig. 4. Possible retrofits in offices (Hirst), commercial buildings and hospitals (EBASCO), and a university (Ohio State). For comparison, a proposed retrofit sequence is included. For details, see LBL-11300. (XBL 809-1845)

The next two sections show how the data compiled through "BECA," along with other sources, have been used both at the state and national levels to develop estimates of maximum cost-justified technical potentials for improving the energy efficiency of buildings.

California Residential Conservation Potential

The work described here was supported by the California Policy seminar and has been published as an LBL report.[1] In order to show the potentials for energy conservation in California's residential sector, we have developed "supply curves of conserved energy" in which individual conservation measures are ranked in order of increasing cost-per-unit of energy saved. Unit costs are measured in constant dollars on the vertical axis, and cumulative annual energy savings on the horizontal axis. In this way, conserved energy is put on a par with other new sources of energy, such as synthetic fuels. A computer program, CPS 1.0, was created to perform the energy accounting.

Figure 5 shows a supply curve of conserved electricity for California residences, as of 1980. Table 1 is a key to the curve, listing the name of each measure and the statewide annual energy savings expected from it. To estimate the available "reserves" of conserved energy, one must choose a suitable cost of conventionally supplied energy for comparison. The measures that are cost-effective are those for which the cost of conserved energy is less than the price of conventional fuels or electricity. For our supply curves, energy savings are always expressed as technically feasible, economically justified potentials--not necessarily as forecasts of a future that is likely to be achieved.

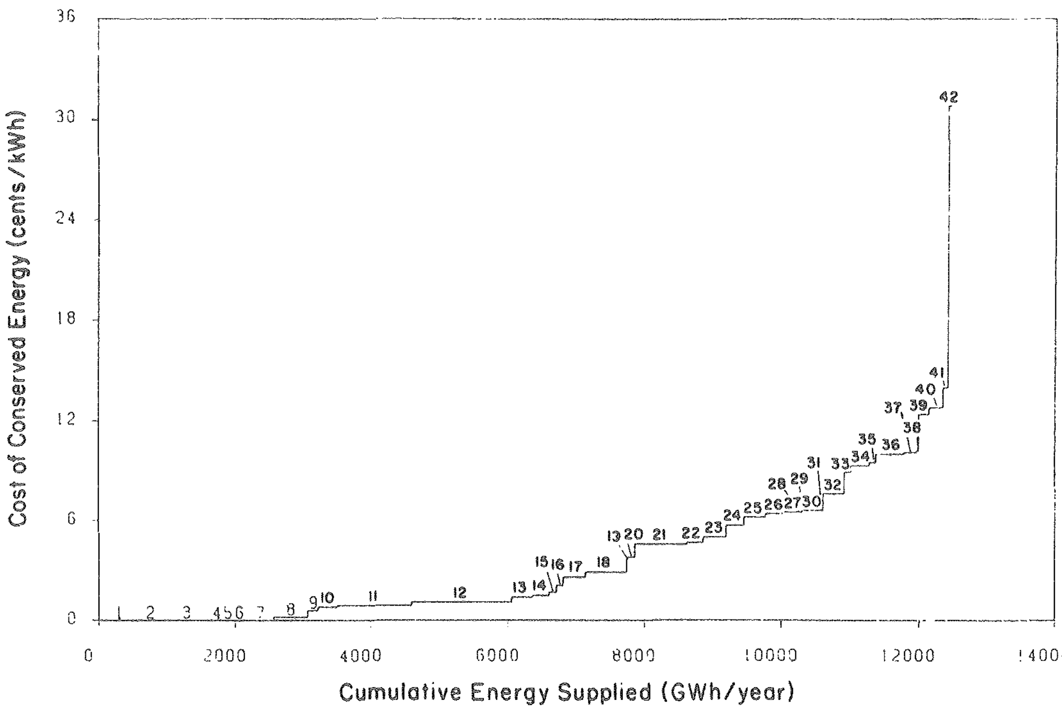


Fig. 5. The grand electricity conservation supply curve for California's residential sector. The total residential use in California in 1978 was 49,000 GWh. Conservation measures with costs up to 6 cents/kWh will save roughly 20% of current use. See Table 1 for a guide to the conservation measures involved. Note that 1000 GWh = 1 billion kWh. (XBL 813-8792)

