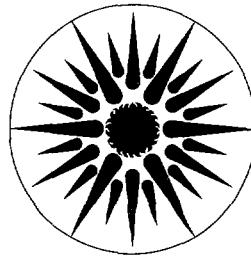
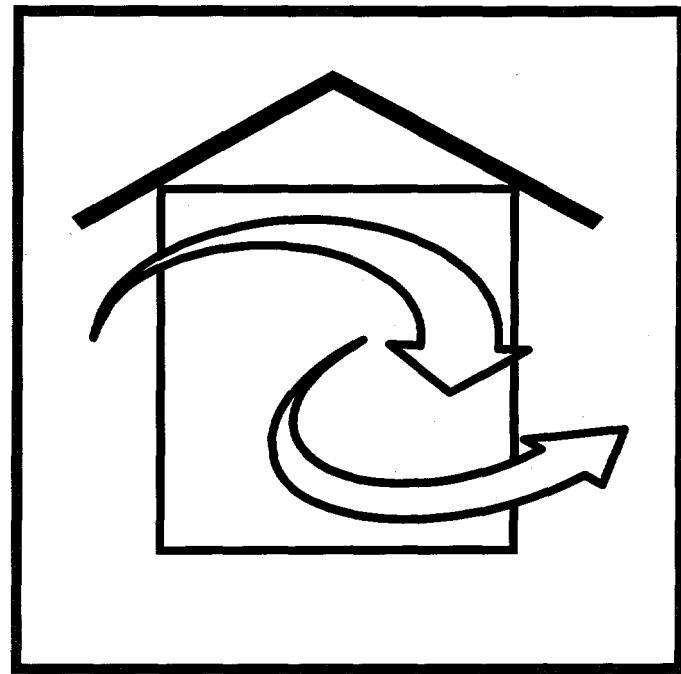


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# Indoor Environment Program

## 1994 Annual Report

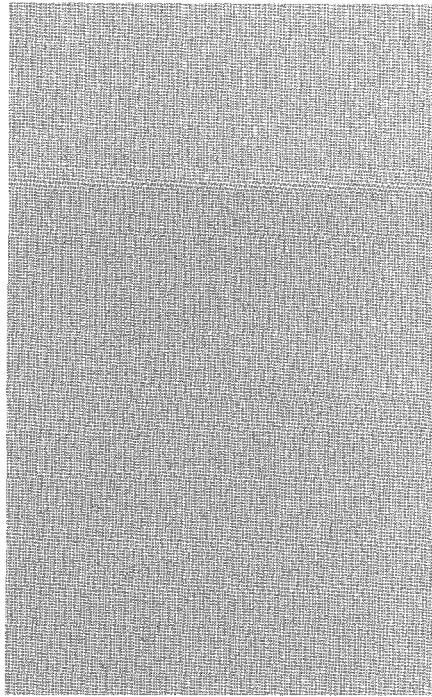


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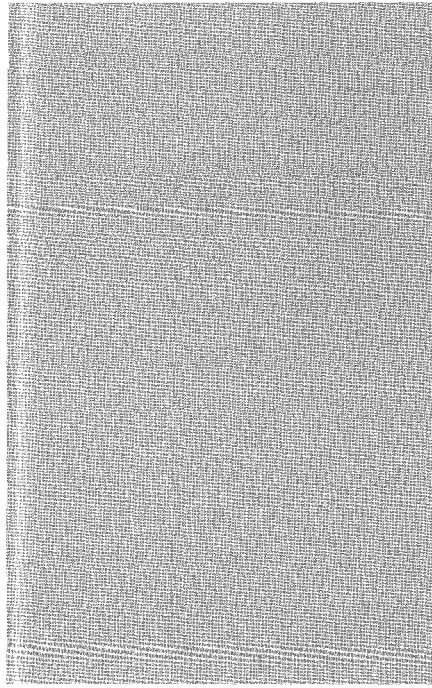


# **Indoor Environment Program 1994 Annual Report**

*Joan M. Daisey, Program Head*

Energy & Environment Division  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, California 94720  
(510) 486-5001

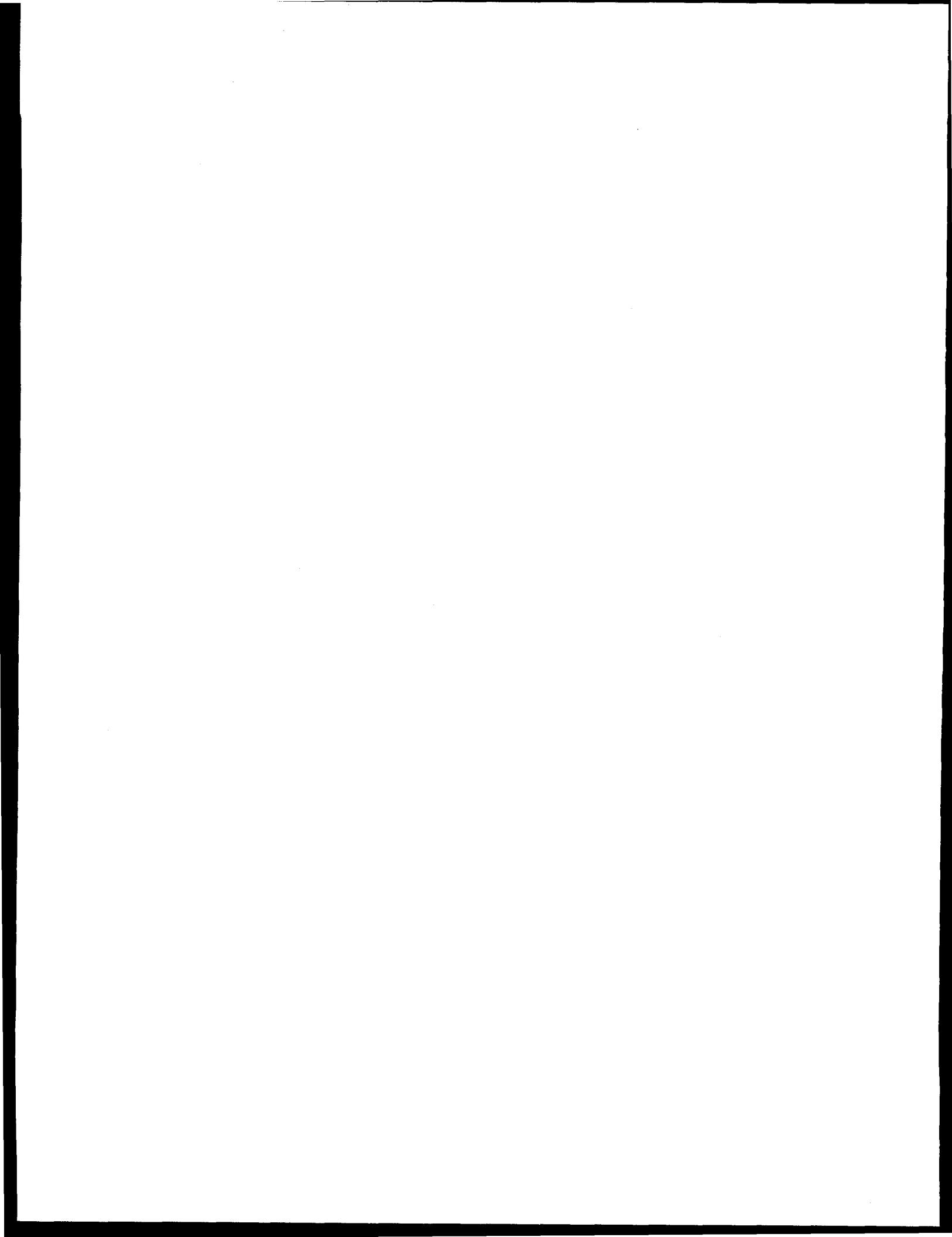
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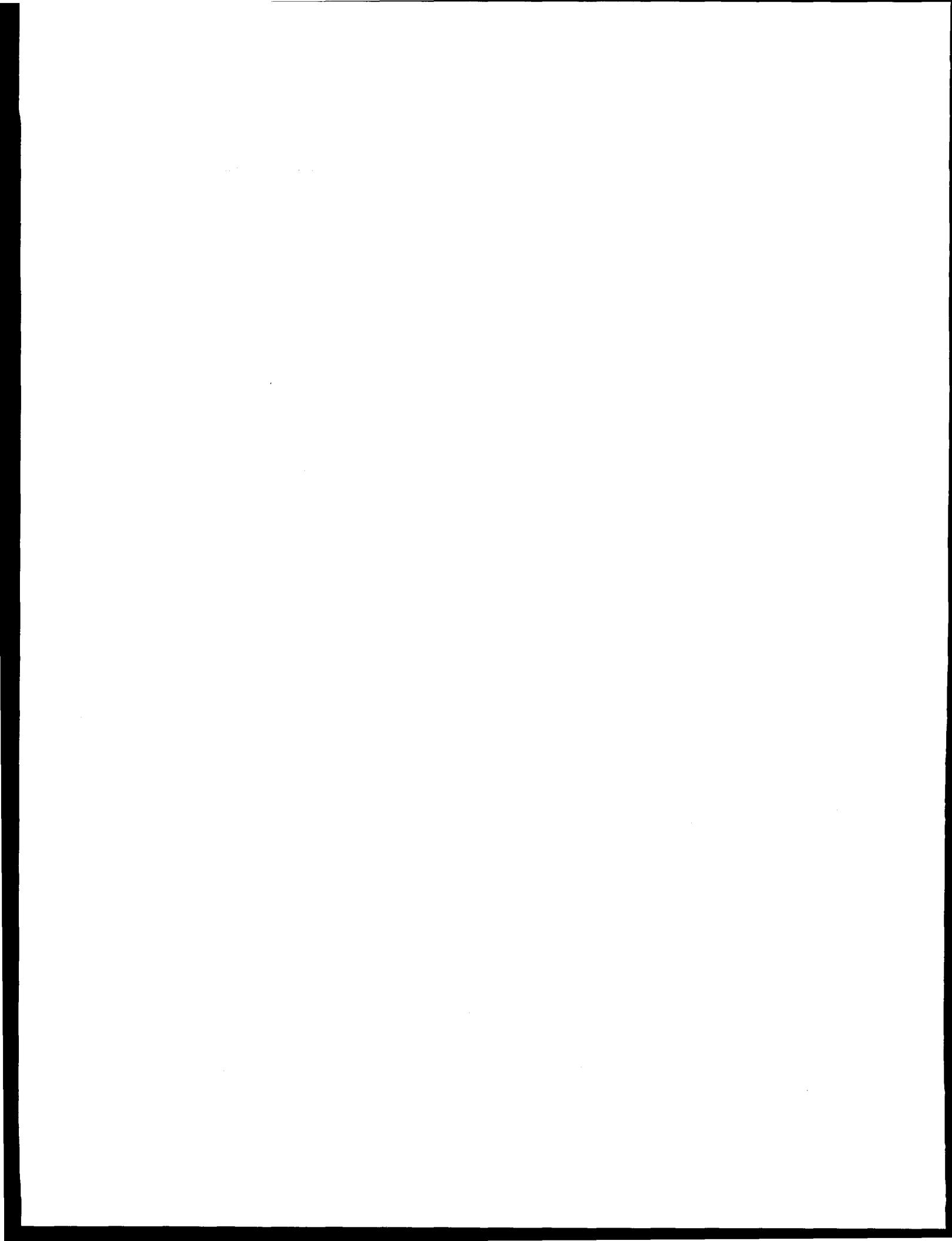
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## Introduction

**B**uildings use approximately one-third of the energy consumed in the United States. The potential energy savings derived from reduced infiltration and ventilation in buildings are substantial, since energy use associated with conditioning and distributing ventilation air is about 5.5 EJ per year. However, since ventilation is the dominant mechanism for removing pollutants from indoor sources, reduction of ventilation can have adverse effects on indoor air quality, and on the health, comfort, and productivity of building occupants.

The Indoor Environment Program in LBL's Energy and Environment Division was established in 1977 to conduct integrated research on ventilation, indoor air quality, and energy use and efficiency in buildings for the purpose of reducing energy liabilities associated with airflows into, within, and out of buildings while maintaining or improving occupant health and comfort. The Program is part of LBL's Center for Building Science. Research is conducted on building energy use and efficiency, ventilation and infiltration, and thermal distribution systems; on the nature, sources, transport, transformation, and deposition of indoor air pollutants; and on exposure and health risks associated with indoor air pollutants. Pollutants of particular interest include radon; volatile, semivolatile, and

particulate organic compounds; and combustion emissions, including environmental tobacco smoke, CO, and NO<sub>x</sub>.

*Research on exposure and risk analysis for indoor air pollutants* provides a broad perspective on indoor air quality and the associated health and comfort risks. Such research helps establish the relative significance of various categories of pollutants. Methods for estimating distributions of exposures for populations and new exposure metrics and risk-assessment methods, based on an understanding of fundamental biological processes, are developed as part of this effort.

*Studies of whole buildings* are undertaken in field experiments. Relationships among human health, comfort and productivity, and environmental and building factors are investigated in such studies. Whole-building field studies also provide knowledge of subsystem dynamics with respect to energy and air movement and aid in the development of representative databases for modeling U.S. buildings' energy use in as well as population exposures to indoor pollutants.

*Air infiltration and ventilation rates* are measured and modeled for residential and commercial buildings to understand energy transport and thermal losses from various components of building shells and ventilation systems. Methods for reducing energy losses are developed

based on these studies. The effectiveness of ventilation systems for pollutant removal is also investigated. Methods for characterizing ventilation and building energy use are developed for experimental and applied uses.

*Indoor air quality studies* focus on understanding the dynamic processes that control pollutant sources, transport, transformation, deposition, re-emissions, and removal. Spatial and temporal variability of pollutants are also characterized. This research provides the basis for developing models for population exposures to various pollutant types.

*Research on control technologies and strategies* is directed toward developing the most cost- and energy-efficient method for each class of pollutant. Since source controls are often the most effective and energy-efficient method to improve indoor air quality, emissions from various types of indoor sources (combustion sources, building and furnishing materials, consumer products, office equipment, and so on) are characterized with respect to chemical composition and rates of emission. Entry of soil gases, containing radon and organic pollutants, into buildings is investigated through modeling and field measurements. The effects of ventilation and other control methods on source strengths and energy usage are investigated and evaluated.

## Program Staff

### Joan M. Daisey\*, Program Head

|                                 |                                      |                                   |                                   |                                     |
|---------------------------------|--------------------------------------|-----------------------------------|-----------------------------------|-------------------------------------|
| Jeff Alexander <sup>†</sup>     | Antonie de Ruijter <sup>†</sup>      | David Jump                        | Anthony V. Nero                   | Max Sherman                         |
| Carmen Alvarez <sup>†</sup>     | Margaret Demco <sup>†</sup>          | Claude Khalizadeh                 | Dale Nesbitt                      | Brian Smith                         |
| Cheryl Anderson <sup>†</sup>    | Richard Diamond                      | Douglas Lane <sup>†</sup>         | Deborah A. Nolan <sup>§</sup>     | Martyn T. Smith <sup>§</sup>        |
| Michael G. Apté                 | Darryl Dickerhoff                    | Arild Larsen <sup>†</sup>         | Timothy Nuzum                     | Robert C. Spear <sup>§</sup>        |
| Fred S. Bauman <sup>  </sup>    | Anushka Drescher <sup>†</sup>        | Victor Lee <sup>†</sup>           | Jonathan Owens <sup>†</sup>       | Corina Stetiu <sup>†</sup>          |
| Patrick Beagan <sup>†</sup>     | David Faulkner                       | Ken Leiserson <sup>†</sup>        | Bernd Paatsch <sup>†</sup>        | Carol A. Stoker                     |
| Abra Bentley <sup>†</sup>       | Helmut Feustel                       | Gina Leong                        | Doo Park <sup>†</sup>             | Holger Suess <sup>  </sup>          |
| Frederic Y. Bois                | Marc Fischer                         | Yanxia Li                         | Andy Peri <sup>†</sup>            | Eugene Suhh <sup>†</sup>            |
| Yves C. Bonnefous <sup>  </sup> | William J. Fisk <sup>†</sup>         | Tsair-Fuh Lin <sup>†</sup>        | Thu Phan                          | Doug Sullivan                       |
| F. Remi Carrié <sup>†</sup>     | Jennifer Frantz <sup>†</sup>         | Andres Litvak <sup>†</sup>        | Phillip N. Price                  | JoAnn Ten Brinke <sup>†</sup>       |
| Gee-Min Chang                   | Nathalie Furst <sup>†</sup>          | K.R.R. Mahanama                   | Richard J. Prill                  | Tracy Thatcher <sup>†</sup>         |
| Elizabeth Chong                 | Ashok J. Gadgil                      | Don Maszle <sup>†</sup>           | Kenneth L. Revzan                 | Chuong Tran <sup>†</sup>            |
| Tegan Churcher <sup>†</sup>     | Katherine Ann Gallagher <sup>†</sup> | Nance Matson                      | William Riley <sup>†</sup>        | Gregory W. Traynor                  |
| Joyce D. Cordell                | Karina Garbesi                       | Jan Maurer <sup>†</sup>           | Allen Robinson <sup>†</sup>       | Burke Treidler                      |
| Bruno DeMartinis <sup>†</sup>   | Karine Guillot <sup>†</sup>          | Mark J. Mendell <sup>†</sup>      | Lev Ruzer <sup>†</sup>            | Arnaud Van Den Bossche <sup>†</sup> |
|                                 | Lara A. Gundel                       | Shelly Miller-Leiden <sup>†</sup> | Payam Saisan <sup>†</sup>         | Mike Van Loy <sup>†</sup>           |
|                                 | Alfred T. Hodgson <sup>†</sup>       | Mark Modera                       | Tony Sasse <sup>†</sup>           | John D. Wooley                      |
|                                 | Nori Hudson                          | William W. Nazaroff <sup>§</sup>  | Gail Schiller-Brager <sup>§</sup> | Mindi Xu                            |
|                                 | Richard Jansky                       | Matty Nematiollahi                | Richard G. Sextro                 | Derek Yegian <sup>†</sup>           |
|                                 | Patricia Johnson                     | Eilif Nerland <sup>†</sup>        | Bharat Shah <sup>†</sup>          | Andrew Young <sup>†</sup>           |
|                                 |                                      |                                   |                                   | Lan Zhou <sup>†</sup>               |

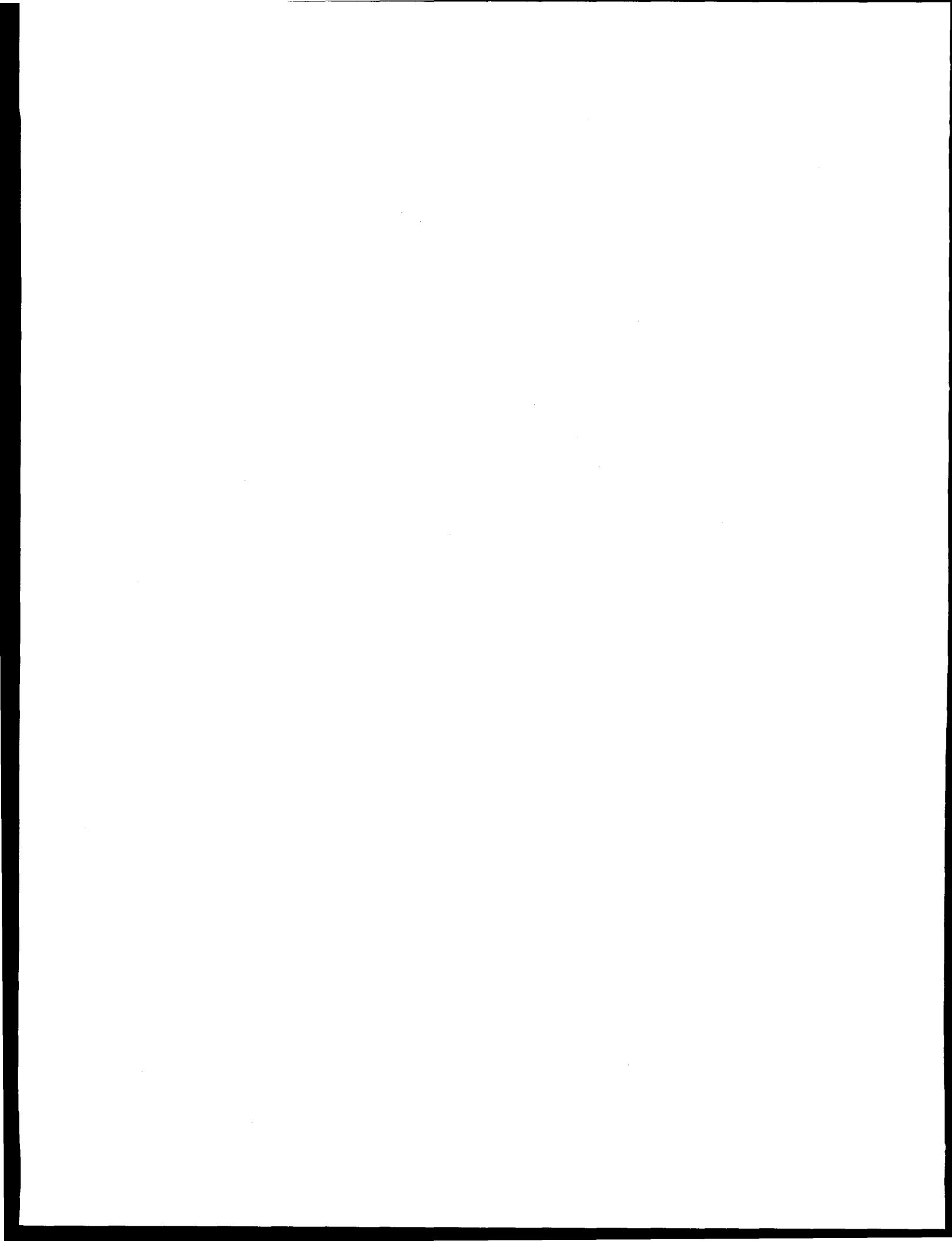
\*Group Leader

<sup>†</sup>Student

<sup>‡</sup>Deputy Group Leader

<sup>§</sup>Faculty Scientist

<sup>||</sup>Participating Guest



# Energy Performance and Ventilation in Buildings

## Existing Buildings Efficiency Research

R. Diamond, M. Modera, H. Feustel, D. Dickerhoff, D. Jump, C. Stetiu, B. Treidler, J. Warner

With current forecasts for only a modest growth rate for new residential and commercial buildings, most short-term energy-savings potential lies in existing buildings. In addition to improving the energy efficiency of existing buildings, improved comfort for occupants is an important issue when buildings are retrofitted or rehabilitated.