The current tailblock price for residential electricity in California is roughly 8 cents/kWh. About 22% of California's current residential electrical use could be saved at costs of conserved electricity below 8 cents/kWh. A similar conservation supply curve for natural gas (not shown) indicates that roughly 34% of current residential use could be saved at costs of conserved energy below $7/MBtu.

Conservation supply curves can also be generated for single end-uses, such as water heating or refrigeration. In these cases, the thermodynamic limits to the reserve of conserved energy can also be displayed.

Technical Potentials for Energy-Efficient U.S. Buildings by the Year 2000

This work was supported by the Solar Energy Research Institute (SERI) and is detailed in an LBL report[2] as well as in a book to be published by the University of California Press.

Looking at energy use in U.S. residences and commercial buildings from a perspective of conservation and solar technical potentials leads to a very different picture for the year 2000 than do even the "low-growth" energy-demand forecasts that have recently become conventional wisdom in technical and policy circles. Recent demand forecasts by the Energy Information Agency at DOE anticipate that today's annual energy use of about 27 quads will probably grow to about 32 quads by the year 2000, or an average annual growth rate well under 1%. (Actually, fuel use, now about 13 quads, is expected by EIA to shrink to about 10 quads, with increased electricity consumption making up the difference.)

In contrast to this conventional outlook based on demand, our analysis suggests that it is technically feasible and economically cost-justified (even with current technology and at today's average energy prices) to dramatically reverse the expected 4-quad increase in energy demand in buildings. By the year 2000, the U.S. building stock could use as little as 16 quads--two-thirds of today's consumption levels -- despite the addition of more than 40 million new housing units and 20 billion new square feet of commercial space (see Table 2). This would be the result if virtually all existing buildings were retrofitted over the next two decades with cost-effective measures now commercially available, and if the efficiency of new buildings and newly-manufactured appliances and equipment were designed to minimize life-cycle costs.

The difference between a conventional demand forecast for the year 2000 and our "least-cost potentials" outlook is significant in absolute as well as percentage terms. By the year 2000, the difference in annual energy consumption for the buildings sector alone is greater than today's total imports of foreign oil (most of which go to sectors other than buildings, particularly industry and transportation).

A major capital investment in improved building and appliance efficiency would be required to

Table 1. Supply table for the electricity supply curve (Fig. 5). The time horizon is 10 years; the discount rate is 5%. For comparison, note that in 1978 the California residential sector used 49,600 GWh; thus conservation estimates out to a marginal cost of 6.4¢/kWh (Col. 1), which save 10,000 GWh (Col. 4), save about 20% of residential electricity, or the output of two standard generating plants.