Our work in residential buildings encompasses duct retrofits in single-family houses, air-leakage studies in low-rise multifamily buildings, and ventilation studies in high-rise multifamily buildings. In single-family houses, thermal conditioning is usually provided by forced-air systems. In addition to a poor performance in transporting conditioning energy, forced-air systems usually permit duct and system losses due to air leakage and insufficient insulation, which increase energy use and decrease performance. In multifamily residences we studied the leakage characteristics before and after rehabilitation and retrofitting. Airflow distribution simulations were performed for a high-rise multifamily building to determine changes in air-flow patterns and energy use before and after the building was retrofitted. Our work also shows that small commercial buildings offer significant energy-savings potential by improving their systems' performance. Part of our effort in understanding these buildings was to characterize HVAC performance and to understand the interactions between the buildings and the systems.

### Duct Retrofits in Single-Family Residences

Inefficiencies in air-distribution systems have been identified as a major source of energy loss in U.S. sunbelt homes. Research indicates that approximately 30-40% of the thermal energy delivered to ducts passing through unconditioned spaces is lost through air leakage and conduction through the duct walls. Field experiments over the past several years have documented the expected lev-

els of air leakage and the extent to which retrofits can reduce that leakage. Energy savings have been documented to a more limited extent, based upon a few field studies and simulation model results. Simulations have also indicated energy loss through ducts during the off cycle caused by thermosiphon-induced flows; however this effect had not been confirmed through experiments.

We undertook a major field study to measure the impact of duct retrofits—both duct sealing and duct insulating. A key part of the work was to optimize a retrofit protocol that could be used in utility Demand Side Management (DSM) and other programs. Preliminary results from eleven houses (six measured in winter, five measured in summer) indicate that the retrofits reduced overall duct leakage area approximately 64%, which translated to a reduction in envelope Equivalent Leakage Area (ELA) of approximately 14%. Wrapping ducts and plenums with R-6 insulation translated to a reduction in average flow-weighted conduction losses of 33%. These experiments confirmed the appropriateness of using duct ELA and operating pressures to estimate leakage flows for the population, but also indicated significant variations between these estimates and measured flows on a house-by-house basis. In addition, these experiments confirmed the existence of the predicted thermosiphon flows under winter and summer conditions. Finally, average duct leak-sealing and duct insulation costs per house (1800 ft<sup>2</sup> floor area on average) were \$300 and \$380, respectively. These costs were high because of the detailed protocol involved in this study. In an actual DSM program, we would expect that the costs would be considerably less.

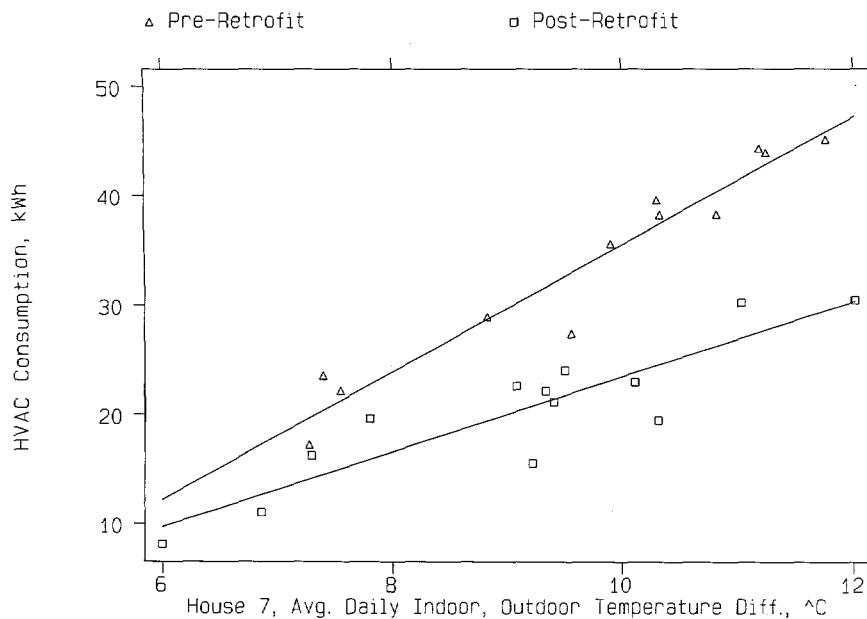
### Impacts of Duct Retrofits on Heat-Pump Performance

Research efforts to improve residential heat-pump performance have tended to focus on laboratory and theoretical studies of the equipment itself, with some

limited field research focused on in-situ performance and installation issues. One issue that has received little attention is the interaction between the heat pump and the duct system to which it is connected. We took field performance measurements before and after sealing and insulating the duct systems on three heat pumps. From the pre-retrofit data we found that reductions in heat-pump capacity due to low outdoor temperatures or coil frosting was accompanied by lower duct-system energy-delivery efficiencies. We found the reductions in conduction loss (and thus improvements in the delivery temperature improvements due to adding duct insulation) to vary widely, depending on the length of the particular duct section, the thermal mass of that duct section, and the cycling characteristics of the heat pump. In addition, we found that the use of strip heat back-up decreased and that heat-pump cycling increased dramatically after the retrofits, which respectively increased and decreased savings due to the retrofits. Finally, normalized energy use for the three systems, which were operated consistently pre- and post-retrofit, showed an average reduction of 19% after retrofit, which corresponds to a change in overall distribution-system efficiency of 24% (Figure 1).

### Ventilation in High-Rise Multifamily Buildings

The DOE-HUD Initiative is a response to the National Energy Strategy's directive to improve the energy efficiency in public housing. Under the Initiative's guidance, a collaborative project has been established to demonstrate energy efficiency in public housing as part of a utility's DSM program. The partners in this project include the U.S. DOE Boston Support Office, the Boston Edison Company, the Chelsea Housing Authority, with technical support from the Citizens Conservation Company and two national laboratories—Oak Ridge National Laboratory (ORNL) and LBL. The



**Figure 1.** Energy savings due to duct leakage and insulation retrofits. The figure plots total daily HVAC consumption versus indoor/outdoor temperature differential for a house using a heat pump for space-heating needs. The figure shows the significant reduction in energy consumption due to the duct retrofits.

demonstration site is the Margolis Apartments, a 150-unit high-rise apartment building for the elderly and handicapped, located in Chelsea, Massachusetts, in the greater Boston metropolitan area.

To better understand the air-flow patterns within the high-rise building, air-leakage measurements were made at the site and used with the multizone air-flow simulation model, COMIS. We performed parametric studies taking into consideration infiltration, mechanical ventilation, wind speed, wind direction, and temperature difference between inside and outside, as well as leakage distribution.

The simulation results show a strong tendency to have cross ventilation when high winds blow perpendicular to the facades (as often occurs during the winter). Furthermore, the three shafts (two staircases and one elevator shaft) introduce a significant stack effect when temperature differences between inside and outside exist. This effect is magnified by heating the staircases during the winter.

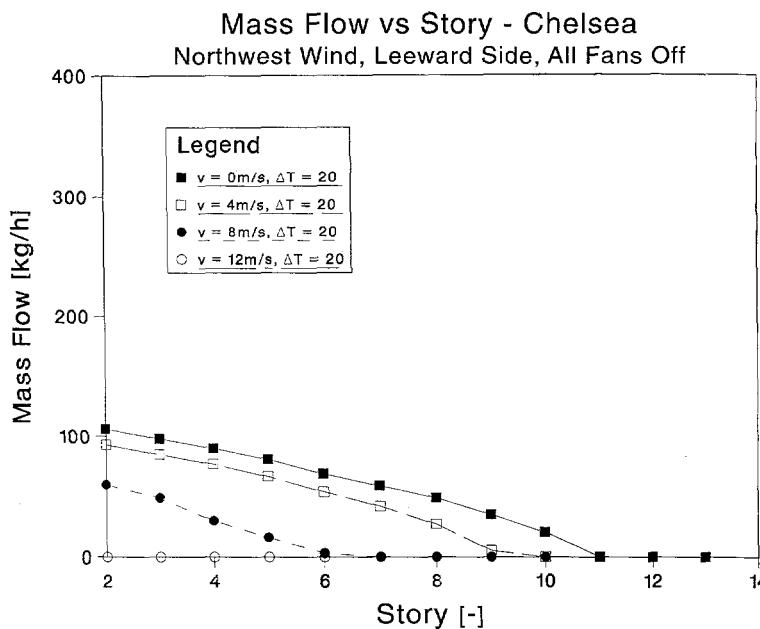
The results show that the mechanical ventilation systems cannot avoid cross ventilation or reduce the stack effect significantly. Local exhaust, however, keeps units at a lower pressure than ambient, thus increasing the overall infiltration for the building. Ventilation air supplied to the corridors cannot reduce the cross flow; however, it mixes with the air

coming from the windward-side apartments and therefore reduces pollutant concentrations in the air flowing into the leeward-side apartments on the same story (Figure 2).

### Packaged Air Conditioners in Small Commercial Buildings

As part of our research in improving the energy efficiency of small commercial buildings we examined relatively new 5-ton packaged rooftop air conditioner/furnaces in two strip-mall retail stores in California. The experiments included measurements of distribution-system leakage: distribution-system leakage to the outside, the relative leakage on the return and supply sides of the fan, flows through all diffusers/registers, building-envelope leakage, fan power and compressor power, duct and plenum pressures during normal operation, and distribution-system temperatures (all diffusers and plenums) during normal cyclic operation.

For all three systems, a large fraction of duct/equipment leakage was to the outside. The average leakage area to the outside was found to be  $225 \text{ cm}^2$ . Assuming an outside temperature of  $35^\circ\text{C}$ , a supply plenum temperature of  $10^\circ\text{C}$ , and a room temperature of  $25^\circ\text{C}$ , these leakage levels and an average pressure differential of  $60 \text{ Pa}$  translate to a thermal energy loss of 3 to  $7.5 \text{ kW}$ , depending upon whether the leaks are on the return or supply side of the fan. For the 5-ton units studied, these losses should result in an increase in system on-time of 17% to 43% under the assumed temperature conditions.



**Figure 2.** Air flow for the leeward-side apartments with the mechanical ventilation turned off, for the Margolis Apartment building in Chelsea, Massachusetts. The upper floors receive no infiltration, and air flow is below the ASHRAE ventilation standard (roughly  $50 \text{ kg/h}$ ) for several of the apartments, particularly at higher wind speeds.

Because 35%-65% of the ducts were located outside the conditioned space for the three systems, we measured conduction losses from these ducts and examined two means of reducing these losses. A key observation was that surface temperatures were as high as 65°C on the sunlit surfaces of the ducts, whereas the roof-side surfaces were 35°C

and the outdoor temperature, 33°C. Increasing the insulation levels to 2 inches would save 54 watts on the surface of the box and 200 watts on the surfaces of the ducts, whereas painting the surfaces of the box and ducts white would provide thermal energy savings of 70 and 250 watts for the box and ducts respectively. A 320-watt load reduction would reduce

the on-time of a 5-ton system by 2%.

A surprising result of these case studies was that the building envelopes were significantly less tight than residential envelopes: 10 to 12 cm<sup>2</sup> of ELA per m<sup>2</sup> of floor area versus 6 cm<sup>2</sup>/m<sup>2</sup> for pre-1980 California houses. Visual inspection of the buildings showed that little care had been taken to keep the envelopes tight.

## Residential Thermal Distribution Systems

M. Modera, R. Jansky, D. Jump, B. Treidler

Residential thermal distribution systems, which in the U.S. are predominantly duct systems, are a key determinant of space-conditioning energy use. In collaboration with Brookhaven National Laboratory, we performed a study that estimated a current savings potential (i.e., with dissemination of existing technologies and knowledge) of almost 1 quad per year in 2020 and a full savings potential (i.e., with an integrated research, development, and dissemination effort) of somewhat more than 2 quads per year in 2020. In 1990, we initiated a multi-year research program focused on understanding and improving the efficiency of residential duct systems. Co-sponsored by the California Institute for Energy Efficiency, the U.S. Department of Energy, and the U.S. Environmental Protection Agency, this research program includes performance modeling, field experiments, technology development, and codes and standards development. The overall goal of this vertically integrated research program is to help transform the marketplace for residential thermal distribution systems into one that produces energy-efficient, cost-effective systems on a regular basis, in both existing houses and in new construction.

### Performance Modeling

The goal of our modeling work is to develop and utilize the tools required to evaluate the energy and comfort performance of existing and alternative thermal distribution technologies. Our performance modeling work was focused in two areas this year: 1) development and application of a simple technique for predicting the energy implications of thermosiphon-induced air flows through duct systems, and 2) development and application of a model for predicting the interaction between duct systems and variable-capacity HVAC equipment.

Buoyancy differences between warm and cold air in ducts and houses produce thermosiphon-induced flows through duct systems when heating or cooling equipment is not operating. The goal of our work this year was to be able to predict the impact of duct insulation levels on thermosiphon air-flow and heat-transfer rates. Simulations performed for the first week in January on a well-insulated house in Atlanta, Georgia, showed that for a duct system with airtight attic supply ducts and crawlspace return ducts, the energy losses due to thermosiphon-induced flows were 12% for R-4 ducts and 7% for R-8 ducts.

Earlier work has shown that the heating or cooling capacity of the equipment connected to a duct system has a significant impact on the efficiency of that duct system. We augmented our simulation tool this year to allow us to simulate the performance of two-speed air conditioners. The key finding, obtained by applying the new model, was that two-speed (dual-capacity) air conditioners are much more sensitive to duct-system efficiency compared with single-capacity equipment. One reason is that the efficiency of the duct system is lower when the air conditioner is operated in its low-speed high-efficiency mode. However, an even

larger issue was that inefficient ducts increase the efficiency of single-speed equipment and decrease the efficiency of two-speed equipment. The increased load resulting from duct losses reduces cycling losses for single-capacity equipment, but increases the fraction of time that two-speed equipment is forced to operate in its high-speed, low-efficiency mode. The end result is that the fractional energy savings associated with replacing the single-speed unit with the higher efficiency two-speed unit is reduced by approximately 50% due to typical attic duct-system inefficiencies (Table 1).

### Field Experiments

Our field experimentation seeks to improve our understanding of how thermal distribution systems perform in the field, to validate our modeling techniques, and to develop and test diagnostic and efficiency-improvement technologies. During the past year we performed a field study of a residential duct retrofit protocol including duct sealing and insulation retrofits. (The impacts and costs of those retrofits are discussed in the previous article). Our field study has also provided detailed data on the interactions among duct systems, air-conditioning and heating equipment, houses, and people.

**Table 1.** Simulated impacts of duct-system efficiency on the cooling season energy consumption of single-speed and two-speed air conditioners

| Parameter   | Single-Speed A/C<br>(SEER ~12) | Two-Speed A/C<br>(SEER ~16) | Ratio |
|---|--------------------------------|-----------------------------|-------|
| Cooling energy use (100% efficient ducts)                         | 1228 kWh                       | 866 kWh                     | 0.71  |
| Cooling energy use (typical ducts)                                | 1770 kWh                       | 1548 kWh                    | 0.88  |
| Typical duct system efficiency                                    | 0.68                           | 0.65                        | 0.96  |
| A/C equipment efficiency ratio<br>(typical ducts over 100% ducts) | 1.08                           | 0.91                        | 0.84  |

Our analysis of pre- and post-retrofit data from three houses with heat pumps confirmed two effects predicted by our simulation tool: equipment cycling should increase after the retrofit, and the use of electric-resistance back-up heat should decrease after the retrofit. Due to the larger impact of the retrofit under more extreme weather conditions, the increase in cycling due to reduced duct losses was most prominent at low outdoor temperatures, the post-retrofit cycles per hour being more than twice the pre-retrofit value at outdoor temperatures of 35-40 °F. Similarly, at outdoor temperatures of 40-50 °F, the energy consumption of the electric resistance heaters was reduced by 87%, whereas the overall savings was only 27%, indicating the reduced need for electric resistance back-up after the retrofit. Both of these results confirm the effective increase in HVAC system capacity associated with duct repair (Table 2).

Another important result obtained from the heat-pump field monitoring was a confirmed improvement in comfort associated with duct repair. Specifically, monitoring of all register temperatures showed that the long duct runs benefited disproportionately from the addition of duct insulation, resulting in an improvement in the uniformity of heating. In addition to the improvement in room temperature uniformity, most of the long runs were providing air to the registers that was too cold for comfort. Since the occupants responded very favorably to the retrofits for these reasons, these results can prove very useful in the marketing of more efficient thermal distribution systems.

### Technology Development

Our technology development work this year included three research efforts:

- development of an aerosol-based sealing system,
- development of ducts based on a novel insulation technology (air gaps bounded by low-emissivity plastic films), and
- development of air-tight duct fittings.

The aerosol sealing technology is described in a separate article. The work on advanced insulation and airtight fittings resulted in a technical report describing our progress on each of the technologies, as well as our assessment of the commercial feasibility of the conceptual products developed. The general conclusion of the feasibility study was that the airtight fittings merit further pursuit in the short term, and that the advanced-insulation

**Table 2.** *Measured impact of a duct-sealing and insulation retrofit on electric resistance and total space-conditioning energy consumption on comparable nights for a heat pump in a Sacramento, California, house with attic ductwork.*

| Parameter                        | Pre-Retrofit | Post-Retrofit | Change |
|----------------------------------|--------------|---------------|--------|
| Average outside temperature (°F) | 45.0         | 45.5          | n/a    |
| Total HVAC energy use (kWh)      | 17.1         | 12.5          | -27%   |
| Strip heat energy use (kWh)      | 3.3          | 0.5           | -85%   |

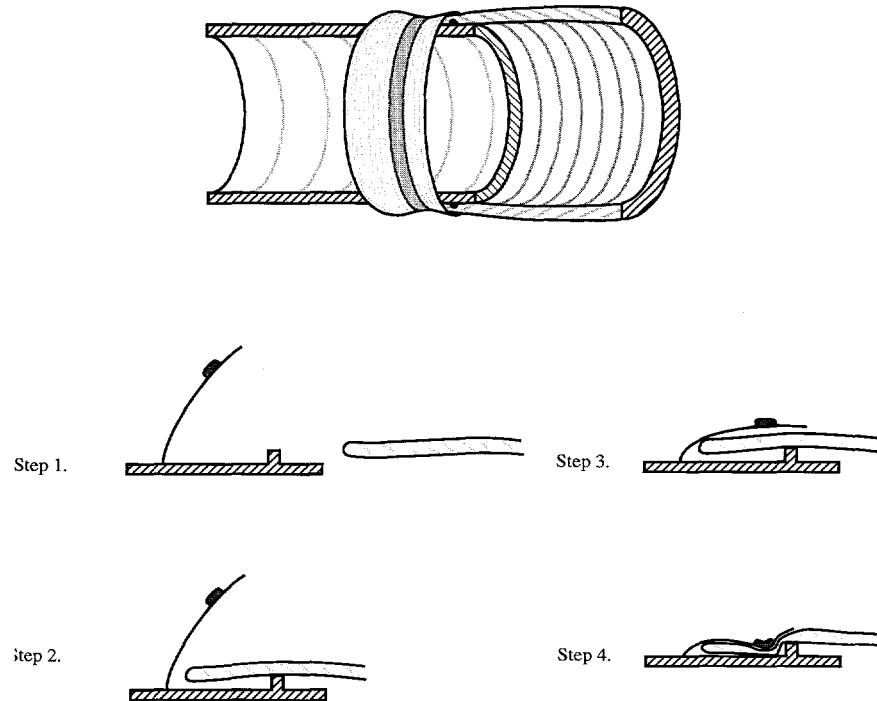
ducts may not prove to be competitive in the present market. The key issue with the advanced insulation ducts was the need to use high-cost fire-retardant plastics. The airtight fitting concept did not encounter any significant barriers, and will be pursued during the next year (Figure).

### Codes and Standards

A significant barrier to improving the energy efficiency of residential duct systems is the present lack of appropriate incentives for improvement and penalties for poor performance. Our codes and standards efforts are directed towards addressing this barrier. We had two major codes and standards efforts this year: 1) a sensitivity analysis of the cost-effectiveness of increasing duct insulation requirements in building codes, and 2) di-

rection of the ASHRAE Standards Project Committee (SPC152P) charged with developing a standardized method for determining the efficiency of residential thermal distribution systems.

Tightening the requirement for duct insulation in building codes should reduce conduction losses from conventional duct installations to cost-effective levels. The idea is to elevate the bottom of the market by means of minimum standards that can be enforced by building inspectors. Our sensitivity analysis confirmed the expectation that typical insulation levels could be increased without incurring increased first cost to the consumer. As an example, increasing the insulation level of flexible plastic supply ducts in the attic of a 1500 ft<sup>2</sup> house from R-4 to R-8 entails an increase in duct costs of \$60-\$100. However, the increase in overall system



**Figure.** *A new method for attaching wire-flex ductwork to fittings. The intention of the design is to eliminate the taping and strapping currently done by installers.*

capacity at design weather conditions due to this insulation allows the air-conditioning equipment to be downsized, yielding a first-cost savings of \$60-\$100. In this example the consumer would receive a \$30-\$40 annual energy cost savings without any additional first cost.

The purpose of the ASHRAE standard is to develop a yardstick to compare the efficiencies of various duct systems and hydronic distribution systems on an

equal footing, and thus to provide a flexible means for rewarding improved performance or penalizing poor performance. The standard is presently organized so as to provide three pathways for determining distribution-system efficiency. One pathway, geared towards researchers and measurements on unconventional systems, makes a direct measurement of overall system efficiency, from which distribution efficiency is derived. A second

pathway, based upon relatively common diagnostic measurements, is geared towards home energy-rating systems and utility programs that reward improved efficiency. The third pathway does not entail any measurements, as it is directed towards houses that have not yet been built. In this case the efficiency is estimated from design specifications (e.g., duct location, layout, materials, sealing procedures, insulation level, and so forth).

## Aerosol-Based Duct-Sealing Technology

M. Modera, F. Remi Carrié

Because the largest cost associated with sealing leaks in existing air-distribution systems is the labor for the location and sealing process, there is a large potential for improving the cost-effectiveness of such a retrofit by reducing the required labor. Field studies of duct-sealing programs using HVAC contractors show that labor costs vary between three and six times the material costs. Moreover, these studies have found that in many instances leaky ductwork is impossible to access. Over the past three years we have obtained proof-of-concept within the laboratory for a technique to seal duct systems remotely by an internally injected aerosol. Our laboratory tests have shown that both holes in the ducts, as well as leaks between duct joints, can be sealed remotely, and that the sealing can be accomplished even for ductwork that has bends and junctions.

### Aerosol Sealing

To develop a successful technology for remotely sealing leaks with an aerosol, we needed to solve two fundamental problems: how to preferentially deposit aerosol particles at the leaks (rather than on the walls) of the duct, and how to ensure that particles spanned and ultimately fully sealed the leaks. The solution to the first problem involved two steps: 1) choosing an aerosol small enough to reach the leaks before settling out of the flow stream, yet large enough to leave the air-flow streamlines at the leaks, and 2) choosing and controlling the flow rate and pressure in the duct system to expand the range of acceptable aerosol sizes. The solution was to use turbulent flow to minimize particle transit time through the duct system and gravitational settling, and to use particles of 2-20  $\mu\text{m}$  in diameter (Figure 1). The problem of spanning the leaks was solved by assuring that the particles were essen-

tially solid phase and therefore would not deform when they were deposited at the leak boundaries. This step was accomplished by controlling the flow rate and relative humidity of the pressurizing

airstream to assure that all of the carrier liquid evaporates within a short distance of the aerosol injection point.

To help us understand and predict the efficiency of the sealing process, we

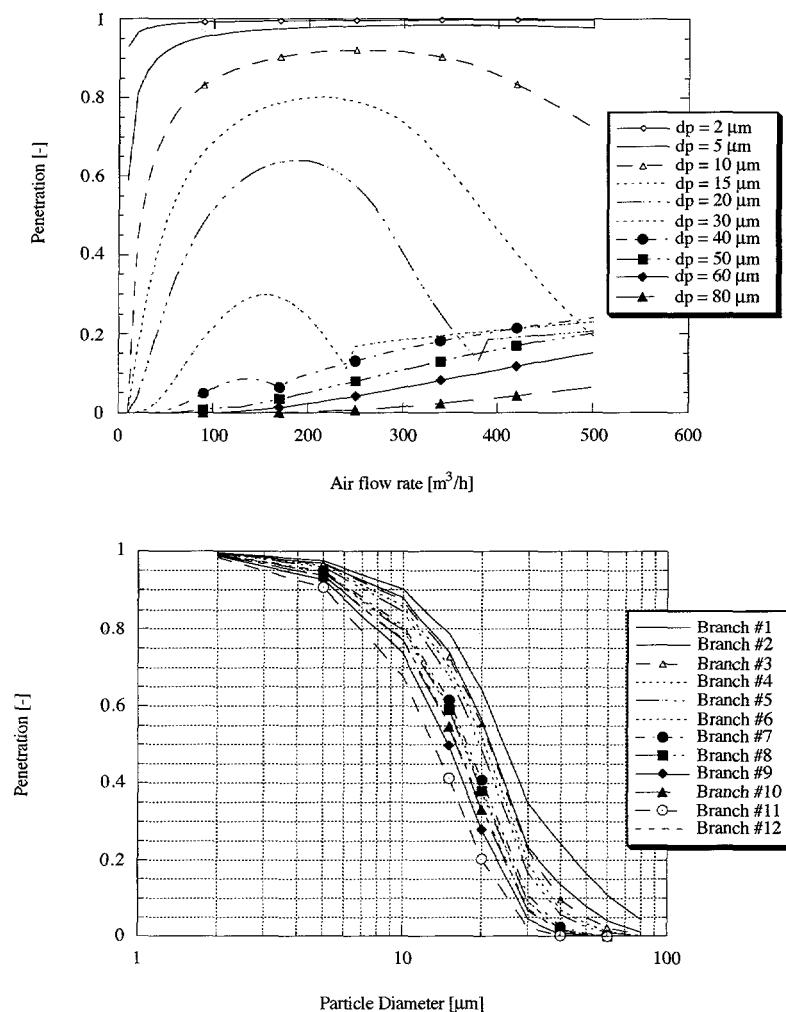


Figure 1. Fraction of aerosol particles that reach the end of a 10-m long, 15-cm diameter duct as a function of flowrate and particle size.

developed a simplified model of the rate of particle deposition on the leak boundaries. This model predicts the fraction of aerosol passing through the leak that will be deposited on the boundaries of the leak as a function of the particle size, the pressure and flow conditions, the size of the leak, and the thickness of the leak boundaries. This model was verified by videotaping the sealing process (Figure 2) and was shown to work remarkably well over the range of our experiments (Figure 3).

#### In-Situ Sealing Apparatus

We designed, built, and field-tested an in-situ aerosol sealing apparatus this year. This apparatus is designed for portability and ease of use. It does not require the use of desiccants and simply requires two 15A/110V circuits. In addition to performing the sealing process, the field apparatus also measures the leakage of the duct system before and after sealing, thereby eliminating the need for additional hardware (Figure 4).

During the past year the in-situ sealing apparatus performed well in a field test of one house. The device was found to seal approximately 60% of the leakage in the duct system within about 15 minutes of sealing time, with approximately \$6 worth of sealing material. In fact, the tape used to seal the registers temporarily during the sealing process cost more than the sealing material. Set-up time far exceeded the sealing time. Present efforts are focused on designing reusable, quick-installation seals for the registers and HVAC heat exchangers. The field test included testing of particle and volatile organic compound (VOC) concentrations before and after sealing. Total Suspended Particles (TSP) were found to decrease after the sealing process, and no change in VOC concentrations was detected after the sealing process. The longevity of the seals is being studied by tracking the duct-system air-tightness. The degree of sealing has remained stable over the four months of non-operation since the original sealing process. However, a more difficult test will come this winter, when the system will cycle continuously in heating mode, thus creating larger stresses on the seals.

Efforts next year will include accelerated laboratory testing of the seals produced by the aerosol, as well as larger-scale field testing, construction of a second prototype, and related activities required for commercialization.

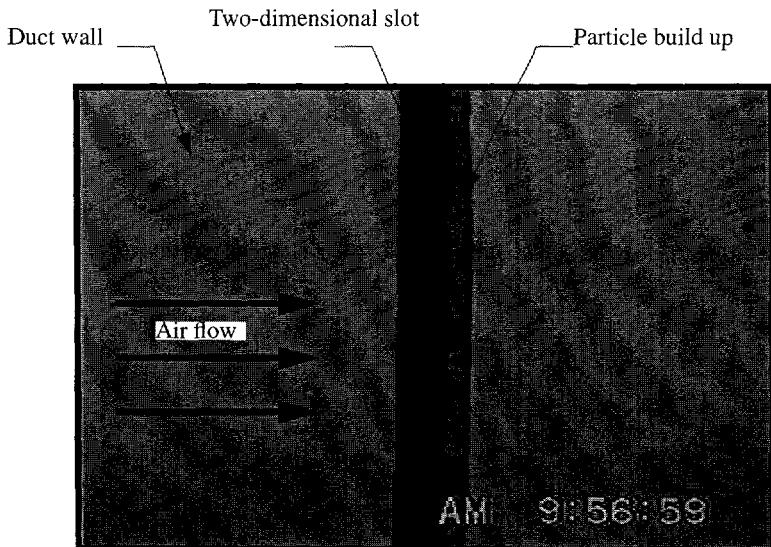


Figure 2. Top view of a 3-mm by 40-mm slot after 20 minutes of injection.

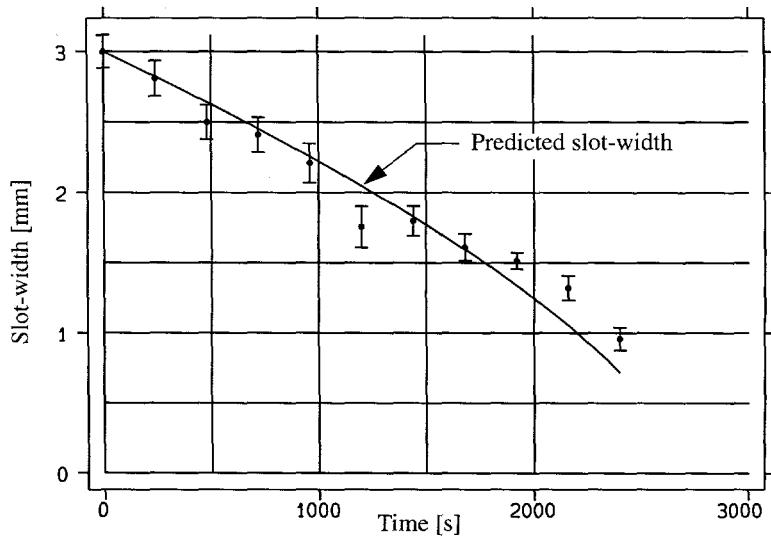


Figure 3. Predicted and measured slot width over the course of the sealing process for a 3-mm by 40-mm leak.

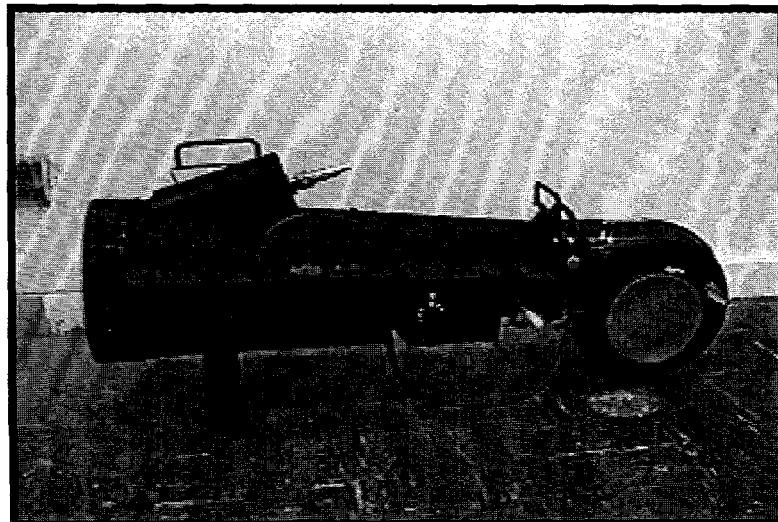


Figure 4. First prototype of in-situ sealing apparatus.

## Air Leakage in U.S. Houses

M. Sherman, D. Dickerhoff

Blower doors are used to measure air tightness, the prime factor determining infiltration and leakage of air in buildings. All information about the air tightness of buildings is derived from field measurements of fan pressurization using blower door technology. This project, which focuses on single-zone buildings, summarizes the measured air-leakage data for U.S. dwellings. While fan pressurization techniques are sometimes used for component or multizone leakage measurements, the vast majority of measurements have been made for whole-building, single-zone situations, such as single-family homes. The data summarized here pertain to a wide variety of vintages, construction types, and conditions of single-family homes throughout the United States.

Air-leakage data are now used to understand both qualitative (e.g., construction quality control) and quantitative (e.g., envelope tightness standards) factors. As the key envelope property related to air flow, leakage data are used in one form or another for infiltration-related modeling. Given such diverse uses, these data are often treated as a stand-alone quantity, even though air-leakage values are only intermediate quantities.

In gathering our dataset we required that all data be of single-family detached dwellings from known locations in the United States. In addition to air-tightness data, we required that the size and number of stories of the dwellings be known. We requested, but did not always receive, more detailed information including the leakage exponent, the year of construction, the type of construction, floor/basement type and HVAC system, the building height, and any information regarding retrofits or the general building condition.

Most of the data we used were not collected by the LBL team, but were either published or volunteered by other researchers or practitioners. The full LBL report (see References) acknowledges the sources. Included in our database are 12,946 individual measurements on more than 12,500 houses from the listed sources, including about 450 homes from the numerical database of the Air Infiltration and Ventilation Centre (AIVC).

The sample collected cannot statistically represent the almost 75 million

single-family households in the United States. Furthermore, different constituent datasets and measurements have different qualities and should not be treated equally. Taking into account these restrictions, we must accept that these data represent the best set currently available and we use that set to summarize the important physical characteristics. Work continues on extrapolating this dataset to represent the U.S. housing stock.

We analyzed the data first to determine some overall trends in the leakage dataset without regard for the building properties and then to examine the relationship between the details of the building and its leakage. The table summarizes the overall content of the dataset and includes several variables relating the leakage information.

We can use the dataset to determine if a useful correlation exists between the two methods of quantifying leakage. The average ratio between air changes per hour at 50 Pa ( $ACH_{50}$ ) and Normalized Leakage (NL) is 17.5, with a standard deviation of 2.3, indicating that a 13% extra uncertainty can be introduced when converting directly between these two quantities. In general we will use Normalized Leakage rather than air changes at 50 Pa to make our leakage comparisons.

The leakage values in the table are averages of pressurization and depressurization values whenever both existed. One question that has often been posed is whether there is a significant difference between the two. We analyzed all the cases in which both were measured and found that of the 280 usable measurements, pressurization tests reported 9% higher leakage on average than did depressurization tests. Since the mean error is 2%, this difference is significant. The 9% value was calculated from the NL

values. We repeated the analysis using the air changes at 50 Pa. We observed the same trend but with a larger average (i.e., 12%) value and a narrower distribution.

This result suggested that there might be a difference in exponent between pressurization and depressurization, but our analysis shows no statistically significant difference. We also looked at the general distribution of exponents and they appear quite clustered, even though there were many nonphysical outliers. The average exponent for the 1973 measurements that reported exponents is 0.65, with a standard deviation of 0.08.

In examining regional trends we attempted to use regression techniques to determine if any leakage trends were created by climate, latitude, and other variables. Our analysis showed no significant trends with these climate-related parameters, indicating the trends in leakage are more dominated by construction quality, local practices, age distribution, and so forth than they are by weather. We also examined the dataset in some detail to look at five building criteria that may impact leakage: number of stories, floor/basement type, thermal distribution system, retrofitting, and dwelling age.

### Number of Stories

Most of the U.S. housing stock consists of one- and two-story, single-family dwellings. We examined the entire dataset to determine if differences in construction type affect the leakage. Approximately 56% of our measurements are for multistory dwellings, and we found that multistory houses are 11% leakier than single-story houses with an error of the mean near 1%. This statistically significant value leads us to conclude that leakage is different between single- and multiple-storied dwellings.

**Table. Summary of leakage measurements**

| Kind of Measurements         | Number of Measurements | Mean  | Std Dev. | Min.  | Max.  |
|------------------------------|------------------------|-------|----------|-------|-------|
| Year Built                   | 1492                   | 1965  | 24.2     | 1850  | 1993  |
| Floor Area [m <sup>2</sup> ] | 12946                  | 156.4 | 66.7     | 37    | 720   |
| Normalized Leakage           | 12946                  | 1.72  | 0.84     | 0.023 | 4.758 |
| $ACH_{50}$                   | 12902                  | 29.7  | 14.5     | 0.47  | 83.6  |
| Exponent                     | 2224                   | 0.649 | 0.084    | 0.336 | 1.276 |

### Floor/Basement Type:

We restricted our consideration of this issue to two classes: those dwellings that had floor leakage to the outdoors (i.e., houses with crawl spaces and unconditioned basements) and those that had no floor leakage to the outdoors (i.e., slab-on-grade and fully conditioned basement homes). The vast majority (80%) of our dataset had floor leakage. The subset that did not was slightly (5%) tighter and this value was statistically significant.

### Thermal Distribution System

Because of the current interest in the efficiency of residential thermal distributions systems, we analyzed those homes (1442) where we had knowledge about the existence (or absence) of a duct system. The surprising (and not yet explained) result was that the homes with duct systems (43% of this subset) were tighter ( $NL = 0.7$ ) than those without ( $NL = 0.9$ ). Where duct systems were measured separately (only about 130 homes), they accounted for just under 30% of the

total leakage—a finding consistent with other studies.

### Retrofitting

A subset (465 houses) was measured as part of retrofit or weatherization projects. Both pre- and post-retrofit measurements were available. We found that the average retrofit reduced leakage by about 25% (from  $NL = 1.34$  to  $NL = 0.99$ , with the error of the mean difference being  $NL = 0.03$ ).

### Dwelling Age

We examined those data for which the year of construction was available to ascertain if leakage trends correlated to the age of the dwelling. Detailed examinations indicated a break point at the year 1980. The 628 houses built after 1980 did not show any leakage trend with age and were tighter ( $NL = 0.47$ ) than average. The 869 houses built prior to 1980 showed a clear increase in leakage with increasing age and were, on average, leakier ( $NL = 1.05$ ) than new houses. However, those houses were

still tighter than the average of the entire dataset.

The impact of ducts, the effect of retrofits, and information about the year of construction are available only for subsets of the data. Furthermore, these subsets themselves appear to be tighter than the dataset as a whole. We believe this probably reflects the fact that in the larger, broader studies, less information was recorded, whereas the detailed studies tended to include more information about better construction.

Another significant finding is that dwellings appear to be even leakier than previously estimated. This current analysis includes large datasets that represent much more comprehensive cross sections of ordinary homes in particular locations (e.g., Rhode Island, Alaska, Vermont, and so on) than had been previously studied. Although not evenly distributed around the United States, these more intensive studies suggest that our previous leakage estimates were biased toward tighter housing, probably because more energy-efficient houses have been studied in detail.

## Thermal Conditioning of Commercial Buildings

H.E. Feustel, H.-G. Kula, J. Maurer, C. Stetiu, H. Suess, F. Winkelmann

### Hydronic Thermal Distribution

Thermal energy-distribution systems represent the vital link between heating and cooling equipment and conditioned building spaces. In the United States, approximately 10 EJ of primary energy annually pass through generally inefficient thermal distribution systems in buildings. Because the load shape due to inefficient distribution systems is often more peaked than general space-cooling demand, distribution efficiency improvements can provide even larger savings during peak electricity demand.

Fans that transport cool air through ductwork for cooling non-residential buildings with all-air systems contribute a significant share to the energy use of a building. This energy consumption can be lowered by reducing the cooling load of the building, reducing the requirements of mechanical cooling, and improving thermal distribution within the building.

If ventilation and thermal conditioning are separated (air-and-water systems), the amount of air transported through buildings can be reduced significantly. In this case, the cooling would be provided

either by convection (e.g., fan coils) or by radiation and convection (e.g., cooled ceilings). Water is used as the transport medium, and the ventilation is provided by outside air systems without recirculating the air. Due to the physical properties of water, hydronic thermal distribution systems can remove a given amount of thermal energy using less than 5% of the fan energy otherwise necessary.

### Hydronic Radiant Cooling

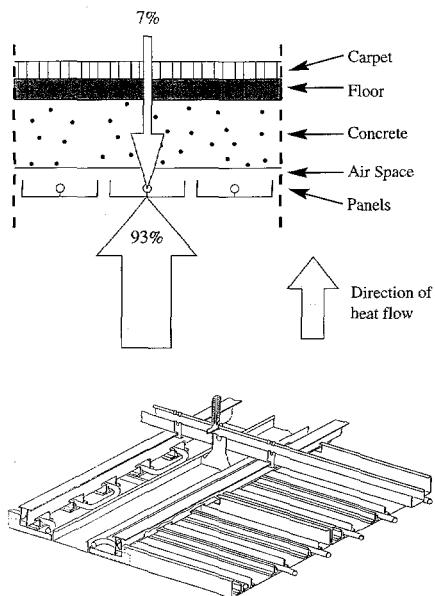
Buildings can be cooled by convection only or by a combination of radiation and convection. The latter strategy uses cool surfaces in the conditioned space to cool the air and the space enclosures. Although only about 60% of the heat transfer is due to radiation, these systems are called "radiative" cooling systems.

Most hydronic radiant cooling systems can be categorized into three different designs. The most often used system is the panel system (Figure 1a), which uses suspended aluminum panels connected to metal tubes. The second system contains cooling grids made up of closely placed small plastic tubes (Figure 1b).

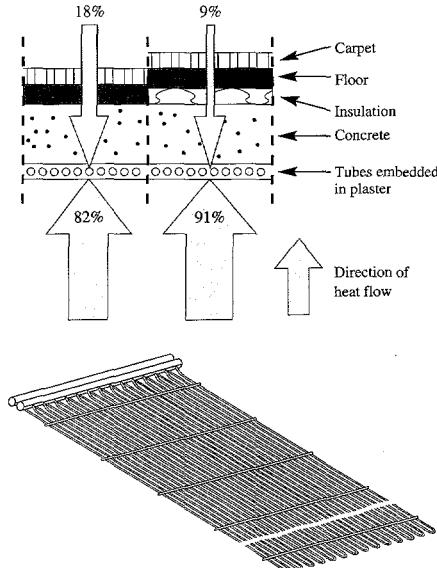
The grids can be imbedded in plaster, gypsum board, or mounted on metal ceiling panels. The third system is based on the idea of a floor heating system. Metal or plastic tubes are imbedded in the core of a concrete ceiling (Figure 1c). The thermal storage capacity of the ceiling allows for peak shifting.

When compared with conventional all-air systems, hydronic radiant cooling systems show several advantages. Owing to the large surfaces available for the heat exchange, the coolant temperature is only marginally lower than the room temperature, allowing the use of either heat pumps with high COP values or alternative cooling sources. The reduced air supply not only lowers the fan power requirement but reduces noise and draft, thus enhancing human comfort. In combination with a displacement ventilation system, an even temperature distribution can be achieved in the space. Reduced convective heat transfer improves the level of thermal comfort for the occupants.