	Conservation Measure[a]	Cost of Conserved Energy[b] (cents/kWh)		Energy Supplied (GWh/y)[c]		Total Dollars Invested
		Marginal	Average	Per Measure	Total	(millions)
1	Solid-state color TV	0	0	599.1	599	0
2	Solid-state black-and-white TV	0	0	322.3	921	0
3	CEC standard refrigerator	0	0	728.0	1,649	0
4	CEC standard room A/C	0	0	152.1	1,802	0
5	CEC standard central A/C	0	0	168.0	1,970	0
6	Water heater temp. setback	0	0	186.2	2,156	0
7	Cold-water laundry	0	0	407.4	2,563	0
8	Low-flow showerhead	0.2	0	496.6	3,060	8
9	Night setback of 10 °F	0.6	0.1	153.1	3,213	20
10	Savings on pool filter from cover	0.8	0.1	287.0	3,500	24
11	Most efficient refrigerator	0.9	0.3	1092.0	4,592	102
12	Refrigerator package "A"	1.1	0.5	1466.4	6,058	227
13	Most efficient freezer	1.4	0.5	305.8	6,364	259
14	Water heater insulation blanket	1.5	0.6	240.6	6,605	275
15	3-way bulb to GE Halarc	1.7	0.6	110.6	6,715	283
16	Sealed attic bypasses	2.1	0.6	92.5	6,808	307
17	Freezer package	2.6	0.7	327.6	7,135	373
18	Kitchen fluorescent lights	2.9	0.9	608.9	7,744	511
19	R-19 ceiling insulation	3.7	0.9	9.9	7,754	515
20	Diversion of electric clothes dryer vent	3.8	0.9	105.4	7,860	546
21	Gas clothes dryer	4.6	1.3	766.7	8,626	821
22	Exterior fluorescent lights	4.7	1.4	239.0	8,865	909
23	100 W bulb to fluorescent (1)[d]	5.0	1.5	334.5	9,200	1,039
24	Storm windows	5.7	1.6	258.4	9,458	1,224
25	Central A/C wall insulation	6.2	1.7	308.7	9,767	1,462
26	Most efficient central A/C	6.4	1.9	252.0	10,019	1,630
27	Manual refrig. improvement	6.5	2.0	208.0	10,227	1,734
28	Most efficient electric dryer	6.5	2.0	62.0	10,289	1,765
29	Fireplace damper	6.5	2.0	13.4	10,302	1,772
30	100 W bulb to fluorescent (2)[d]	6.6	2.1	290.3	10,593	1,920
31	R-11 insulation in walls	7.4	2.1	8.8	10,601	1,928
32	3-way bulb to fluorescent	7.6	2.3	305.3	10,907	2,108
33	Caulking	8.9	2.3	102.1	11,009	2,178
34	Gas range	9.3	2.5	274.2	11,283	2,374
35	Window shading for central A/C	9.5	2.6	94.5	11,377	2,443
36	Refrigerator package "B"	10.0	2.8	405.6	11,783	2,755
37	100 W bulb to fluorescent (3)[d]	10.1	2.9	191.2	11,974	2,904
38	Most efficient room A/C	10.2	2.9	24.3	11,999	2,926
39	75 W bulb to fluorescent	12.4	3.1	155.8	12,154	3,074
40	Weatherization (apartments)	12.8	3.2	204.0	12,358	3,346
41	Additional R-19 in ceiling	14.0	3.3	68.9	12,427	3,466
42	Weatherstripping	30.8	3.4	47.9	12,475	3,530

[a] The conservation measures are listed in the order they appear in the supply curve, i.e., according to cost of conserved energy.

[b] in 1979 dollars.

[c] Note that 1 Terawatt-hour (TWh) = 1 billion kWh, and 1 gigawatt-hour (GWh) = 1 million kWh.

[d] Residential lamps are divided into three groups according to annual hours of use: (1) = average of 800 hr, (2) = 600 hr, and (3) = 400 hr.

Table 2. Summary of energy consumption in the residential and commercial sectors of U.S.: 1980 vs 2000.

	Year 1980			Year 2000								
				Baseline			Conservation Measures to Current Cost of Oil and Electricity			Conservation and Solar Measures to Curent Cost of Oil and Electricity		
	Fuel (Q)	Elec. (Q resource)	Total	Fuel (Q)	Elec. (Q resource)	Total	Fuel (Q)	Elec. (Q resource)	Total	Fuel (Q)	Elec. (Q resource)	Total
A) Residential												
Existing residences space heating and cooling	7.04	2.65	9.69	5.50	1.98	7.48	1.95	0.88	2.83	1.37	0.66	2.03
New residences space heating and cooling	---	---	---	1.59	1.96	3.55	0.74	0.92	1.66	0.54	0.81	1.35
Water heating	1.29	1.00	2.29	1.46	2.11	3.57	0.75	1.26	2.01	0.55	0.92	1.47
Appliances	0.47	4.16	4.63	0.68	6.67	7.35	0.43	4.13	4.56	0.43	4.13	4.56
Residential total	8.80	7.81	16.61	9.23	12.72	21.95	3.87	7.19	11.06	2.89	6.52	9.41
B) Commercial												
Existing buildings	4.8	5.6	10.4				1.6	2.4	4.0			
New buildings				3.2	10.1	13.3	0.2	3.1	3.3			
Commercial Total	4.8	5.6	10.4	3.2	10.1	13.3	1.8	5.5	7.3			
C) Total (Residential and Commercial)	13.6	13.4	27.0	12.4	22.8	35.2	5.6	12.7	18.3			