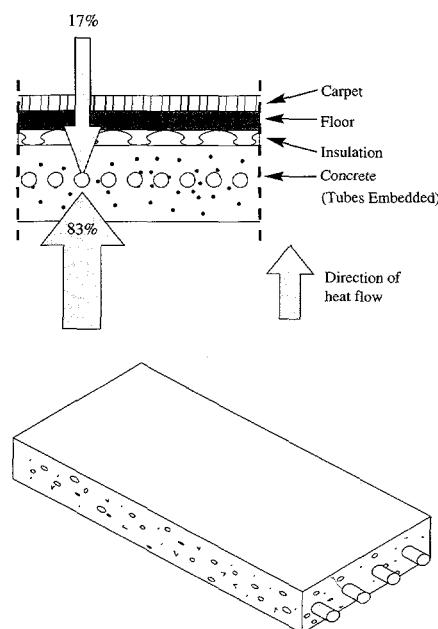
The power-reduction potential of hydronic radiant cooling systems is on



**Figure 1a.** Suspended ceiling-panel system for hydronic cooling. (Drawing courtesy of Fläkt Lufttechnik GmbH)



**Figure 1b.** Capillary tube system for hydronic cooling. (Drawing courtesy of KaRo Information Service)



**Figure 1c.** Concrete core system for hydronic cooling

the order of 40% when compared to conventional all-air systems (Figure 2). If alternative cooling sources are applied, the savings potential increases significantly.

Energy analysis programs such as DOE-2 are not capable of simulating hydronic radiant systems (although attempts to adapt DOE-2 have been made). A separate module designed to model hydronic radiant cooling, including the two-

dimensional heat transfer in concrete slabs, has been developed by EPOB researchers together with LBL's Building Energy Simulation group in the SPARK (Simulation Problem Analysis Research Kernel) environment. This program (RADCOOL) was evaluated using DOE-2 for passive structures and using measured field data from the European Headquarters of Dow Chemicals for active

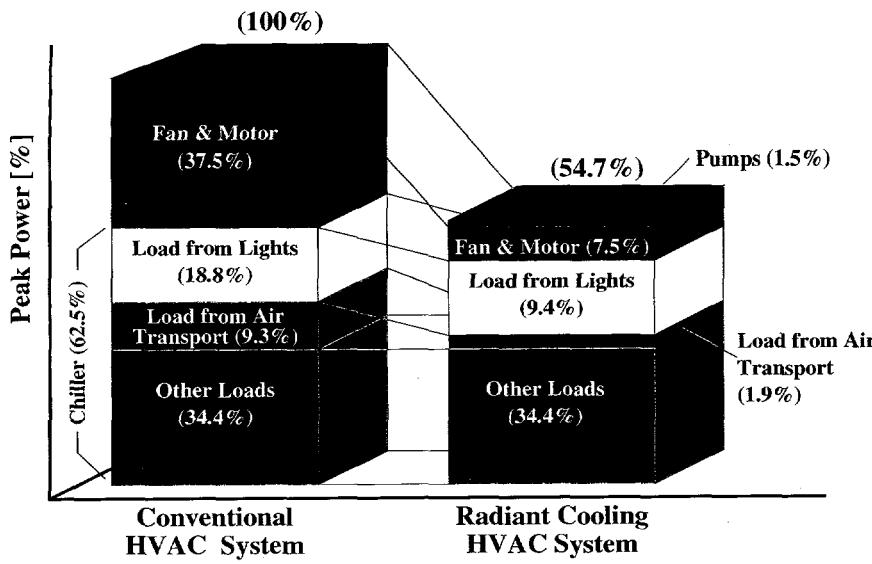
structures. The intermodel comparison as well as the comparison with measured data are satisfactory (Figure 3).

#### Environmental Assessment of Low-Energy Cooling for Commercial Buildings

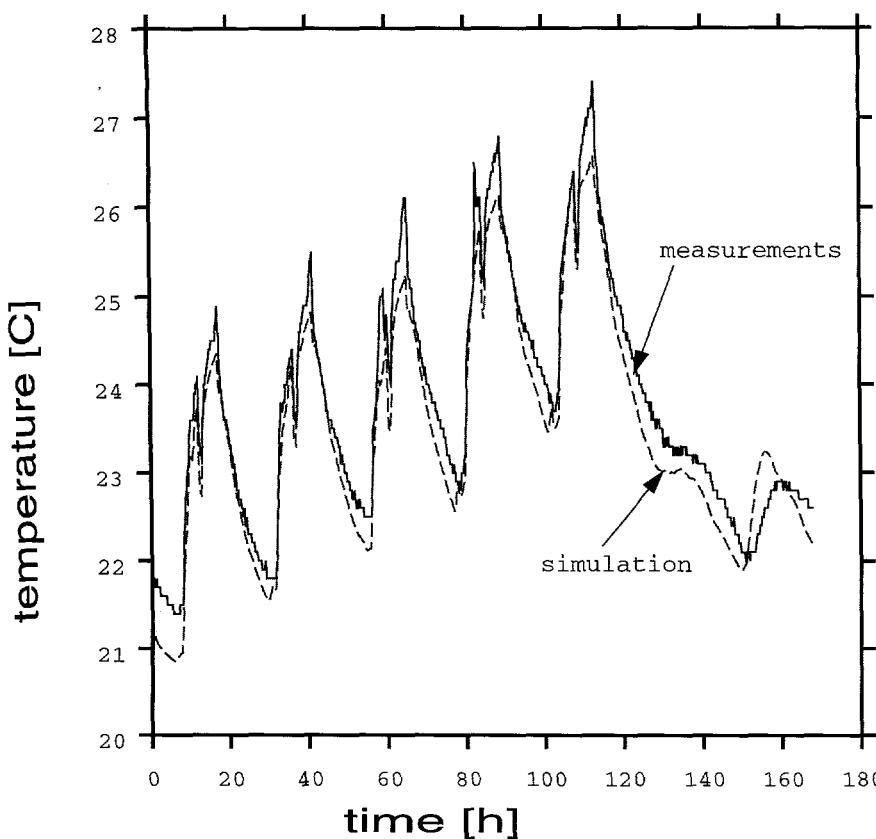
Low-energy cooling systems are alternatives to motor-driven compressor cooling systems. In non-residential buildings, the power to operate the compressor at design conditions amounts to approximately two-thirds of the electrical power required for an all-air system. Therefore, replacing motor-driven compressors constitutes a significant energy conservation measure with peak-power-reduction potential.

Low-energy cooling systems provide a given standard of air quality and thermal comfort to building occupants at a lower primary energy input. Before applying low-energy cooling technologies, the following steps should be taken:

- The building envelope must separate the conditioned space from the ambient influences by means of high-thermal insulation or blockage of irradiation;
- Internal loads must be reduced by improving the lighting efficiency and by use of efficient equipment (plug-load);
- Thermal storage must be implemented to reduce the amplitude and to phase-shift loads into unoccupied hours;



**Figure 2.** Comparison of electrical peak power load for conventional systems and radiant cooling systems. Percentages are relative to overall peak power for the conventional system.



**Figure 3.** Comparison between RADCOOL simulations and measurement data. The temperature profiles correspond to an office space in the DOW-Europe building in Switzerland.

- The buildings' thermal distribution system must be optimized by separating the tasks of ventilation and thermal conditioning; and
- The equipment used to transport air and water through the building, as well as electric motors, must be designed to operate at high efficiency.

Only after these steps have been taken, can low-energy cooling sources effectively perform their task as an alternative to compressor-driven cooling.

We see that low-energy cooling is a result of a combination of architectural design, the selection of materials, equipment, HVAC technology, and the cooling source. However, the general concern is not the "energy" itself but its environmental impact. The energy used to operate the building, i.e., what is used to produce materials, or that consumed in the building processes, and the use of other resources, for example, water to be evaporated for cooling purposes, has effects beyond those of its immediate purpose.

Low-energy cooling systems generally result in reduced energy consump-

tion during operation but often cause increased material input. It is therefore essential to make an integral assessment of the factors influencing the environmental impact of such systems. An assessment must be based on a life-cycle inventory, concerning all relevant substances and effects, and should take care of the real configuration and of the annual performance of such systems including the human behavior.

For this project we considered new, well-built non-residential buildings, several European and North American climate conditions, and a combination of thermal distribution systems and alternative cooling systems.

We are investigating a number of the following thermal distribution systems, cooling technologies, cooling sources, and energy sources for heat-operated machines:

- all-air systems vs. air-and-water systems
- radiant cooling vs. convective cooling (air and water)
- ground coupling (air and water)

- evaporative cooling (direct, indirect, and cooling towers)
- absorption chillers (gas- and waste-heat-operated water-fired units)
- desiccant cooling (air cooling and dehumidification)
- night ventilation (direct and indirect)
- solar collectors
- fuel cells.

These systems will be compared with conventional reference cooling systems to make an integral assessment of both cost and environmental effects such as greenhouse effect, ozone depletion, photochemical smog, and acidification.

#### Energy-Savings Potential of Structural Thermal Storage Utilizing Phase-Change Material

Cooling of non-residential buildings contributes significantly to electrical consumption and peak demand. The peak cooling load requires utilities to provision peak-power plants and size their distribution network accordingly. For a building's owner, the peak cooling load determines the size of the equipment (and therefore, the part-load ratio), the demand charges imposed by the utility, and the choice of the cooling source. To avoid high demand charges, to down-size the cooling systems, and to be able to switch to low-energy cooling sources, building owners can take several steps:

- incorporate facades that provide an effective shelter from ambient conditions
- install high-efficient thermal distribution systems (e.g., hydronic systems)
- apply thermal conditioning by radiation rather than by convection
- provide thermal mass
- utilize low-energy heating and cooling sources.

In the past, large thermal storage devices have been used to overcome the shortcomings of alternative cooling sources, to avoid high demand charges, and to improve the part-load ratio. Buildings designed to make use of thermal storage include features that increase thermal mass. These may be for storage only or they may serve both as storage and as structural elements. Several structural materials, including concrete, steel, adobe, stone, and bricks, satisfy the requirements for sensible heat storage.

Latent heat storage uses a phase change material (PCM) as a storage medium. During transition in phase—freezing, melting, condensing, and boiling—the material absorbs or releases large

amounts of heat without changing temperature. Applications typically involve liquid/solid transitions. The PCM is solidified when cooling resources are available and melted when cooling is needed.

With PCM implemented in gypsum board, plaster, or other wall-covering material, thermal storage can be part of the building's structure. PCMs have two important advantages as storage media: they can offer an order-of-magnitude increase in heat capacity and their discharge is almost isothermal. High amounts of energy can be stored without changing the temperature of the sheathing. As the storage takes place in the part of the building where the loads occur, rather than externally, additional transport energy is not needed.

Phase change material can only store energy, but not remove it. In passive applications of structural thermal storage, the heat is released into the room as soon as the room air temperature falls below the phase change temperature. The thermal energy can then be removed by means of ventilative cooling (night ventilation or economizer mode), which provides significant savings due to reduced chiller operation.

#### Peak Power-Reduction Potential of Solar-Assisted Absorption Chillers

The alternative cooling source to be investigated is a combination of absorption chillers and solar collectors. Both components have seen significant improvements over the last few years. Multi-stage absorption chillers show improved COP values, and new solar collectors covered with transparent insulation material outperform their glass-covered counterparts.

Absorption chillers are heat-operated machines that use an absorbent and a gaseous refrigerant that has been vaporized in the evaporator. The evaporation process absorbs heat, thus providing the needed refrigeration. The absorption cycle uses a heat-generating operator, a heat-rejecting absorber, and a liquid solution pump to produce the pressure differential necessary for the refrigeration cycle. The heat applied to the generator can come from several sources, including natural gas or solar devices. The absorption cycle substitutes a physio-chemical process and a pump for a purely mechanical compressor.

The advantage for the absorption chiller is that only the pumps (solution pump, chiller pump, and condenser pump) consume electrical energy; the main driving force is the thermal energy required for the absorption process. Because of their limited efficiency, absorption chillers are only economical if the thermal energy can be provided at a relatively high temperature level and at low cost. If the required heat cannot be provided by the solar system, this alternative cooling source switches to gas rather than electrical energy. Therefore, the electrical peak power reduction is independent of the availability of solar heat.

If no excess heat is available, the thermal energy requirement can be provided by solar collectors. The main advantage of solar-assisted cooling is the correlation between the solar power and the cooling load requirement of the building. While conventional flat plate collectors have a low efficiency at high operating temperatures, newly designed flat plate collectors with transparent insulation material (TIM) exceed the performance even of expensive vacuum tube collectors. The production of these flat plate collectors is as simple as the production of collectors without honeycomb structure. The price should be only slightly higher than the price of a conventional flat plate collector, but considerably lower than the price of a vacuum tube collector.

The use of solar-assisted absorption heat pumps as a cooling source for non-residential buildings has a significant

peak-power reduction potential. The electrical energy used to operate the absorption chiller is very small compared with the electrical energy required to operate a comparable compressor (the electrical energy requirement of the solution pump is less than 1% of the cooling power output of the absorption chiller). The additional energy necessary to operate the solar collector loop and the increased condenser pump consumption are only marginal. Therefore, the Coefficient of Performance (COP) based on the electrical requirement (COP<sub>e</sub>) is much better than that of conventional compressor systems (Figure 4).

The goal of this project is to develop a cooling source module based on existing simulation tools and to assess the cooling power potential of this alternative cooling source for several California climates. The results of this assessment will be compared with the cooling power requirement and the energy consumption for a base-case building equipped with compressor cooling located in the same climate zones.

A solar-assisted absorption chiller has the following advantages:

- Electrical peak power reduction due to fuel-switching (solar collector with gas back-up)
- Reduction of fossil fuel consumption due to solar assistance
- Correlation between maximum solar gain and peak cooling load
- Reduced environmental risks due to avoidance of CFCs
- Availability for retrofit applications.

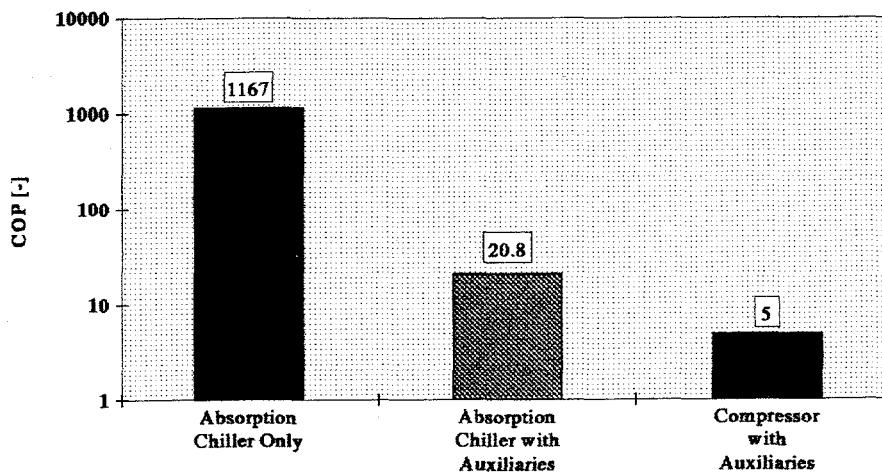


Figure 4. Coefficient of performance (COP) based on the electrical requirement compared with COP of conventional compressor systems.

## International Studies in Ventilation Modeling

H.E. Feustel, B.V. Smith, J.L. Warner

The flow of an air mass within a given building is driven by pressure differences evoked by wind, thermal buoyancy, mechanical ventilation systems, or a combination of these. Airflow is also influenced by the distribution of openings in the building shell and by the inner pathways.

Increased awareness of the effects of air infiltration on the overall conditioning load of buildings has led to tightened construction both of building components as well as the overall building shell. While decreasing infiltration rates and the related ventilation heat losses and cooling requirements, tightening has sometimes created problems with the indoor air quality.

Airflow models can be divided into two main categories: single-zone and multizone models. Single-zone models assume that the structure can be described by a single, well-mixed zone. The major application is the single-story, single-family house with no internal partitions (e.g., all internal doors are open).

Nevertheless, since a large number of buildings have floor plans that would categorize them as multi-zone structures, more detailed models, taking internal partitions into account, have been developed. The building is described by a set of zones interconnected by flow paths. Each node represents a space (zone) with uniform pressure conditions inside or outside the building and the interconnections correspond to impediments to airflow. These network models are usually based on the conservation of mass in each of the zones in the building.

The COMIS workshop (Conjunction Of Multizone Infiltration Specialists) at LBL led a multinational team of experts to develop a multizone airflow model on a modular basis. The group at LBL gave special emphasis to the modular structure to facilitate the further development of the simulation tool.

### Annex 23

Within the framework of a technical committee, known as an annex, established by the Energy Conservation in Buildings and Community Systems program of the International Energy Agency (IEA), we are studying physical phenomena causing air flow and pollutant transport (e.g., moisture) in multizone buildings. An important part of this annex is the comparison between model results and results from in-

situ tests. Before these datasets could be used for model evaluation however, internal model comparisons based on benchmark buildings had to be made.

The annex participants have undertaken a task-sharing project that spans five and a half years and involves model development, data acquisition, and analytical studies. The project is structured into three subtasks:

#### *Subtask 1: System Development*

A multizone air-flow and pollutant-transport model is being developed on the basis of the COMIS model by developing flexible expert routines, incorporating additional modules, and developing user-friendly interfaces for input and output.

#### *Subtask 2: Data Acquisition*

Datasets are being obtained for evaluation and as input for the model.

#### *Subtask 3: System Evaluation*

The model is being evaluated using intermodal comparisons as well as data obtained from Subtask 2.

Results of these subtasks are intended for researchers and consultants and will promote energy-efficient building designs. Close cooperation is intended to coordinate state-of-the art reviews, data collection, and defining cases for evaluation with other pertinent projects. As part of its ongoing work plan, the Air Infiltration and Ventilation Centre (AIVC) will disseminate the results of this particular annex. A database for evaluation purposes has already been prepared by AIVC.

In 1994, COMIS 1.3 was tested and distributed to interested parties. It includes calculation of two-directional air-

flow through large vertical openings (e.g., open doorways) brought about by air-density differences (i.e., temperature or humidity differences in rooms connected by large openings). The User Guide has been updated to reflect the status of the program and a Programmer's Guide has been written. Measurements have been performed to obtain data to be used in the evaluation exercise. Intermodal comparisons have been performed, and the results of a first user test have been analyzed.

Due to its international character, COMIS is expected to become a standard in multizone air-flow modeling. COMIS is currently being used in Belgium, Canada, China, France, Germany, Great Britain, Italy, Japan, The Netherlands, Sweden, Switzerland, and the United States. LBL's Energy Performance of Buildings Group is using the model for several of the studies currently being performed and is planning its use for future work. COMIS is currently used for the "Duct Leakage Study" performed for the California Institute of Energy Efficiency (CIEE), the "Modeling Radon Entry into Florida Crawlspace Homes" project co-sponsored by EPA and the State of Florida, the "Residential Ventilation Systems" project co-funded by New York State Research and Development Authority (NYSERDA) and CIEE, and the "Alternatives to Compressor Cooling" project sponsored by CIEE.

Lawrence Berkeley Laboratory is managing the annex on behalf of the U.S. Department of Energy. By the end of FY 1994 Belgium, Canada, France, Greece, Italy, Japan, The Netherlands, Switzerland, and the United States had officially committed to participate in the annex.

## Residential Ventilation Systems

H.E. Feustel, N.E. Matson, J.L. Warner

We have undertaken a study 1) to evaluate air tightness in recently constructed single-family dwellings, 2) to evaluate the effectiveness of various strategies to provide adequate ventilation, and 3) to study the use of ventilation strategies by builders and heating, ventilation and air-conditioning (HVAC) contractors. This research project focuses on single-family detached dwellings in the states of California and New York. The New York portion of this ongoing project is presented here.

### Evaluation of Building Tightness and Ventilation Rates

Two New York State leakage datasets were examined. One dataset consists of 50 houses (control houses) in New York State built after 1980, while the other dataset consists of 47 houses from the NYSE-Star energy-efficient residential building program (NYSE-Star houses). The NYSE-Star program is a builder-incentive program sponsored by a consortium of New York State utilities and energy agencies. The program

requires that houses be built to allow a maximum air-change rate of 7/h at 50 Pa pressurization. Mechanical ventilation systems are recommended but not required by the NYSE-Star program.

The NYSE-Star program houses are, on average, slightly larger than those of the control houses (240 m<sup>2</sup> vs. 212 m<sup>2</sup> of floor area). Most of the houses in each dataset are two-story houses with basements. Approximately one-third of the basements are heated. The NYSE-Star houses, with an average of 4.42 air changes at 50 Pa (std. dev. = 1.70), are tight compared to other U.S. residences that have been measured. In comparison, the control houses tend to be somewhat looser, but still relatively tight, with an average of 6.81 air changes at 50 Pa (std. dev. = 2.50).

Low- and peak-infiltration days were identified using the RESVENT model (an hourly simulation model based on the LBL infiltration model). On the low-infiltration days, for both datasets the average hourly air-change rates derived using the LBL infiltration model are below the 0.35/h minimum set by ASHRAE Standard 62. On the peak-infiltration days, the average hourly air-change rates are higher but not always high enough to meet Standard 62.

The figure shows the combined effective air-change rate as a function of the measured air-change rate at 50 Pa for the two datasets.

Only 23% of the NYSE-Star houses meet the ASHRAE ventilation standard, while 79% meet the ASHRAE tightness standard. This suggests that adequate ventilation is sacrificed in tightening the houses and lowering the infiltration-related space-conditioning loads. On the other hand, the control dataset has a higher percentage of houses (56%) meeting the ventilation standard while 52% of the houses meet the tightness standard. Only a small percentage, 2% of the NYSE-Star dataset and 8% of the control dataset, are able to meet both standards, suggesting that it is difficult to strike a balance between air tightness and adequate ventilation.

#### Evaluation of Residential Ventilation Strategies

COMIS, a multizone air flow model, was used to evaluate the air-change rates of a base case scenario and three ventilation strategies in a prototypical house on peak- and low-infiltration days in Buffalo, New York. The ventilation strate-

gies modeled include a central exhaust system with an outside air duct, a central exhaust system with room intake louvers, and a balanced ventilation system with heat recovery. The appropriate peak- and low-infiltration days for the air flow simulations were determined using RESVENT.