Note: The conservation and solar technology potential is based on conservation measures with a cost less than 7.5 $/million Btu or 5.7 cents per kWh. The additional savings for all measures with a higher cost is 0.70 quads.

achieve this technical potential of $450 billion cumulatively over the next 20 years (in undiscounted 1980 dollars). But the direct economic returns to such investments would be even greater, due to reduced needs to import high-priced oil and to construct costly new power plants and other energy facilities. For example, the conservation and solar measures we analyze can save energy at an average cost of about $10 per barrel-of-oil-equivalent--an attractive investment by any criterion.

We based these estimates on a detailed, end-use analysis of energy waste and inefficiency in today's buildings and appliances, and the opportunities for improved efficiency in new additions to the stock. For purposes of the analysis, we accepted (without necessarily agreeing with) all of the EIA projections of stocks, appliance saturations, and fuel choice, but adjusted the assumed building and equipment efficiency levels to minimize overall life-cycle costs. For the residential sector, individual conservation and solar measures were ranked in order of cost-effectiveness (cost per unit of conserved energy), as with the California residential analysis. The result was once again a series of "supply curves of conserved energy," illustrated in Figures 6A and 6B. End-use data were not available in sufficient detail for the various categories of commercial buildings to permit us to compile conservation supply curves for that sector; this task will be part of our continuing efforts in 1981 and 1982.

A statement of technical potentials is not the same as a forecast of what is actually expected to occur through the workings of the market or the effects of public policies. Achieving most or all of this technical potential will require a massive effort to retrofit the existing building stock, improve building operation and maintenance practices, and introduce the best available energy-efficient technologies in new construction and new appliance manufacture.

"House Doctor" Demonstration, Training, and Retrofit Monitoring Project

Researchers at LBL are currently conducting a cooperative project with Pacific Gas and Electric Company (PG&E) to determine the energy savings resulting from "house doctor" retrofitting of single-family residences in Walnut Creek, CA. The standard house-doctor visit is designed to increase the effectiveness of residential audits by including instrumentation and ~2 person-days of retrofitting. House doctoring also has potential as a contractor type business similar to, or combined with, insulation installation.

The procedure emphasizes use of a "blower door," a device which can both pressurize and depressurize a house to facilitate the measurement of infiltration levels and permit quick identification of air leaks. An infrared scanner is used in conjunction with the blower door to detect leaks in the attic and to check the quality of wall insulation.

From the audit portion of the visit, a series of recommendations are made to the homeowner, as in other audit procedures. The principal feature of the retrofit portion is that the auditor, at the time of the visit, will implement simple energy-saving measures while the house is pressurized. The convenience to homeowners is that the work is not only done immediately (and correctly) but also at low materials cost.

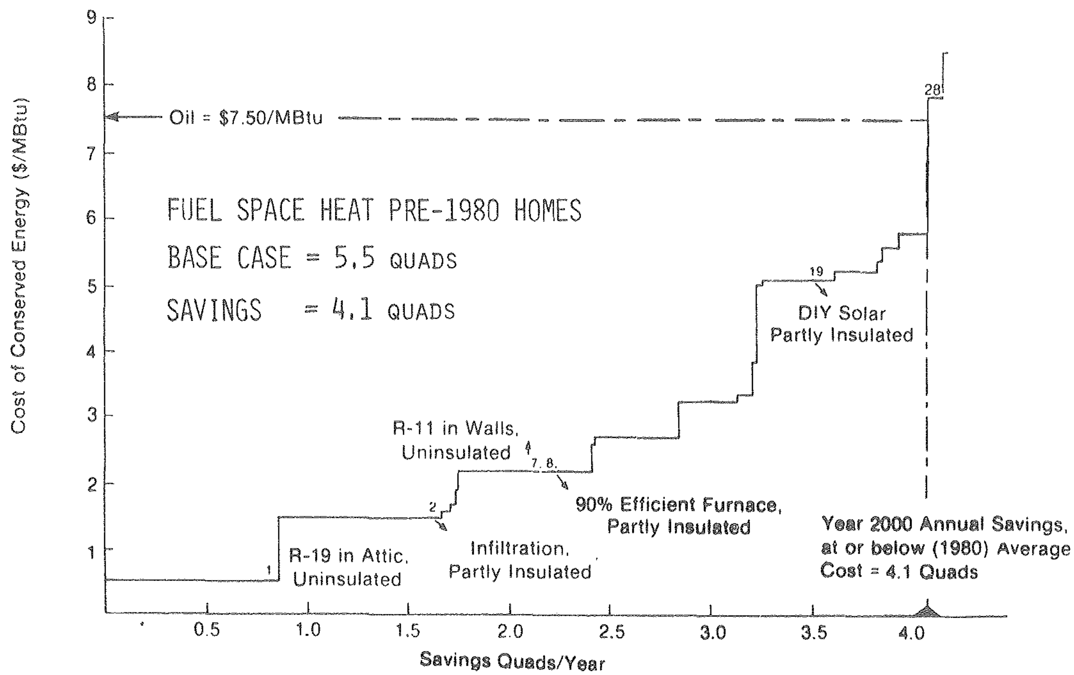
Thirty houses were included in our study. Ten of the houses were "active controls" which received house-doctor audits only (no retrofit). Ten received a standard house-doctor visit, and ten received an "extended retrofit," which is a house-doctor visit plus additional retrofit to be performed by contractors. In our experiment, the house-doctor audit is essentially the PG&E Enercom computerized audit with the addition of an infiltration measurement and a few extra items on the audit form/prescription. Our retrofits included installation of electronic ignition devices on the furnace--not always considered part of house doctoring. The contractor retrofits will be installed in Spring 1981, selected on the basis of economic attractiveness from a list that includes: increased insulation in attics, walls, and floors; installation of storm windows; taping and insulating furnace ducts; further house-doctor-type leak plugging; and replacement of incandescent with fluorescent light fixtures.

The energy use of each house will be monitored for at least one year after the retrofitting occurs. Consumption by furnace, water heater, pool heater (if any), and air conditioner will be recorded weekly. A regression of energy use with respect to temperature data from a nearby site, done before and after the retrofits, will allow calculation of energy savings in an average year.

Several useful materials have been developed as part of this project. One is a comprehensive House Doctor Manual which describes the on-site audit and retrofit procedure. Another is a complete list of the equipment, tools, and retrofit materials needed for a house-doctor visit. In addition, a curriculum for training house doctors was developed and used in a two-week intensive training course for seven PG&E "weatherization specialists." These trained PG&E house doctors completed the twenty partial retrofits and thirty audits during November and early December of FY 1980.

Various members of the public were invited to observe a series of retrofit demonstrations in October. This program was designed so that the observers could get a first-hand idea of the kind of retrofit procedure that becomes possible when the various instruments mentioned above are used. The houses were house-doctored by two members of our LBL staff, while a third explained the procedure to the observers.