Based on this analysis, on both the low- and peak-infiltration days, the base case scenarios do not have adequate ventilation as required by ASHRAE Standard 62. The central exhaust/outside air duct option, while providing adequate ventilation on the peak-infiltration day, does not provide sufficient ventilation on the low-infiltration day. This standard is met on both the low- and peak-infiltration days by using either the central exhaust fan with intake louvers or the air-to-air heat exchanger.

#### Residential Ventilation Surveys

Two surveys are currently being conducted. One survey focuses on residential builders and HVAC contractors, while the other survey focuses on equipment distributors and retailers. Of the 60 builders and 40 HVAC contractors surveyed in New York, most (80%) have experience with the basic systems (bathroom and kitchen exhaust fans). More than half of the respondents (53%) have installed outside air ducts into a central system. Whole-house fans (18%), central

exhaust fans (14%), and intake louvers (13%) were installed by fewer respondents. Only a few have installed economizers (7%), located windows for optimum ventilation (6%), and installed ventilation shafts (2%). The total number of systems installed looks impressive, but in actuality, only a handful of respondents have installed the bulk of the systems reported. Most of the builders and contractors have installed only a few of the advanced ventilation strategies.

This project encompasses a wide spectrum of issues relating to building tightness, effectiveness of various ventilation strategies, and the reality of the marketplace and industry. We found there is a need to consider ventilation when building a tight house. Our analysis of ventilation strategies shows that central exhaust with intake louvers and air-to-air heat exchangers are effective in providing sufficient ventilation for both low- and peak-infiltration days in Buffalo, New York. And, while New York builders and contractors do have experience with various ventilation strategies, the number of installed advanced ventilation systems is still low in New York. This work is continuing, studying additional components and tasks related to ventilation in other New York and California climates. We are also preparing a Ventilation Guidebook for New York builders and contractors.

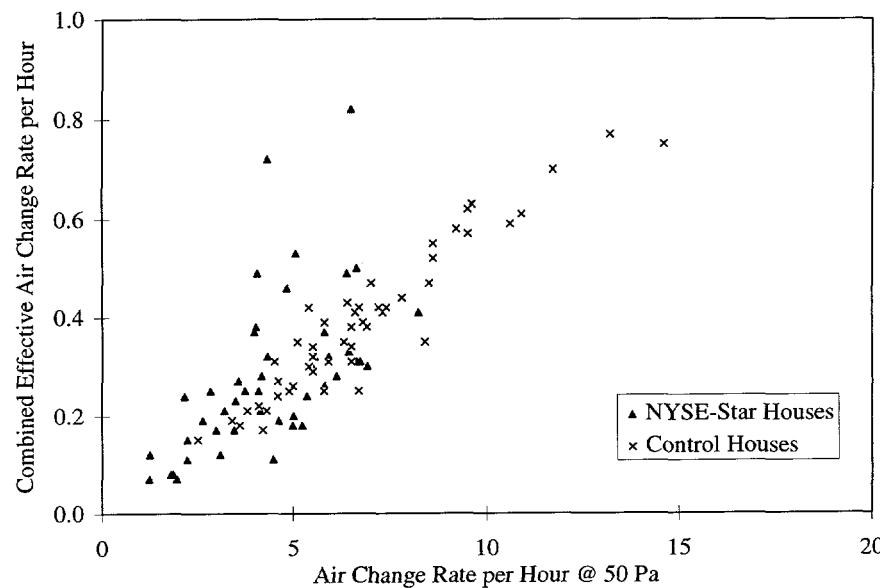


Figure. Calculated Air Change Rate (ASHRAE Standard 136) vs. Measured Air Change Rate (ACH50)

## Development of Smart Ventilative Cooling Systems

H.E. Feustel, H.-G. Kula, J.L. Warner

Ventilation has been identified as a prime candidate to replace compressor cooling in some climates. Ventilative cooling is any strategy that utilizes outdoor air in the cooling process, whether by direct cooling ventilation, in which ventilation air is supplied as cooling is desired, or by thermal storage ventilation, in which ventilation air is supplied primarily during off-peak hours to reduce the temperature of the thermal mass in a building. Direct cooling ventilation works by removing internal heat gains. The cooling effects of direct ventilation are enhanced because people feel cooler when air moves over them. Direct ventilation is primarily used in the transition climates, that is, those that are not extreme (outdoor temperatures below 32°C) with small (less than 10°C) diurnal temperature swings. For example, such a system appears to work well in Hawaii.

Thermal storage ventilation only works in climates with large diurnal tem-

perature swings. Air is supplied to the building during cool periods, both cooling the indoor air and storing coolness in the structure. Ventilation is reduced when the outdoor temperature rises. The indoor temperature rises more slowly than the outdoor temperature because the cool structure absorbs heat from the indoor air. Thermal energy storage is a means of accommodating the delay between the availability of cooling resources and the need for building cooling load.

Both methods of ventilative cooling may be either natural or induced. Induced ventilation must be used when the natural driving forces are inadequate or when the large openings in the building envelope that are required for natural ventilation would create an unacceptable security problem.

Control of many of the alternative systems is inherently more complex than compressor cooling. A "smart control strategy" for a single-zone building has been

developed within the framework of the multi-year, multidisciplinary "Alternatives to the Compressor Cooling for Residences" project. The control strategy begins with a determination of the need for cooling, based on whether the operative temperature (the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment) is above the upper summer limit. The control includes evaporative cooling, ventilative cooling, and ceiling fan operation. Evaporative cooling is invoked by override or if the operative temperature is above 27.5°C. If neither of the conditions is met, ventilative cooling is used when the interior/exterior temperature difference is greater than 2°C, and ceiling fans are turned on otherwise. If the operative temperature is between 20 and 26°C and at least 2°C higher than the outdoor temperature, precooling might be used in the form of ventilation.

## Indoor Radon Research

### Regional and National Estimates of the Potential Energy Use, Energy Cost, and CO<sub>2</sub> Emissions Associated with Radon Mitigation by Sub-Slab Ventilation

W.J. Riley, W.J. Fisk, A.J. Gadgil

Sub-slab ventilation (SSV) is the most commonly applied and thoroughly tested technique currently available to reduce radon entry into houses. A typical system consists of a pit in the sub-slab gravel layer into which a pipe connected to outdoor air has been inserted. A small fan in the pipe draws radon-bearing soil gas from the gravel layer and exhausts it to the outdoors. For the system to be effective, the pressure gradient between the basement and the gravel layer must be reversed throughout the gravel layer. This requirement drives the selection of fan power and the placement of the system pit(s).

For many houses, SSV systems effectively reduce indoor radon concentrations. However, the system's energy requirements can be considerable. In

addition to removing soil gas and radon from below the slab, house air may be drawn into the gravel layer and exhausted to the outdoors thereby increasing the overall house ventilation rate. Energy must be supplied to heat or cool this increased ventilation air flow and power the system fan.

In this study we estimated U.S. regional and national energy requirements, operating expenses, and CO<sub>2</sub> emissions associated with SSV systems. We assumed that the systems are installed in homes with indoor radon concentrations above the EPA remediation guideline and either basement or slab-on-grade construction. The analysis accounts for regional distributions of housing characteristics, types of heating fuels used, and heating and cooling loads. Estimates of

SSV system-operating expenses are computed with regional fuel prices. The associated CO<sub>2</sub> emissions are computed by considering each region's mix of fuel use and the emission factor associated with each fuel. The primary source of uncertainty in these estimates is the impact of the SSV system on house ventilation rates; 95% confidence intervals are provided based on this uncertainty.

Individual SSV system operating expenses are highest in the Northeast and Midwest at about \$93 ( $\pm 16$ ) per year per house, and lowest in the South and West at about \$62 ( $\pm 10$ ) per year per house. Regional impacts are largest in the Midwest because this area has a large number of mitigable houses and a relatively high heating load. We estimate that installing SSV systems in houses across the United

States—where it is both appropriate and possible—will annually consume  $1.6 \times 10^4 (\pm 4.0 \times 10^3)$  TJ of end-use energy, cost \$210 ( $\pm 37$ ) million (at current energy prices), and generate  $1.8 \times 10^9 (\pm 3.0 \times 10^8)$  kg of CO<sub>2</sub>. The energy consumed nationally by these SSV systems is approxi-

mately equal to the energy used by 2.3  $\times 10^5$  average U.S. cars; the CO<sub>2</sub> emissions are about equal to the emissions of 3.3  $\times 10^5$  cars.

Little research has been conducted to optimize the energy efficiency of SSV systems. Passive, or energy-efficient, sys-

tems offer opportunities to reduce the required fan energy and the additional house ventilation generated by an SSV system. Therefore, the heating and cooling expenses associated with SSV systems could be avoided and the overall operating costs significantly reduced.

## The Effect of Steady Winds on Radon Entry into Houses

W.J. Riley, A.J. Gadgil, Y.C. Bonnefous, W.W. Nazaroff

Wind has a substantial effect on radon entry rates and indoor concentrations in houses with basements. In addition to the well-established results that wind increases the building's ventilation rate and relative depressurization, soil-gas flow generated by wind-induced ground-surface pressures flushes radon from the soil near the house. This depletion of radon has been observed by several researchers in previous field experiments with actual houses, although it has not been accounted for in most studies of the impacts of wind on radon transport and entry. Depending on soil permeability, this flushing can result in a substantially lower radon entry rate than would be expected if the ground-surface pressures were ignored.

We investigated the effects of the wind-induced ground-surface pressure field by employing a previously tested three-dimensional numerical model of soil-gas flow around houses, a commercial computational fluid dynamics code, a standard model for determining ventilation rates in the presence of wind, and new wind tunnel results for the ground-surface pressure field caused by wind. By applying these tools and data under steady-state conditions to a prototypical residential building, we 1) determined the complex soil-gas flow patterns that result from the presence of wind-induced ground-surface pressures, 2) evaluated the effect of these flows on the radon concentration in the soil, and 3) calculated the effect of wind on the radon entry rate and indoor concentration.

Figure 1 shows a parameter designed to indicate the extent of flushing of radon from the soil gas as a function of both wind speed and soil permeability. This parameter,  $C_{char}$ , is the normalized average soil-gas radon concentration in a plane surface bounded by the lower interior edges of the footers. For the case of no wind, there is a small depletion with increasing soil permeability due to soil-gas being drawn into the basement. In contrast, when wind-induced ground-surface pressures are

present, the average radon concentration near the house decreases sharply with increasing soil permeability. The ground-surface pressures also reduce the soil-gas entry rate (not shown here) into the building, although to a lesser extent.

Figure 2 presents the normalized indoor radon concentration for the case of no wind, a 3.6 m/s wind, and an 8.3 m/s wind. The effect of the wind-induced ground-surface pressures is especially pronounced at high soil permeabilities. If this pressure field is not accounted for, the

predicted indoor radon concentration can be orders of magnitude too large.

Our recent studies of a passive mitigation system installed in a house in Spokane, Washington, suggest that the system's performance can be degraded by wind. This degradation may be a result of transient wind conditions; we are currently enhancing our modeling tool to study this phenomenon. The simulation tool will also provide us with a means of examining the effects of a fluctuating wind on an unmitigated house.

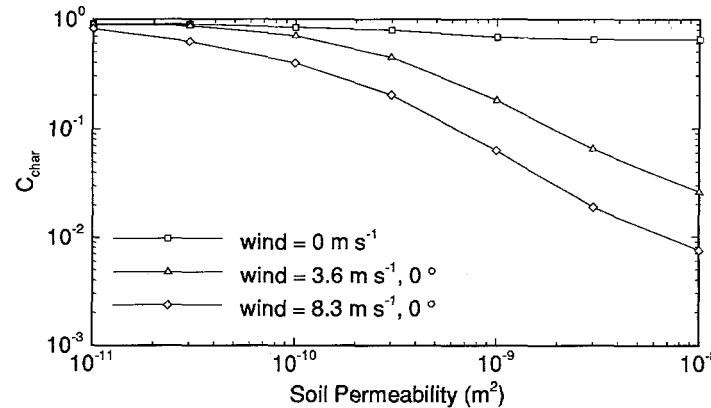


Figure 1. Average soil-gas radon concentration ( $C_{char}$ ) at a horizontal plane located at the bottom of the footers and bounded by the footers (the concentration is normalized with respect to the deep-soil radon concentration).

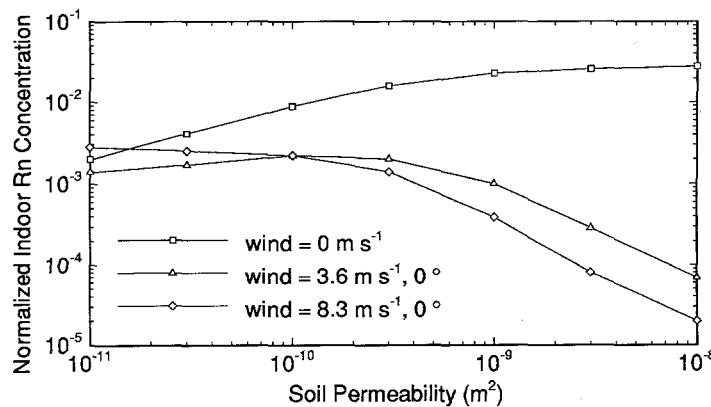


Figure 2. Normalized indoor radon concentration (the concentration is normalized with respect to the deep-soil radon concentration).

## Soil-Gas Entry into Houses Driven by Fluctuations in Atmospheric Pressure

A.L. Robinson, R.G. Sextro, Y. Tsang, \* W.J. Fisk

Advective flow of soil gas is the primary transport mechanism of radon into houses. Advective soil-gas entry has been traditionally studied as a steady-state process in which a slight underpressure of the interior of a house, usually on the order of a couple of pascals (Pa), draws radon-laden soil gas through cracks in a building's substructure. This small depressurization is caused by indoor/outdoor temperature differences, by wind blowing over the building shell, or by the operation of an unbalanced building ventilation system. However several field studies have observed elevated indoor radon concentrations in the absence of any steady driving mechanism.

Fluctuations in atmospheric pressure several orders of magnitude larger than these steady driving pressures commonly occur. Pressure changes on the order of a few Pa occur over periods of minutes, and fluctuations of a few hundred Pa occur diurnally. A weather front can produce large, rapid changes in atmospheric pressure of more than 1000 pascals. Fluctuations in atmospheric pressure cause soil-gas transport between the soil surface and the interior of the soil, due to the time constant of the soil to pressure changes. Similarly, gas will flow between the house interior and the underlying soil.

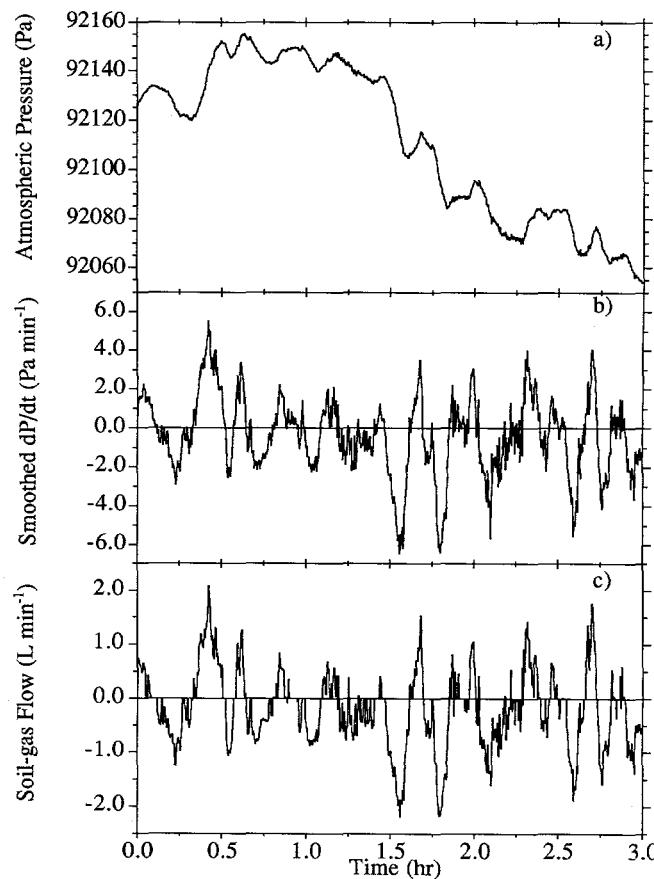
To examine the importance of changes in atmospheric pressure on advective radon entry into houses, we measured the transient flow of soil gas into an experimental basement structure. This primarily below-grade structure was designed and constructed to study the effect of structural and environmental factors on radon and soil-gas entry into houses. The floor slab of the structure rests on a 0.1-m-thick gravel layer. Gas flow between the structure's interior and the gravel layer occurs through a 3.8-cm-diameter hole in the center of the floor of the structure. Flow rate and direction are determined by measuring the linear velocity of air in a pipe inserted in the hole. During experiments the interior of the structure communicates with the atmosphere through several 0.95-cm-diameter holes, ensuring there is no pressurization/depressurization of the interior of the structure relative to the atmosphere.

The figure presents a 3-hr portion of more than 15 days' worth of data, compar-

ing the soil-gas flow into the experimental structure with the fluctuations in atmospheric pressure. Part (a) shows the variations in atmospheric pressure and part (b) presents the time-rate of change in this pressure, smoothed with an exponential time-weighting factor. As can be seen, rapid changes in atmospheric pressure lead to large positive or negative peaks in the  $dP/dt$  spectrum. The soil-gas-flow profile, shown in part (c), is almost identical in shape to the smoothed  $dP/dt$  spectrum in part (b). Soil-gas flow into the structure is indicated by the negative portion of the profile, while flow from the structure into the soil is indicated by the positive portion. The larger the rate of change of atmospheric pressure, the greater the pressure difference between the soil and the interior of the structure and the larger the soil-gas flow rate. Overall, the correlation between the measured soil-gas flow rate and the

time-rate-of-change in the atmospheric pressure for the entire data set has an  $R^2$  at 0.9.

Although the overall average flow rate of soil gas into the structure, driven by fluctuations in atmospheric pressure, is zero, this flow causes a net flux of radon into the structure because the radon concentration of the soil gas is several orders of magnitude larger than that of the air inside of the structure. The effective net radon entry rate is equivalent to that produced by a steady structure depressurization of  $\sim 0.5$  Pa. For this structure, the equivalent radon entry rate is 0.6 Bq/s, which is approximately six times that observed for radon diffusion. Thus soil-gas entry driven by atmospheric pressure fluctuations may explain the elevated indoor radon concentrations observed in some houses during periods when steady driving conditions are absent.



**Figure.** a, Variations in atmospheric pressure as a function of time. b, Time-rate of change in atmospheric pressure; data smoothed with an exponential weighting factor. c, Soil-gas flow rates driven by fluctuations in atmospheric pressure; negative values indicate flow of soil gas into the structure, while positive values indicate gas flow out of the structure into the soil.

\* Earth Sciences Division, LBL

## Development of a Methodology for Identifying High-Radon Areas of the United States

A.V. Nero, P.N. Price, K.L. Revzan

Radon concentrations in houses vary substantially from one area to another, so houses with particularly high levels, e.g., exceeding 20 pCi/L (740 Bq/m<sup>3</sup>), tend to be found in geographic clusters. We are developing a statistical methodology that will estimate radon levels on small scales (such as census tracts), so that areas likely to contain a disproportionate fraction of high-radon homes can be identified.

Work is proceeding along two main avenues. One approach involves finding explanatory variables that can be used to predict indoor radon levels. These variables may be available at the level of individual homes, for example, the presence or absence of a basement, or as area averages, such as heating infiltration degree-days or surface soil radium content. Preliminary analyses, using ordinary multiple regression, indicated substantial explanatory power for some of these variables. However, a common problem with such studies has been the presence of substantial statistical noise due to small samples in various categories. For example, an individual county

or census tract may have only a few sampled homes, or may have few homes in one of the explanatory variable categories. We have begun successfully applying a statistical technique known as Bayesian Hierarchical Modeling to these problems. The technique allows for the creation of models to estimate actual county mean radon concentrations, as opposed to observed county mean radon concentrations, which are subject to substantial small-sample-size variation.

The second approach involves the use of existing radon measurements in an area to estimate parameters describing the actual annual-average radon concentrations. Existing data are sparse and are frequently collected in such a way that they do not provide direct estimates of actual risk. For example, most states in the U.S. have performed radon surveys in which short-term, winter, basement radon measurements were made in a few homes in every county. Although these measurements are useful in determining relative radon levels in various counties, they cannot be used directly to estimate

the main parameters of interest, which concern annual-average living-area concentrations. A smaller dataset, from the National Residential Radon Survey, does provide actual annual-average living area concentrations. Investigations over the past year have yielded methods that allow joint use of both types of data to improve estimation of the parameters of interest. This method has already been applied to generate improved regional and county-level estimates of actual average indoor radon concentrations. The same basic methodology may be used when several datasets that include data collected according to different sampling protocols are available.

These approaches will be combined into a methodology for including all available measurements and explanatory variables to predict mean radon concentrations, with known uncertainties, for relatively small areas such as census tracts. Such small-area predictions will be used for efficient and rapid identification of homes having very high indoor radon levels.

## Characterization of Indoor Pollutants

### Computed Tomography of Airborne Pollutant Concentrations

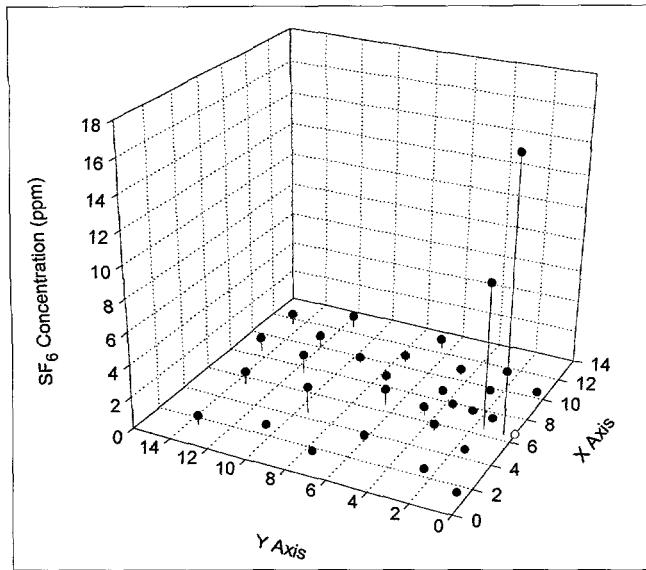
A. Gadgil, A.C. Drescher, W.W. Nazaroff

We earlier suggested and demonstrated the novel idea of combining remote sensing and computed tomography (CT) to measure the spatial distribution of gaseous pollutant concentrations. LBL researchers have conducted chamber experiments to test this proposal using an Open-Path Fourier Transform Infrared Spectrometer (OP-FTIR) to obtain ray integral concentration data, which are then inverted with CT. The computed tomography algorithms (a class of techniques called Algebraic Reconstruction Techniques, or ART) suggested in the literature and used in such experiments so far have been unsatisfactory. The reconstructed concentration profiles predicted using ART commonly provide excellent

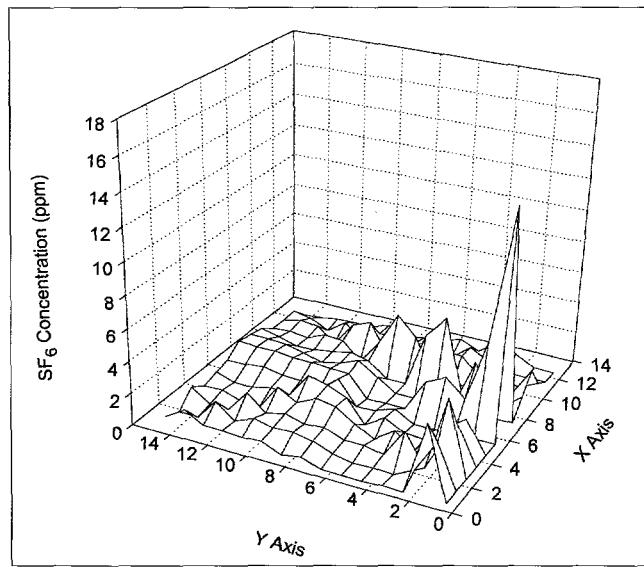
agreement with the measured ray-integral concentration, but agree poorly with measured point-sampled data. We developed a novel technique for the tomographic inversion of data that offers a substantially improved agreement of the reconstructed concentration data with the measured point-sampled data.

The agreement with the measured ray-integral data is somewhat degraded but stays well within experimental error. The new technique is based on the superposition of smooth basis functions to model the concentration distribution, and uses a simulated annealing minimization routine to find the parameters of the gaussians that result in the best fit to the ray-integral concentration data. The new technique,

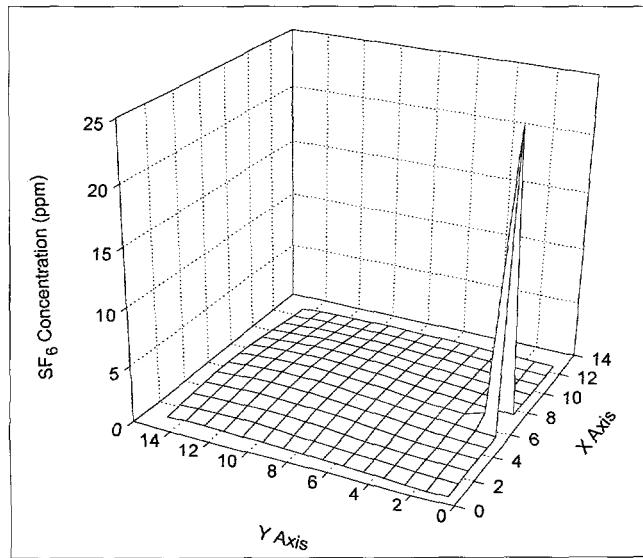
called Smooth Basis Function Minimization (or SBFM), was used for reconstructing the spatial distribution of tracer gas in a room-sized chamber, 6 m × 7 m. Figure 1 shows the point-sampled concentrations in the measurement plane; Figure 2 shows the spatial concentration distribution reconstructed from ray-integral data using ART; and Figure 3 shows the reconstruction from the same data using SBFM. The SBFM reconstruction has better overall agreement with the point-sampled data and is free of the artifacts visible in the ART reconstruction. SBFM thus offers a substantial improvement over the traditional methods (based on ART) for reconstruction of pollutant concentrations in indoor and outdoor air-monitoring applications.



**Figure 1.** The point-sampled tracer-gas concentrations in an experimental chamber about 6 m  $\times$  7 m, in a horizontal plane at a height of 1.3 m. The concentrations measured by 31 point-samplers are shown in units of ppm.



**Figure 2.** The concentration distribution in the same plane reconstructed from 56 ray-integral concentration data collected with OP-FTIR, using an ART algorithm.



**Figure 3.** The concentration distribution reconstructed from the same 56 ray-integral concentration data using SBFM. The larger height of the peak concentration in the reconstructed distribution compared to the point-sampled data (Fig. 1) is believed to result from the lateral displacement of the nearest point-sampler from the tracer-gas release point.

## Mixing of a Point-Source Pollutant by Forced Convection in a Room

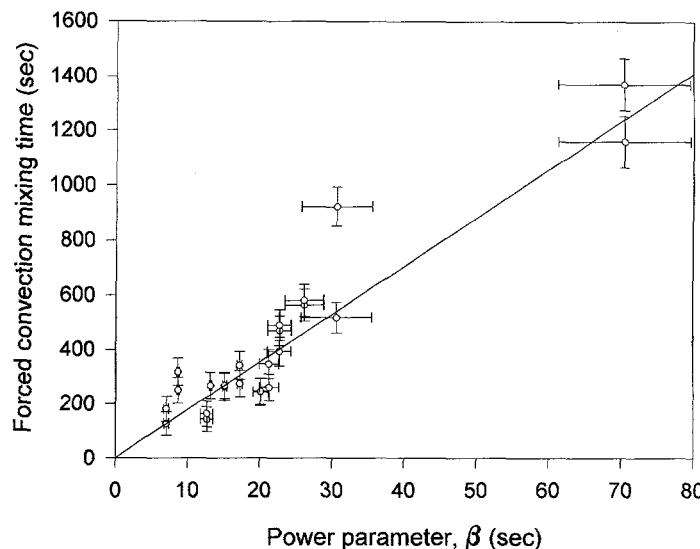
A.C. Drescher, C. Lobascio, A.J. Gadgil, W.W. Nazaroff

The mixing rate of pollutants influences the rate of removal by ventilation and the potential variability of exposure for a given release scenario. Quantitative information is scant on the mixing rate and the factors governing it. Pollutants released from indoor sources are often assumed to mix instantaneously and perfectly for want of a better model. We conducted experiments to gather mixing-rate data for an instantaneously released tracer gas, carbon monoxide, in a sealed, unoccupied room under various conditions of forced air flow induced by blowers. The mixing time was defined as the time from the gas release to the time when the relative standard deviation of gas concentrations throughout the room was less than 10%. The resulting mixing times, from 2 to 42 minutes, were related to the mechanical power of the air jet produced by the blowers. Mixing times were found to correlate well with the inverse of the cube root of power (Figure 1), in accordance with theoretical predictions and experimental observations for mixing in chemical reactors.

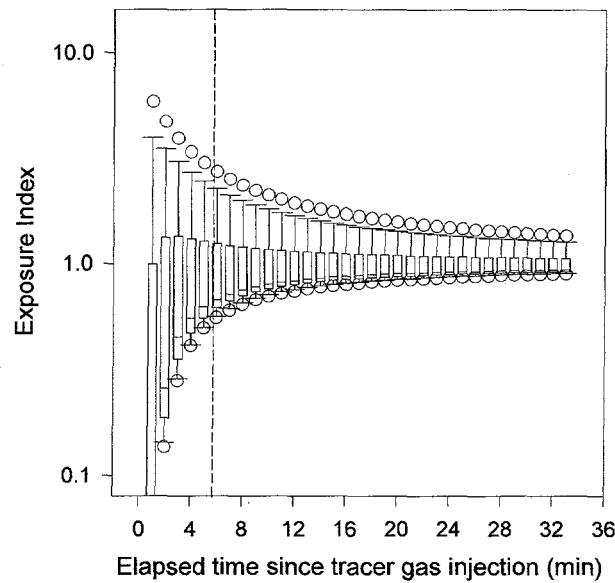
The exposure index, defined as the time-averaged concentration at a point relative to the time-averaged concentration for the room as a whole, was calculated as a function of space and exposure time (since pollutant release) for five experimental conditions, yielding quantitative information on the appropriateness of the well-mixed hypothesis under various flow conditions. In general, we found that the exposure period following instantaneous release of a point-source pollutant must be much greater than the mixing time for the assumption of uniform mixing (i.e., exposure index of unity) to hold (Figure 2).

We then employed the correlation between mixing time and power input to predict the mixing time from the mixing action of a supply air jet for a typical ventilation scenario. The resulting mixing time,  $t_{\text{mix}} \sim 7$  min, was predicted to be substantially lower than the time scale for removal by ventilation,  $t_{\text{vent}} \sim 48$  min. Under these conditions, complete mixing of an instantaneous release point-source pollutant would be approximately attained within the interior space well before the pollutant would be thoroughly removed by ventilation.

Despite their empirical nature, simple working models such as the one we have



**Figure 1.** Mixing time for each experiment as a function of the power parameter,  $\beta$  ( $\beta = \rho^{1/3} V^{5/9} P^{-1/3}$ , where  $\rho$  = air density,  $V$  = room volume,  $P$  = mechanical power input). The line has slope 17.6, the calculated constant of proportionality between mixing time and  $\beta$ .



**Figure 2.** Box plot of exposure-index distribution as a function of time for a mixing experiment with a mixing time of 5.7 minutes (indicated by the dashed vertical line) and 9 CO sampling points. The circles and horizontal lines comprising each box represent, from top to bottom: data point above 90th percentile, 90th percentile, 75th percentile, 50th percentile, 25th percentile, 10th percentile and data point below 10th percentile.

developed, relating power and mixing time, are useful and appear worth further investigation. They bridge the gap between computational fluid dynamics models, which require enormous computing capacity to handle realistic three-dimensional dispersion situations, and the assumption—commonly unsubstantiated—

of complete and instantaneous mixing. An understanding of mixing processes at an intermediate level of complexity helps build intuition for solving practical pollutant and heat-dispersion problems and is needed to further develop effective and energy-efficient indoor air quality control techniques.

## Development of a Carbon Monoxide Passive Sampler

G.W. Traynor, M.G. Apte, and G. Chang

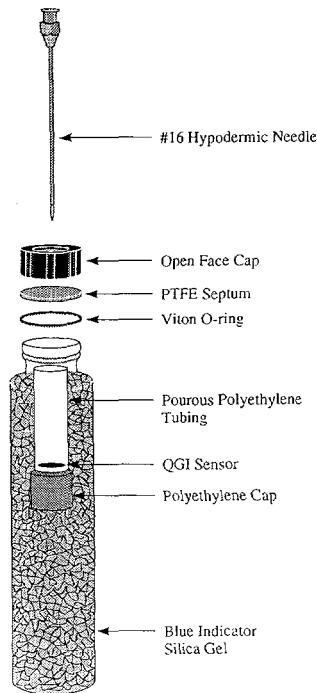
Some 15,000 to 20,000 carbon monoxide (CO) poisonings every year in the U.S. contribute to hundreds of deaths and thousands of cases of physical or mental damage. There is also some evidence that exposures to high concentrations of CO may damage fetuses and cause the onset of heart attacks. Residential combustion appliances such as unvented kerosene- and gas-fired space heaters or malfunctioning combustion space heaters and water heaters can produce high concentrations of CO. Other causes include the indoor use of charcoal and the indoor operation of an internal combustion engine (e.g., operating cars or generators in a garage). Some poisonings can be avoided by better education; while others (for example, those caused by malfunctioning vented appliances) can only be detected by an active mitigation program or the widespread installation of CO alarms. Of special concern are the poor and the elderly who often cannot afford routine inspections and maintenance of gas or other combustion appliances.

The dangers of CO poisoning point to the critical need for a cost-effective CO sampling device for gas appliance diagnostic studies, indoor exposure studies, and targeted mitigation studies. A CO passive sampler would be the ideal measurement tool for such studies. The goal of our research program is to develop a passive sampler that will require no power, be suitable for deployment through the mail, be stable for several weeks before and after deployment, and have an accuracy and precision within 20%.

Our research group has concentrated on modifying a commercially available

disk (from Quantum Group Inc., San Diego, California) that changes its transmission of near-infrared radiation in the presence of CO. Working closely with the staff at Quantum Group, we tested many new formulations to increase the sensitivity of the disks, to reduce the batch-to-batch variations, and to reduce the reversibility of the disks. To date, we have established the linearity of the sensors' response to CO; developed and tested a critical non-reversible formulation of the sensor; tested new sensor substrates that are free from impurities; and developed our first laboratory prototype (Figure).

The CO passive sampler prototype was first field-tested over a one-week period during the past year. Four locations (with five passive samplers at each location) were used for the tests: Bldg. 44 at LBL, a parking garage toll booth, a residence with a gas range, and an environmental chamber with an unvented gas-fired space heater (UVGSH) operating on an intermittent basis. The results of the field tests were very promising. The "true" time-weighted average concentrations of the field sites were 1.2 ppm at Bldg. 44, 11.8 ppm at the parking garage booth, 1.5 ppm in the house with an unvented gas range, and 3.6 ppm for the chamber. The CO passive samplers measured 0.2, 10.7, 2.1, and 3.9 ppm, respectively. All values were within 1.1 ppm of the true concentration measured by analyzing air collected with low-flow bag samplers. Only at the lowest concentration site, Bldg. 44, did the passive sampler and true concentrations different significantly, which indicates that 1 ppm-week may be close to our limit of detection.



**Figure.** Schematic diagram of a laboratory prototype carbon monoxide passive sampler using a Quantum Group Inc. (QGI) sensor

The precisions of the five passive samplers deployed at each location were about 12% at the parking garage toll booth and about 25% at the residence with a gas range and the chamber with an UVGSH. Our goal of having a precision and accuracy of near 1 ppm-week at low concentrations (2-5 ppm-week) and less than 20% at higher concentrations was met. Further refinements of the CO sensors and the passive sampler configuration are planned to optimize performance.

## Concentrations of Indoor Pollutants (CIP) Database

M.G. Apte, G.W. Traynor, C.N. Tran

Research indicates that people spend 60-80% of their time indoors, which is why air pollution in the indoor environment is an important environmental issue. In many cases, a significant—if not dominant—portion of exposure to air pollution is likely to occur indoors, especially when an indoor pollutant source exists and energy conservation measures have been undertaken that reduce building ventilation.

Research in indoor environmental issues is a rapidly growing field, with the

number of publications increasing yearly. The Concentrations of Indoor Pollutants Database (CIP Database) is a bibliographic management tool designed to keep track of this rapidly expanding volume of literature. The CIP Database contains references to articles explicitly reporting concentrations of pollutants measured in such actual, unmodified indoor environments as office buildings and residences.

During the past year, activity focused on creating a database of pollutant ranges

and continuing the ongoing literature search for relevant articles. One major accomplishment was the completion of the pollutant range database for the 433 references in Version 4.0. In addition, we worked with Fourth Floor Databases, Inc. (Palo Alto, California), a software development company, to complete the compilation of a database of abstracts of the first 433 references. These additions will be incorporated into the next release of the CIP Database.

## Transport and Sorption of Volatile Organic Compounds in Soil and Activated Carbon

T.-F. Lin, M.D. Van Loy, W.W. Nazaroff

Environmental applications such as modeling the entry of indoor volatile organic compounds (VOCs) into buildings from subsurface contamination and the removal of VOCs from air using activated carbon adsorption require a comprehensive understanding of the transport and sorption of VOCs in porous media. Such an understanding is essential for reliable predictions. For example, improved cognition of the relationships among the kinetics of adsorption and desorption, the equilibrium isotherm, and transport through packed columns can reduce the number of parameters that must be measured to predict transport in engineered or natural systems. In a previous study, we developed a porous sphere model to describe the transport behavior of VOCs within individual dry soil grains. The model couples mathematical descriptions of internal diffusion in spherical grains with a nonlinear Freundlich isotherm to interpret the kinetics of adsorption and desorption. Good fits of the model to experimental sorption kinetic curves were obtained. The model reveals that the degree of asymmetry between adsorption and desorption rates depends on the degree of nonlinearity of the equilibrium Freundlich isotherm.

Since both kinetic and equilibrium parameters are needed to predict adsorption in a packed column, multiple experiments are normally required to provide the data needed for accurate design. Our current study develops a streamlined approach to obtain the necessary parameters. In this method, results of a single kinetic experiment, which can be conducted in a matter of hours, serve as the basis for predicting both the sorption isotherm and column breakthrough curves (BTC).

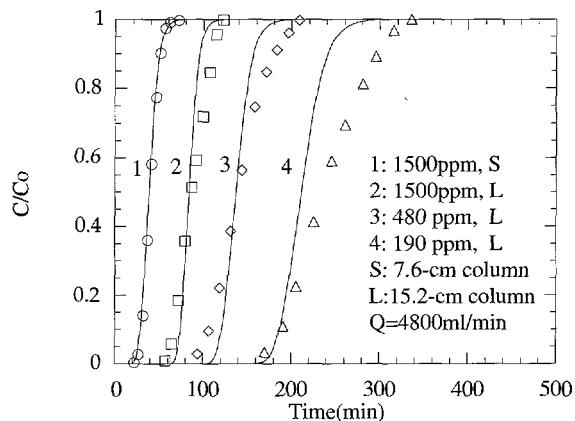
To test this approach, we measured VOC sorption and transport in porous, granular sorbents. One soil sample and two activated carbons (AC) were selected as representative adsorbents: synthetic soil matrix (SSM) prepared by the U.S. Environmental Protection Agency, granular activated carbon (GAC) from Calgon, and activated carbon fibers (ACF) from American Kynol. The sorbent properties, including specific surface area, grain density, and grain size, were either measured or obtained from the manufacturers. Two VOCs commonly found at contaminated sites, benzene and vinyl chloride, were chosen

as sorbate species. In the experiments, the gas-phase VOC concentration was varied between 100 and 1500 ppm. Sorption experiments, determining both sorption kinetics and sorption capacity at a specific sorbate concentration, were conducted with a Cahn-1000 electrobalance for the VOC/AC system and with a differential adsorption bed (DAB) for the VOC/soil system. The transport of VOCs through columns packed with sorbent was also directly measured. A stainless steel column, 7.6 or 15.2 cm in length and 2.3 cm in diameter, was filled with either GAC or soil. In performing a column experiment, a step increase of predetermined VOC concentration was introduced into the column inlet while maintaining a steady air flow through the column, and the BTC was obtained from monitoring the VOC concentration in the effluent of the column until it rose to the inlet concentration.

The porous sphere model (for GAC and soil) or a similar porous cylinder model (for ACF) was used to interpret the data from the kinetic adsorption-desorption experiments. The models provide good fits to the experimental data using two adjustable parameters: the effective diffusivity of the VOC within the pores of the sorbent grain and the exponent ( $n$ ) in the Freundlich isotherm. The extracted  $n$  value, along with the measured sorption capacity from the same kinetic experiment, determine the sorption isotherm for the

same sorbate/sorbent system. Small differences, less than 5% on average, were observed between the isotherms developed by this means and the corresponding experimental data.

A dispersed plug flow model for the column, combined with the porous sphere model for diffusion within individual sorbent grains, was then used to predict the BTCs for the column experiments. All the input parameters for the model were generated from the same kinetic experiment for isotherm determination. Typical model results of the BTCs and corresponding experimental data are shown (Figure). The model predictions conform well to the data for all the cases in both soil and activated carbon systems except for the low-concentration run (190 ppm) of vinyl chloride through GAC. This case reflects a discrepancy at this concentration between the predicted adsorption capacity based on the kinetic data and the measured adsorption capacity. Overall results, however, show that the model not only can predict the BTCs at the same concentration as used in the kinetic experiment, but also can be extrapolated to either higher or lower concentrations while maintaining very good agreement. The close agreement between model predictions and experimental results for two different sorbents substantiates this method for predicting both isotherms and BTCs from a single kinetic experiment.



**Figure.** Predicted and experimental breakthrough curves (BTCs) for vinyl chloride through granular activated carbon columns, where  $C$  represents the measured concentration at the effluent of column and  $C_0$  is the influent concentration. The open symbols denote experimental data, while the predictions based on the dispersed plug flow model with internal diffusion are shown as solid lines. The only experimental data used to generate the predictions were a single kinetic adsorption-desorption experiment conducted in an electrobalance at a vinyl chloride concentration of 490 ppm.

# Environmental Tobacco Smoke

## The Contribution of Environmental Tobacco Smoke to Concentrations of Volatile Organic Compounds in Buildings

A.T. Hodgson, J. Ten Brinke, K.R.R. Mahanama, J.M. Daisey, L. Alevantis\*

Environmental tobacco smoke (ETS), which is a mixture of sidestream and exhaled mainstream smoke, consists of particles and gases with nearly 4000 identified compounds. Concern over the exposures of non-smoking building occupants to these compounds has resulted in smoking restrictions or bans in many public and commercial office buildings.

The objective of this study, which was conducted in collaboration with the California Department of Health Services, Air & Industrial Hygiene Laboratory, was to estimate the contributions of ETS to concentrations of volatile organic compounds (VOCs) in the designated smoking areas of five office buildings. In each building, samples for VOCs, including formaldehyde, were collected in the smoking area over the period of a normal work day. The ventilation rate for the area was concurrently measured, and smoking rates were observed. Many of the volatile compounds emitted in ETS have other commonly occurring sources. Therefore, it is necessary to have emissions data for ETS in order to determine the contributions of this source. These data were obtained from a separate laboratory study in which the emission rates (mass of compound emitted per cigarette) of ten target VOCs and three tobacco-specific volatile compounds were measured in an environmental chamber for six popular brands of cigarettes.