The preliminary results from this project are summarized in Tables 3 and 4. The average reduction in infiltration (as calculated from the blower-door measurements) is 30%, with a range from 14% to 65%. The average infiltration rate for the 16 houses included in the preliminary calculations is 0.75 air changes per hour (ach) before, and 0.52 ach after house doctoring. We estimate the costs



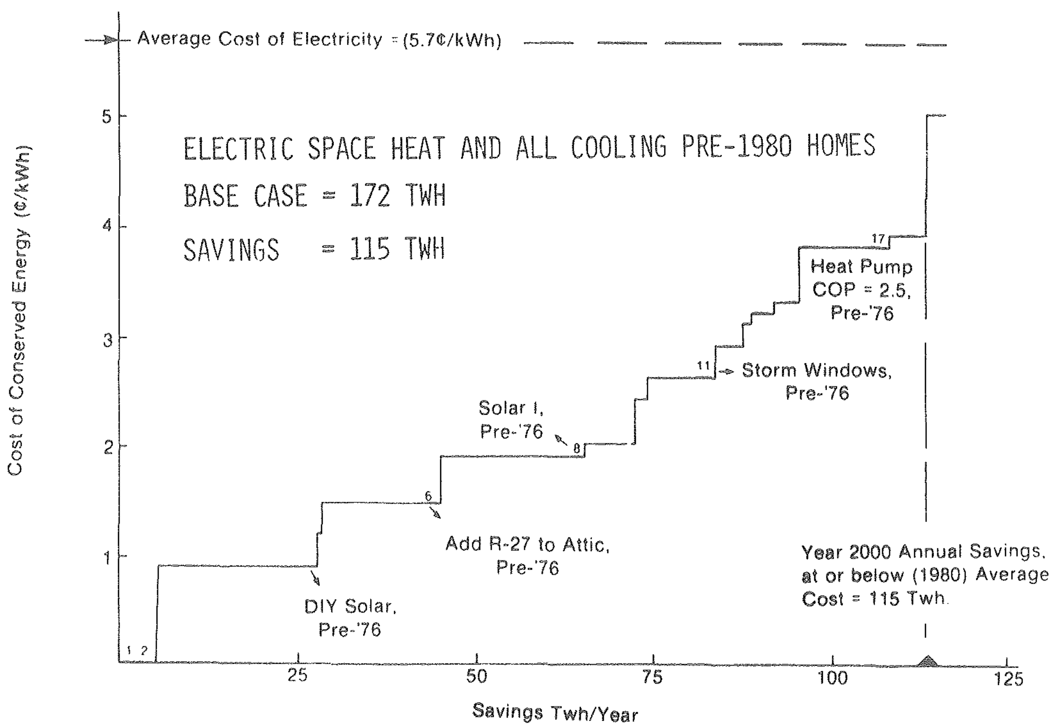


Fig. 6A, 6B. Supply curves for space heat and cooling for pre-1980 homes surviving in 2000. Note that 1 TWh = 1 billion kWh. For details, see LBL-11300.

(XBL 813-8791)

Table 3. Infiltration reduction from house-doctor retrofits.

House	Year Constructed	Volume (m^3)	Leakage Area (cm^3)		Heating Season Average Air changes/hour		Infiltration Reduction (%)
			Before	After	Before	After	
A2	1969	430	1421	1081	.62	.47	24
A3	1955	350	1499	1282	.78	.67	14
A5	1965	370	1325	789	.68	.40	41
A6	1956	350	1126	951	.62	.52	16
A7	1969	600	1638	1319	.52	.42	19
A9	1966	420	1148	944	.68	.56	18
A10	1960	340	2010	1510	1.12	.84	25
B1	1965	490	2091	1606	1.06	.82	23
B2	1970	520	1916	1297	.70	.47	33
B4	1969	640	2712	950	1.06	.37	65
B5	1970	510	1761	1106	.67	.42	37
B6	1960	440	1437	1049	.62	.45	27
B7	1969	640	1462	1127	.57	.44	23
B8	1969	600	3164	1827	.99	.57	42
B9	1965	480	2148	1458	.85	.58	32
B10	1969	770	1230	881	.40	.28	30
Average	--	497	1756	1199	.75	.52	29

(including labor, materials, and overhead) of a standard house-doctor visit at $365, (or $556 including the cost of IID installation). This yields a cost of conserved energy, over the useful lifetime of the retrofits, of $0.22/therm.