The predicted concentrations of the tobacco-specific tracer compounds were calculated for each smoking area with a time-dependent mass-balance model using as inputs the emission rate data, the smoking rates, the size of the area, and its ventilation rate. These modeled concentrations were compared to the corresponding measured concentrations. The smoking rate in one area was so low that the concentrations of the tracer compounds

were at or below their limits of detection. For a large cafeteria with a smoking section, the data suggested that the measured ventilation rate was probably not representative of the entire area. For the remaining three areas, there was good agreement between the measured and modeled concentrations of the tracer compounds. The best agreement was obtained for pyrrole, a nitrogen-containing compound, for which the variation between measured and modeled values was within approximately 25%.

The contributions of ETS to the concentrations of the ten target VOCs in the three study areas were estimated using the measured concentrations of pyrrole and the average ratios of the target com-

pounds to pyrrole that were obtained from the ETS chamber experiments. For two of the study areas, this analysis demonstrated that about one-half or more of the measured concentrations of formaldehyde, 2-butanone, benzene, and styrene derived from ETS as the source. The contributions of ETS to the concentrations of the remaining compounds were about 15-30%. The third area had higher concentrations of many of the target compounds so the relative contributions of ETS for this area were lower. In summary, this study unambiguously demonstrated that ETS can, at least, make significant contributions to the concentrations of VOCs in building areas where smoking is permitted.

## Exposures to Air Toxics From Environmental Tobacco Smoke

J.M. Daisey, K.R.R. Mahanama, A.T. Hodgson

Environmental tobacco smoke (ETS) is the smoke to which non-smokers are exposed when they are in an indoor environment with smokers. ETS is composed largely of sidestream tobacco smoke (SS), the smoke emitted by the smoldering end of a cigarette between puffs, with minor contributions from exhaled mainstream smoke (the smoke which is directly inhaled by the smoker), and any smoke that escapes from the burning part of the tobacco during puff-drawing by the smoker. ETS differs from SS in that it is highly diluted and dispersed within a room and it undergoes aging. Previous studies identified ETS as a potentially important source of a number of the toxic air contaminants in indoor air, including 1,3-butadiene, acetaldehyde, acrolein, N-nitrosamines, xylenes, phenols, and cresols.

Recent research indicates that about 60% of Californians are exposed to ETS for an average of approximately 5 hours per day. Thus, exposures to toxic air

contaminants from this source are widespread in California. Although ETS is likely to be the major source of exposure for many of these compounds, quantitative data to evaluate population exposures are often lacking or inadequate. The primary goal of this study was to provide up-to-date emission factors for selected volatile organic compounds (VOCs) in ETS to be used in models to estimate exposures for the California population.

ETS emission factors were determined from concentration measurements made in a room-sized (20 m<sup>3</sup>) environmental chamber with stainless steel walls and low background concentrations of species of interest. The chamber was operated under static conditions with a minimal air exchange rate. Experiments were conducted over 4.5 hours at constant room temperature and humidity. Sidestream smoke was generated in the chamber with a smoking machine, using

\*California Department of Health Services, Air & Industrial Hygiene Laboratory.

a standard puff cycle, and diluted and mixed to simulate ETS. Experiments were individually conducted for six commercial cigarette brands, which together account for 62.5% of the total market in California.

Emission factors were determined for four volatile N-nitrosamines, three aldehydes, and 19 additional VOCs including pyridine, pyrrole, and 3-vinylpyridine. The latter three compounds were investigated as possible tracers for the vapor-phase components of ETS. Vapor-phase nicotine and suspended particulate matter (PM-2.5<sub>EQ</sub>)<sup>\*</sup> were also measured. Emission factors,  $\mu\text{g}/\text{cigarette}$ , were calculated based on a time-dependent mass balance equation.

The Table summarizes the averages and standard deviations of the ETS emission factors determined for the six commercial brands. For most of the VOCs, there were no significant changes in concentration over time. The concentrations of 3-vinylpyridine, phenol, o-cresol and m,p-cresol, however, showed a first-order exponential decay with time indicating that these compounds were partially lost by deposition to chamber surfaces. For these compounds, the deposition rate constants were calculated and the reported emission factors were corrected for this loss. Butyl acetate, butyraldehyde, ethyl acetate, ethyl acrylate, 3-methyl-1-butanol, N-nitrosodiethylamine, and N-nitrosomorpholine were not detected in any of the ETS samples. For these compounds, the emission factors were calculated using the minimum detection limits and were reported as less-than values. The aldehydes, acetaldehyde and formaldehyde, had the highest emission factors among the volatile components.

The variabilities in the ETS emission factors among brands of cigarettes were relatively small, ranging from 16 to 31% (expressed as the coefficient of variation) among the six brands. The ratios of the highest to the lowest emission factors among brands was 1.5 to 1.6 for most of the VOCs and ranged up to 2.0 for pyridine. Mentholation of the cigarettes did not seem to affect the ETS emissions of the target VOCs. The ETS emissions of light and regular brands were also not signifi-

**Table.** Summary of environmental tobacco smoke emission factors determined for six commercial cigarette brands,  $\mu\text{g}/\text{cigarette}$ .

| Compound                        | Emission Factor,<br>Average $\pm$ Std. Dev. <sup>a</sup> | Compound                           | Emission Factor,<br>Average $\pm$ Std. Dev. <sup>a</sup> |
|---------------------------------|--|------------------------------------|--|
| Acetaldehyde                    | 2150 $\pm$ 477   | Nicotine                           | 919 $\pm$ 240  |
| Acrylonitrile                   | 99 $\pm$ 18  | N-nitrosodiethylamine <sup>b</sup> | <0.020   |
| Benzene                         | 406 $\pm$ 71   | N-nitrosodimethylamine             | 0.57 $\pm$ 0.12  |
| 1,3-Butadiene                   | 152 $\pm$ 27   | N-Nitrosomorpholine <sup>b</sup>   | <0.020   |
| 2-Butanone (MEK)                | 291 $\pm$ 56   | N-nitrosopyrrolidine               | 0.10 $\pm$ 0.02  |
| Butyl acetate <sup>b</sup>      | <3   | Phenol                             | 281 $\pm$ 61   |
| Butyraldehyde <sup>b</sup>      | <18  | Pyridine                           | 428 $\pm$ 122  |
| m,p-Cresol <sup>c</sup>         | 83 $\pm$ 26  | Pyrrole                            | 402 $\pm$ 90   |
| o-Cresol <sup>c</sup>           | 35 $\pm$ 5   | Styrene                            | 147 $\pm$ 24   |
| Ethyl acetate <sup>b</sup>      | <4   | Toluene                            | 656 $\pm$ 107  |
| Ethyl acrylate <sup>b</sup>     | <3   | 3-Vinylpyridine <sup>c</sup>       | 662 $\pm$ 155  |
| Ethylbenzene                    | 13010  | m,p-Xylene                         | 299 $\pm$ 52   |
| Formaldehyde                    | 1310 $\pm$ 348   | o-Xylene                           | 67 $\pm$ 16  |
| 3-Methyl-1-butanol <sup>b</sup> | <14  | PM-2.5 <sup>c</sup>                | 8100 $\pm$ 2000  |

<sup>a</sup>Average  $\pm$  Standard Deviation for six brands of commercial cigarettes.

<sup>b</sup>Less-than values are based on lower limits of detection.

<sup>c</sup>Emission factors are corrected for losses to chamber walls.

cantly different for most of the VOCs. The light brands, however, emitted slightly higher amounts of N-nitrosamines than the regular brands.

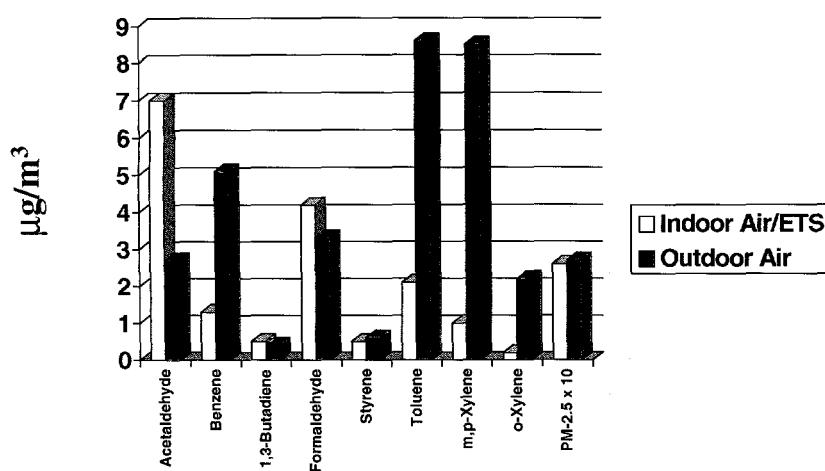
Three nitrogen-containing VOCs, pyridine, pyrrole, and 3-vinylpyridine, were investigated as potential tracers for vapor-phase compounds from ETS. Criteria for an ETS tracer include: 1) uniqueness to tobacco smoke, 2) detectability at low smoking rates, 3) similar emission rates for different tobacco products, and 4) consistent proportions to other ETS compounds for different environments and tobacco products. Based on measurements of VOCs in indoor environments and emissions data for products and materials, these three VOCs appear to be unique to tobacco smoke in indoor air. All three compounds can be easily detected at low smoking rates, although they are not as abundant in ETS as nicotine. The coefficients of variation for the pyridine, pyrrole, and 3-vinylpyridine emission factors among the six commercial brands were 29, 22, and 23%, respectively. The ratios of the highest to lowest emission factors for these compounds were about two or less. Thus, all three compounds meet the third criterion rea-

sonably well. A tracer must also exhibit indoor behavior similar to that of the vapor-phase compounds it traces. Only pyridine and pyrrole meet this criterion, since 3-vinylpyridine was found to deposit onto chamber surfaces. Thus, mass-balance estimates of the contributions of ETS to the indoor concentrations of vapor-phase VOCs that have multiple indoor sources (e.g., benzene, styrene, and toluene) should be based on their ratios to pyridine or pyrrole as the tracer compounds.

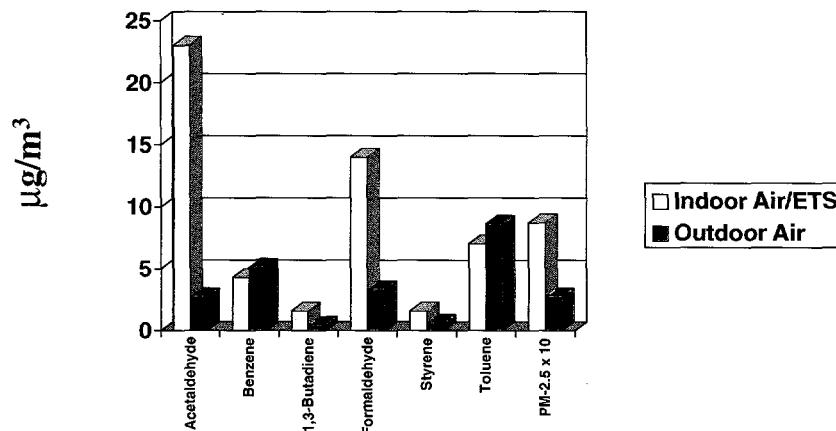
The average emission factors were used in a time-dependent mass-balance model to estimate indoor air concentrations and exposures for scenarios in a typical office building and in an average residence. For the office scenario, we assumed a small office with a volume of 1059 m<sup>3</sup> and 16 occupants with 20% smokers each smoking 2 cigarettes per hour. The volume of the building was based on the average floor area for 70 small buildings and an assumed ceiling height of 3 m. An air-exchange rate of 0.51 per hour (based on the ASHRAE standard of 20 cfm of outside air per occupant) was used for daytime working hours and a value of 0.41 per hour was used for the remainder

\* Total airborne particulate matter was collected in the chamber. Based on other studies in our laboratory, 98% of the particles collected in the chamber were less than 0.8 mm. Thus, the samples were equivalent to those which would have been measured with a PM-2.5 sampler and are designated PM-2.5<sub>EQ</sub>.

**a) Comparison of Concentrations of Selected VOCs  
Residential Scenario vs Outdoor Air**



**b) Comparison of Concentrations of Selected VOCs  
Small Office Scenario vs Outdoor Air**



**Figure** Comparison of concentrations of selected air toxics and PM-2.5<sub>EQ</sub> from ETS in indoor air for (a) the small office and (b) residential scenarios to median concentration in outdoor air

of each day. The latter was the average measured for eight federal office buildings. The smoking rate was based on reported data. Indoor concentrations were averaged over a 40-hour work week.

For the residential scenario, we used reported values from a field study of indoor aerosols in Suffolk County, NY. The average house volume was 352 m<sup>3</sup>; the average air exchange rate was 0.58 per hour; and an average of 16 cigarettes were smoked per day in each house. Indoor concentrations were averaged over a 7-day period. The figure compares concentrations of selected air toxics and PM-2.5<sub>EQ</sub> from ETS in indoor air for (a) the small office and (b) residential scenarios to median concentrations in outdoor air.

For both scenarios, which were selected to represent typical rather than extreme conditions, the indoor concentrations from ETS are generally comparable to or greater than those in outdoor air. For PM-2.5<sub>EQ</sub>, the indoor concentrations from ETS alone from the residential scenario were comparable to average outdoor concentrations. For the office scenario, the indoor concentrations of a number of the ETS components were about three times higher than outdoor concentrations. It should also be noted that the total exposures to the air toxics and to PM-2.5 for these settings would be the sum of the concentrations from ETS plus the concentrations generated in the building from other sources and the concentrations which penetrate from outdoor air into the building.

## Phase and Size Distributions of Polycyclic Aromatic Hydrocarbons in Environmental Tobacco Smoke

L.A. Gundel, V.C. Lee, S.V. Hering, J.M. Daisey

Phase and size distributions of polycyclic aromatic hydrocarbons (PAH), an important class of environmental carcinogens, influence exposure and lung dosimetry for environmental tobacco smoke (ETS). Gas-phase components of ETS, especially water-soluble species, deposit more efficiently than particles, but they tend to deposit in the upper airways of the human respiratory system where they

are quickly cleared and swallowed. Typical ETS particles of 0.1 to 0.5 μm diameter are not deposited as efficiently as gases, but they penetrate deep into the lung and, once deposited, are cleared more slowly than gas-phase components. Although the dosimetry of organic compounds in the particulate phase depends on their particle-size distribution, very little data are available for specific classes such as

PAH in ETS. Nothing is known to date about the dynamic behavior of the size distribution of PAH in ETS as the smoke dilutes and ages. Previous studies suggest that evaporation of compounds with high volatility will "dry out" sidestream cigarette smoke as it is diluted into a room, and this effect will decrease the PAH concentration in smaller particles more than the bigger particles.

Two new tools have been used recently to measure the phase and size distributions of PAH simultaneously in ETS, and they can be applied to study the dynamics of ETS. In this study, phase distributions of PAH have been measured in simulated ETS using the new LBL annular denuder-based Integrated Organic Vapor-Particle Sampler (IOVPS). Simultaneously, the size distribution of particulate PAH has been determined with a new microslot impactor, the Size-Segregated Environmental Tobacco Smoke Sampler (SSETS).

The IOVPS is based on a polydivinylbenzene-styrene copolymer (XAD-4)-coated annular denuder that strips gas phase species from the air stream before collection of particles on a filter. A second denuder downstream of the filter collects species desorbed from ("blown off") the particles (collected on the filter) during sampling. PAH are determined in extracts of both the denuders and the filter. The design of the IOVPS minimizes sampling artifacts that have beset earlier devices used for determination of phase distributions.

The SSETS uses microslots, 100 mm to 1.4 mm in width, for size-segregated particle collection. Previous micro-orifice impactors have used circular jets rather than slots. The advantage of slits is to concentrate the sample and eliminate interferences between jets. The small orifice widths are needed to achieve the 0.1 micrometer cutpoint without using low pressures, thus reducing volatilization losses. The sampling rate is 38 L min<sup>-1</sup>. Cutpoints are 0.1, 0.4, 0.8, and 1  $\mu\text{m}$  at stage pressures of 91-101 kPa. PAH are determined from extracts of the individual stages and afterfilter.

The IOVPS and SSETS were operated simultaneously in an environmental chamber (36 m<sup>3</sup>) to sample PAH in simulated environmental tobacco smoke (diluted sidestream smoke). Figure 1 shows the phase distribution of PAH in ETS at 16 °C, and Figure 2 shows the size distribution of particulate PAH from the same experiment. Good agreement (within 15%) was obtained between the particulate PAH concentrations from the IOVPS and the sum of the PAH concentrations for all impactor stages and the afterfilter. As the volatility of the PAH decreased (as indicated by increasing boiling point), the fraction in the particulate phase increased. High PAH concentrations were found consistently on the afterfilter that collected particles <0.1  $\mu\text{m}$

in aerodynamic diameter and in the size range 0.42-0.8  $\mu\text{m}$ . In general, as the volatility of the PAH decreased, the size distribution favored smaller particles. This observation is consistent with predictions that evaporation will preferen-

tially drive out higher volatility species from the smaller particles.

Future studies will use the IOVPS and SSETS to study the dependence of the phase and size distributions on dilution, aging and chamber temperature.

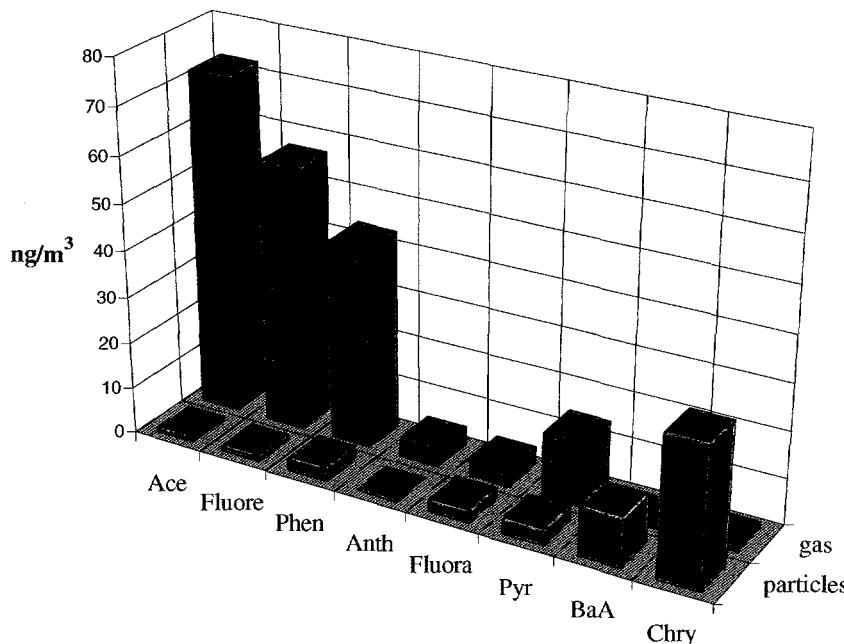


Figure 1. Phase distribution of PAH in simulated ETS sampled in a chamber (36 m<sup>3</sup>) at 16 °C.

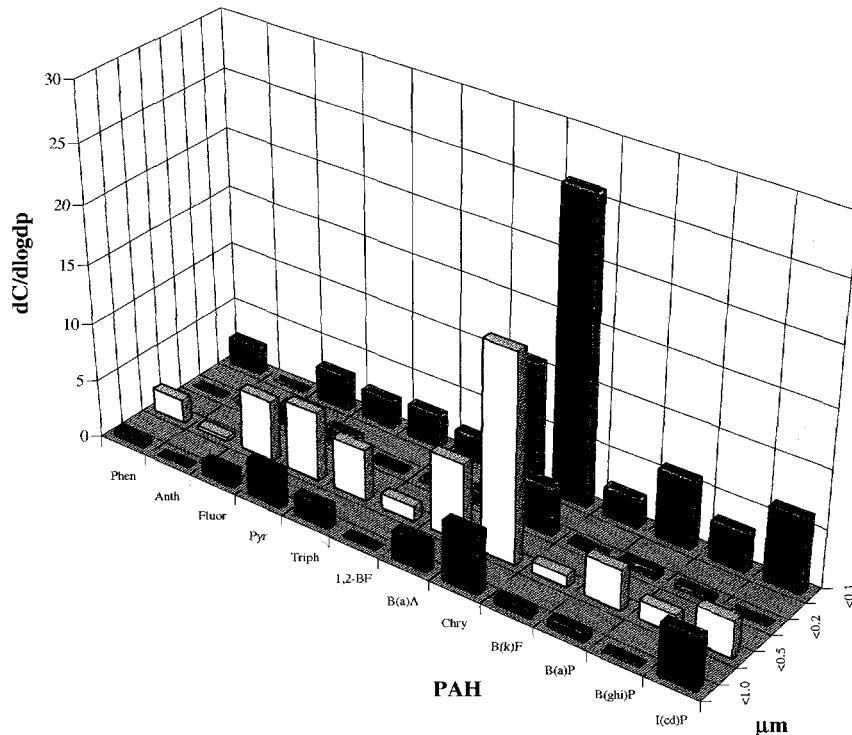


Figure 2. Size distribution of particulate PAH in simulated ETS.

## Emission Factors for Polycyclic Aromatic Hydrocarbons in Environmental Tobacco Smoke

L.A. Gundel, K.R.R. Mahanama, and J.M. Daisey

Despite their importance in indoor air, concentrations of polycyclic aromatic hydrocarbons (PAH) in environmental tobacco smoke (ETS) have rarely been measured. Emission factors (mass of pollutant per cigarette) are generally more useful than concentration data from one environment because they can be used to predict concentrations in a variety of settings with different smoking patterns, ventilation rates, and room volumes. Emission factors are generated by incorporating concentration- and ventilation-rate data into time-dependent mass balance equations. To our knowledge, no measurements of emission factors have been reported for PAH in ETS.