By finding and fixing leaks which are undetectable in current (uninstrumented) audits, house doctoring not only cuts energy waste but can make other conservation measures more effective. For example, if an attic is insulated before leaks are identified and patched, two serious problems arise: some leaks will be hidden by the insulation and harder to find and fix, and (2) loss of heat through these undetected leaks will undermine the benefits of insulation (in energy and dollar savings) and discourage homeowners from investing in energy-efficient strategies. Because of the relatively low materials cost and moderate labor intensity, this audit procedure may be well suited for use by small contractors and community groups.

New homes

Use of the blower door as a diagnostic tool during construction of new homes will probably turn out to be even more effective than its use in occupied houses.

Homes at time of sale

A house-doctor visit at the time of sale is probably a good investment for the future owner. If the house is doctored while it is empty (of furniture, rugs, and material stored in the attic), far more work can be done in one day. Preliminary results indicate that house doctor techniques can save energy at costs below the current fuel prices, and far below the price of new energy supplies. As prices rise and the importance of conservation grows, the importance of testing and refining these techniques will likewise increase.

Table 4. Savings and cost of conserved energy (CCE) for house-doctored homes of Table 3, before final contractor retrofit.

House No.	Therms/year saved by infiltration Reduction[a]	Total therms/year saved[b]	Estimated Cost[c] ($)	Cost of Conserved Energy[d] ($/therm)
A2	41	121	526	.29
A3	28	108	526	.33
A5	70	189	556	.20
A6	24	143	556	.26
A7	45	125	526	.26
A9	32	112	526	.32
A10	62	101	365	.24
B1	77	77	336	.29
B2	71	151	526	.23
B4	269	349	526	.10
B5	89	208	556	.18
B6	44	44	336	.51
B7	53	172	556	.22
B8	151	190	365	.13
B9	78	158	526	.22
B10	55	94	365	.26
Average	74	146	480	.22

[a]Calculated from leakage area measurements. Assumes 65°F heating degree day base and 20% reduction in furnace steady-state efficiency due to cycling and duct losses.

[b]Includes calculated savings from water heater and/or intermittent ignition device (IID) in houses where these were installed.

[c]Includes labor, materials, and 50% overhead. For a typical visit including infiltration reduction and water heater insulation labor costs are $155 and materials costs are $75. Additional costs for IID installation are $67 (labor) and $60 (materials).

[d]CCE calculated on the basis of an amortization period equal to expected useful life of the retrofits (20 years). Real interest rate assumed to be 3%.

PLANNED ACTIVITIES FOR FY 1981

BECA-A (Compilation of New Homes)

We plan to enlarge our data bank of efficient, cost-effective homes from ten to several hundred.

BECA-B (Residential Retrofit)

We will continue to add to and refine the data of Fig. 2, and submit our report for publication during the year.

BECA-C (Commercial Buildings)

We plan to greatly increase our rate of data collection, probably by agreement with Energy Users News, and to publish a regular update in Energy Users News and other trade journals. BECA-C will be submitted for publication.

Technical Potentials for Energy-Efficient U.S. Buildings

We plan to complete this work, incorporate reviewers' comments, and offer it to commercial publishers.

House Doctoring.

We shall continue our collaboration with PG&E, submetering and monitoring the savings in both heating and cooling loads. We shall further collaborate with PG&E and community groups to train more house doctors.

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Energy Efficient Buildings (EEB)--general reports not specific to any subgroup.

Building Energy Analysis Group (BEAG, 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--reports specific to the energy-efficient design of windows.

Lighting--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.

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