Studies of phase distributions and emission factors for PAH in ETS require collection and analysis of small, chemically complex samples. The objectives of this investigation were to develop clean-up and detection methods suitable for both gas- and particulate-phase PAH in small samples of ETS, and to use the methods to measure emission factors for PAH in ETS. We used the Kentucky reference cigarette 1R4F in these studies because its composition is representative of current commercial cigarettes. Emission factors were determined under controlled conditions in an environmental chamber. A time-dependent mass balance model was used to calculate emission factors from measured concentrations, environmental chamber characteristics, and air exchange rates.

The LBL Integrated Organic Vapor/Particle Sampler collected the gas and particulate phases separately. Gas-phase species were trapped on the polymeric-coated surfaces of an annular denuder, and particles were trapped on filters. The samples were extracted with hot cyclohexane, concentrated and passed through silica solid-phase extraction columns for clean up. After solvent change, the PAH were determined by high performance liquid chromatography with fluorescence detection. PAH concentrations in 15-mg aliquots of National Institutes of Technology Standard Reference Material SRM 1649 (Urban Dust/Organics) agreed well with published values. Relative precision at the 95% confidence level was 8% for SRM 1649 and 20% for replicate samples (5 mg) of ETS particles.

The table reports the emission-factor data for the gas and particulate phases of simulated ETS, respectively. Emission factors were calculated using the equation

$$E = \frac{CVa\Delta t}{n(e^{-at_i} - e^{-at_f})}$$

where E is the emission factor in ng/cigarette, C is the concentration in ng/m<sup>3</sup>, a is the air exchange rate including air removal by sampling, V is the chamber volume, t<sub>i</sub> is the time (after smoking cessation) sampling started, t<sub>f</sub> is the time sampling ended,  $\Delta t$  is t<sub>f</sub>-t<sub>i</sub>, and n is the number of cigarettes smoked. The measured total suspended particulate mass

of 0.96 ± 0.03 mg/m<sup>3</sup> led to an emission factor of 13.0 ± 0.5 mg particulate matter/cigarette when wall deposition of particles was neglected. The uncertainties were estimated by propagation of errors in each of the experimental parameters. Literature values of emission factors for three of the same particulate PAH in sidestream smoke from 1R4F reference cigarettes (benzo(b)fluoranthene, benzo(k)fluoranthene, and BaP), included in the table for comparison, show good agreement with the measurements reported here. A typical indoor smoking pattern in an average residential setting was estimated to result in an average indoor naphthalene concentration of about 36 mg/m<sup>3</sup>.

**Table 1.** Emission factors for gas and particulate phase PAH in simulated ETS from Kentucky Reference cigarettes 1R4F, ng/cigarette.<sup>a</sup>

| Compound             | Gas-phase<br>E ± 95% C.I. <sup>b</sup> | Particle phase<br>E ± 95% C.I. | Literature <sup>c</sup><br>E ± E <sub>std dev</sub> |
|----------------------|--|--------------------------------|---|
| Naphthalene          | 11200 ± 920                            |                                |   |
| 1-MeNap              | 4570 ± 400                             |                                |   |
| 2-MeNap              | 7200 ± 630                             |                                |   |
| Fluorene             | 773 ± 167                              |                                |   |
| Phenanthrene         | 590 ± 60                               | <71                            |   |
| Anthracene           | 52.7 ± 4.9                             | <1                             |   |
| Fluoranthene         | 51.0 ± 4.8                             | 31 ± 1                         |   |
| Pyrene               | 189 ± 40                               | 41 ± 10                        |   |
| Triphenylene         |  | 85 ± 20                        |   |
| 1,2-Benzofluorene    |  | 36 ± 8                         |   |
| Benz(a)anthracene    | 2.1 ± 0.3                              | 152 ± 23                       |   |
| Chrysene             | 11.8 ± 1.7                             | 412 ± 36                       |   |
| Benzo(b)fluoranthene |  | 132 ± 55                       | 112 ± 15  |
| Benzo(k)fluoranthene |  | 32 ± 6                         | 34 ± 5  |
| Benzo(a)pyrene       |  | 74 ± 10                        | 113 ± 15  |

<sup>a</sup> Concentration was measured for one hour in a sealed 36-m<sup>3</sup> chamber, starting 30 min. after 3 cigarettes were smoked. Average of measurements from two co-located samplers.

<sup>b</sup> 95% C.I. = uncertainty at the 95% confidence interval, estimated by propagation of measurement errors.

<sup>c</sup> Reported for sidestream smoke.

## Effect of Environmental Conditions on the Regional Lung Deposition of Environmental Tobacco Smoke

R.G. Sextro, M. Xu, A. Nematollahi, A.J. Gadgil

Environmental tobacco smoke (ETS), considered a carcinogen by the U.S. Environmental Protection Agency, is thought to produce other health effects in nonsmokers as well. Nonsmoker exposures to ETS vary widely and often occur in a number of circumstances. The significance of these differing situations for estimating health effects is not well understood. One of the most important factors affecting both the amount and location of ETS particle deposition in the lung is the size distribution of the particles. We have found previously that several factors affect the size distribution of ETS in the indoor environment, including cigarette type, smoking rate, ETS aging, ventilation rate, and indoor temperature.

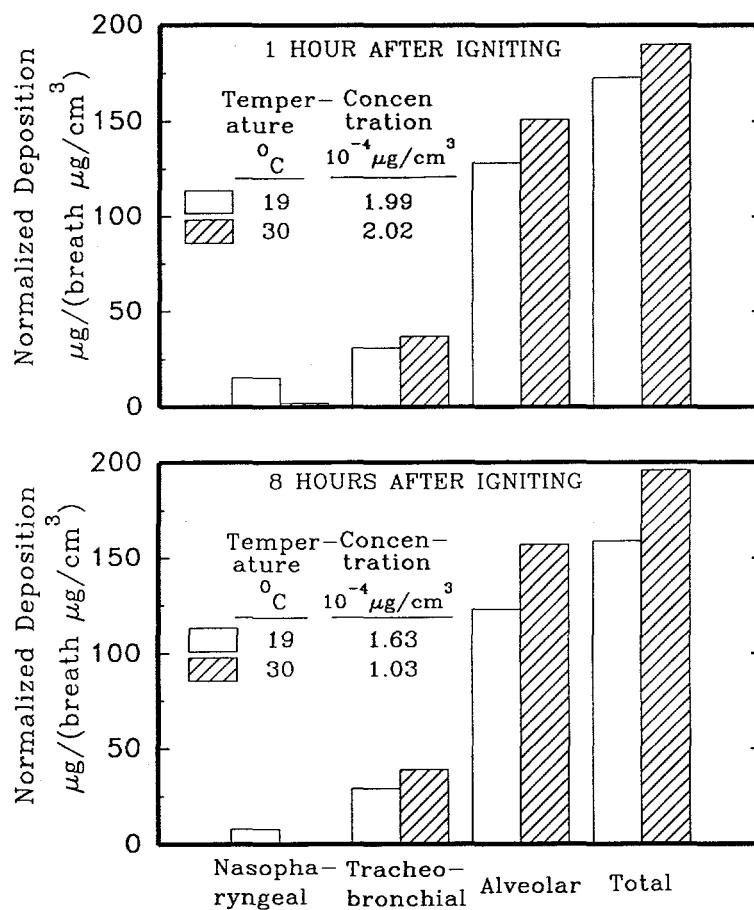
We used an existing regional lung model to examine the influence of these factors on the amount and location of ETS deposition. This lung model assumes that the respiratory tract consists of a branching network of airways, with each generation of branches characterized by the number of airways, their length, and diameter. Particle deposition within each airway occurs due to particle diffusion, impaction, and gravitational settling. The simulations were based on the breathing rates and lung dimensions of 12- and 30-year-old female subjects undergoing light exercise, assuming nose breathing. Lung deposition was calculated at 1 and 8 hours after cigarette ignition for a variety of different smoking and environmental conditions. The lung deposition was simulated for three regions of the lung—nasopharyngeal, tracheobronchial (airway generations 1-16), and alveolar (airway generations 17-25).

Cigarette type was found to be one of the more significant variables influencing regional lung deposition of ETS. Using particle-concentration and size-distribution data as a function of time measured in chamber experiments as input for the model, total lung deposition at 1 hour after cigarette ignition was greatest for high-tar cigarettes and lowest for low-tar cigarettes. Regional deposition differed for the different cigarettes, depending upon the time interval following ignition. Because the high-tar cigarettes produce a greater number of large particles, nasopharyngeal deposi-

tion is greater at 1 hour for the high tar compared to the low tar cigarettes; in contrast, alveolar deposition is larger for low tar than for high tar cigarettes, due to the greater number of smaller particles produced in the ETS from low tar cigarettes. At 8 hours after ignition, the differences in the deposition rates and regions were less significant among the cigarette types because the ETS particle size distributions were similar after this elapsed time.

The influence of room temperature on regional lung deposition for each time period is illustrated in the figure. To compare the effects of ETS concentration

and the particle size distribution, the calculated lung deposition results are normalized by breathing rate and by the mass concentration of airborne particles. As shown (Figure), the normalized deposition is greatest in the alveolar region, accounting for approximately 75-80% of the total normalized deposition. Normalized deposition in both the tracheobronchial and alveolar regions are predicted to be larger at a room temperature of 30 °C than at 19 °C, while nasopharyngeal deposition is greater at 19 °C. Variations in other environmental parameters and smoking conditions did not show as large an effect on deposition.



**Figure.** Regional lung deposition of ETS particles, normalized by breathing rate and by particle mass concentration, for two different room temperatures. The input size distribution data are from a Kentucky reference cigarette 1R4F at 1 and 8 hours following cigarette ignition. The simulation is for a 30-year-old female undergoing light exercise.

## Smokeless Ashtray for Reducing Exposures to Environmental Tobacco Smoke

W.W. Nazaroff, D.A. Wampler, A.J. Gadgil, A. Litvak, K.R.R. Mahanama, S. Miller Leiden, M. Nematollahi

More than 45 million American smokers consume over 500 billion cigarettes per year. It is almost inevitable that a nonsmoker will, at times, be exposed to environmental tobacco smoke (ETS). Such exposure is a subject of increasing public concern, fueled by a recent USEPA report concluding that ETS is a human lung carcinogen, responsible for approximately 3000 lung cancer deaths annually in U.S. adult nonsmokers and, for children, an increased incidence of asthma episodes and lower respiratory tract infections.

The dominant portion of ETS issues from the idling cigarette between puffs. Capturing and removing both gas-phase contaminants and particles from this smoke stream could significantly reduce the exposure of nonsmokers. Control devices with this aim are commercially available and are known as "smokeless ashtrays." We conducted experiments to determine the effectiveness of two commercial smokeless ashtrays for particle removal and found them to be substantially ineffective. We then designed and constructed a prototype smokeless ashtray to overcome the flaws in the commercial devices. In chamber tests, this prototype was found to be very effective in reducing particle and gaseous ETS concentrations that result from a smoldering cigarette.

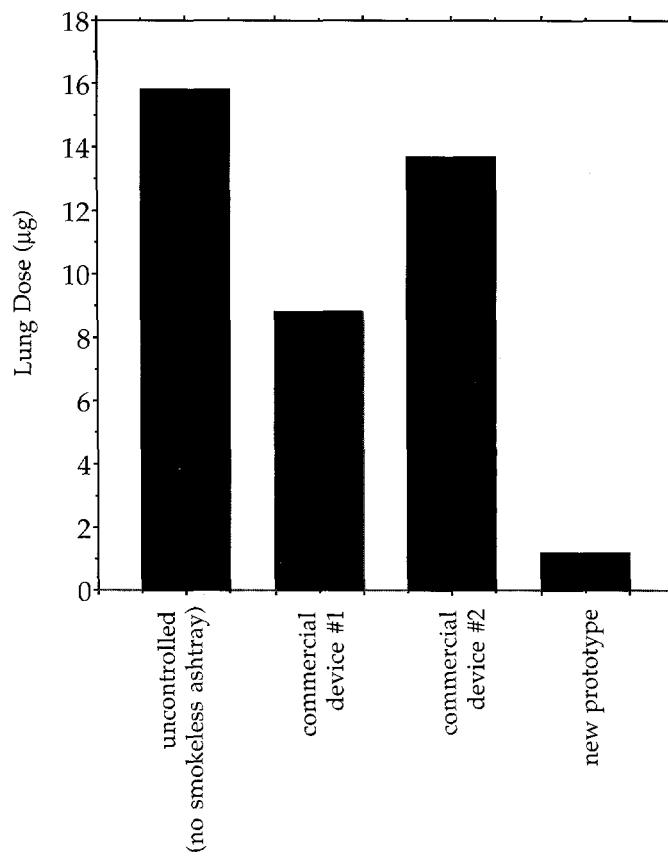
The commercial smokeless ashtrays and our prototype device share the same conceptual design: a small fan draws the smoke plume from an idling cigarette through one or more filters before discharging the treated air into the room. We believe that two design errors account for the observed low particle removal efficiencies of the commercial ashtrays: (1) the ashtrays incorporated ineffective filter media for removing accumulation-mode tobacco smoke particles; and (2) smoke flow through one of the ashtrays was observed, at times, to completely bypass the filter. Our prototype device contains two glass-fiber, pleated HEPA filters in series with granular activated carbon and granular activated alumina. The unit is constructed so that cigarette smoke cannot bypass the filters.

The particle removal effectiveness of the smokeless ashtrays was quantified by conducting experiments in an unoccupied 31-m<sup>3</sup> room at the Indoor Air Quality Research House, in Richmond, Califor-

nia. For each run, a smoldering cigarette (Kentucky reference cigarette 1R4F) was placed in the normal position of the functioning ashtray and the airborne particle concentration in the room was measured as a function of time. In a separate baseline experiment, similar measurements were made with a smoldering cigarette but with no smokeless ashtray in use. To prevent infiltration of particles from the outside and to produce ventilation rates comparable to a typical home, particle-free, HEPA-filtered air was supplied to the room. Total particle number concentration was measured with a condensation nucleus counter. The particle size distribution was determined with a differential mobility analyzer and an optical particle counter. A regional lung deposition model was combined with the

particle size distribution data from each of the experiments to predict deposition of tobacco smoke particles in the respiratory tract of a non-smoker exposed in the room for one hour, starting with cigarette ignition.

The figure compares the lung deposition predictions for the four cases. As expected, the largest mass of deposited cigarette smoke particles, 15.8 µg, occurs for the uncontrolled smoldering cigarette. With the cigarette contained in the two commercial smokeless ashtrays, deposited mass is reduced by 44% and 13%, respectively. For our prototype, the predicted lung dose is reduced by 92%, relative to the uncontrolled case. In field use, overall device effectiveness in reducing airborne ETS particle concentrations would be somewhat lower in each case



**Figure.** Predicted total mass of ETS particles deposited in a nonsmoker's lungs after one hour of exposure. The four cases compare an uncontrolled smoldering cigarette against a smoldering cigarette set in each of three smokeless ashtrays. The commercial devices have relatively low effectiveness at reducing exposure compared with the new prototype. Exposure began with cigarette ignition and occurred in a closed 36 m<sup>3</sup> room, with an air exchange rate of 0.7 - 0.9/h. The exposed individual is a 30-year-old man who breathes 25 L/min, corresponding to light exercise.

due to the uncontrolled contributions of exhaled mainstream smoke and sidestream emissions while the cigarette is being held.

Only our prototype device was tested for removal effectiveness against gaseous species. Three experimental runs were conducted in a 20 m<sup>3</sup> stainless steel chamber: two baseline experiments with no smokeless ashtray present and one run using the prototype device. In each run, three cigarettes were smoked consecutively inside the unventilated chamber using a smoking machine; the mainstream smoke was exhausted outside. The airborne concentrations of 23 selected gas-phase compounds including nicotine,

three aldehydes, and nineteen other volatile organic compounds (VOCs), were measured in the chamber air. Five of the compounds were below detection limit in all runs: butyraldehyde and 3-methyl-1-butanol (detection limits of 2.5 mg/m<sup>3</sup>); ethyl acetate, ethyl acrylate, and butyl acetate (detection limits of 0.5 mg/m<sup>3</sup>). The removal efficiency of our prototype smokeless ashtray for the other eighteen species was in the range ~70% to >95%. Of particular interest are the removal efficiencies for irritating gases, formaldehyde, acetaldehyde, and acrolein, which were 93%, 77% and 72% respectively. Nicotine was removed with an efficiency of approximately 95%.

Efforts to develop effective smokeless ashtrays should be viewed as complementary to other ETS control measures, rather than as a substitute. Clearly, prohibiting smoking in a public building has a greater potential to reduce ETS exposure than implementing any source-control technology. However, legislative regulation of smoking in private residences appears completely impractical, and so alternative means to control ETS exposure should be considered in these settings. The commercial devices we tested are not effective; yet the device we built indicates that the challenge of providing a reliable, high-efficiency, low-cost smokeless ashtray is well within reach.

## Ventilation and Indoor Air Quality

### Air-Change Effectiveness Under Worst-Case Conditions

D. Faulkner, D.P. Sullivan, W.J. Fisk

The building engineering and architectural communities repeatedly express concern about the acceptability of indoor thermal comfort conditions when Variable Air Volume (VAV) ventilation systems are utilized. Many engineers and architects suspect that VAV systems result in a poor air change effectiveness (i.e., poor delivery of outside air to the breathing zone) during some operating conditions.

One configuration of concern is that in which air warmer than the room air is supplied and returned at the ceiling. The concern is that the warm buoyant air remains near the ceiling and is short-circuited from the supply diffuser to the return grille, thus not adequately reaching the breathing level of the occupants. Little experimental research has investigated short-circuiting during heating conditions with the low supply-air flow rates. Field measurements have shown few incidences of significant short-circuiting with ceiling supply and return ventilation systems; however, most field data are from periods of air conditioning with cool supply air.

We conducted a series of experiments to study the effects of various supply

diffusers and supply-air conditions on indoor ventilation and thermal comfort in the Controlled Environment Chamber (CEC) at the University of California at Berkeley in conjunction with staff at the Center for Environmental Design Research. The CEC was partitioned into two workstations and furnished with office furniture, overhead lights, task lights, and personal computers (the sources of heat and air motion) in a configuration typical of actual office settings. Both of the workstations were occupied by a heated, seated mannequin. During heating tests, exterior windows present on two walls were cooled. The ventilation system supplied air at the ceiling and the air exited the room through a ceiling-mounted return grille.

Three supply diffusers used widely in commercial buildings were chosen for the experiments. They were operated with supply flow rates near or slightly below the manufacturers' recommended minimum flows. We choose two perforated supply diffusers most suspected to give poor results in the heating mode at low flow rates. The third diffuser was a slot diffuser, designed to provide a relatively high-velocity jet of supply air even

at low flow rates, which we expected to short-circuit less than the perforated diffusers.

To study indoor air-flow patterns during periods with controlled supply temperatures and flow rates, we injected a tracer gas into the supply air and measured tracer-gas concentrations versus time at multiple points inside the chamber. Local ventilation rates were determined from these tracer-concentration histories. The ratio of the average local ventilation rate at the breathing level to the local ventilation rate at the return grille was calculated. This ratio, called the breathing level air-change effectiveness, is a measure of how efficiently the breathing zone is ventilated with outside air. If the room air is well mixed, the ratio will equal unity. Short-circuiting of the supply air to the return grille will produce a ratio less than unity. A breathing level air-change effectiveness better than the well-mixed reference case is indicated by a value greater than one.

The test variables included the supply air temperature and flow rate, the percent of outside air in the supply air (usually 100%), and the type of diffuser. In heating tests (the supply air was warmer

than the room air), there was short-circuiting evident regardless of the type of diffuser. At the high supply-air flow rate (~160 cfm), the breathing level air-change effectiveness varied from 0.70 to 0.77. At the low flow rate (~80 cfm), this parameter varied from 0.79 to 0.87. In contrast to expectations, the short-circuiting was more pronounced for the higher supply-air flow rates. In several heating tests, the supply air temperature was varied over

time to simulate what might occur in the field with the source of heat repeatedly turned on and off. The breathing level air-change effectiveness values for these tests were not significantly different than values for similar tests with a constant supply air temperature. Additional tests are planned with the slot diffuser, since the tests completed to date are with very low supply velocities. In the cooling mode, the breathing level air-change ef-

fectiveness ranged from 1.03 to 1.11. These values for the cooling mode are in the range of previous measurements in the CEC and in the field.

These experimental data confirm that significant short-circuiting of supply air to return grilles can occur. However, at the operating conditions in our study, which are expected to be near to worst-case conditions, the amount of short-circuiting is not extreme.

## Pollutant Emission Factors from Residential Natural Gas Appliances: A Literature Review

G.W. Traynor, M.G. Apte, G. Chang

A goal of many local, state, and federal agencies in California is to reduce outdoor air pollution levels in the South Coast Air Basin (SCAB) and other urban airsheds. Gas-fired burners that produce low levels of  $\text{NO}_x$  and CO would help reduce outdoor pollution emissions from gas-fired appliances. Measures that reduce the need for gas combustion (improved efficiencies for space and water heaters and increased house insulation) would also help decrease pollutant emissions. The goal of this project is to collect information on pollutant emission factors for the existing stock of residential natural gas appliances. This information can then be included in a quantitative model that can both predict outdoor pollution emissions from residential natural

gas appliances and evaluate various pollutant-reducing strategies on a cost-benefit basis. The model will use detailed information on residential natural gas appliance-emission factors, usage rates, and market penetrations. The model will then be able to evaluate the benefits of various pollutant-reducing strategies, rank the strategies, and compare them to similar measures proposed in other pollutant-producing sectors such as large industrial and mobile sources. Pollutant emission rate data have been collected from published journal articles and reports. To date, we have found more than 80 papers that report pollutant emission rates from over 700 residential gas appliances. The data have undergone a quality assurance review.

The literature survey of pollutant emission rates from residential natural gas appliances reveals mixed results when our literature values are compared with those published by the U.S. Environmental Protection Agency in its *Compilation of Air Pollutant Emission Factors* (AP-42).  $\text{NO}_x$  and fine particulate emission factors collected in our literature search are consistent with the emission factors in EPA's AP-42. However, CO and methane/hydrocarbon emissions collected in our literature search are an order of magnitude greater than the AP-42 values. These results may indicate that the impact of residential natural gas combustion on outdoor CO and hydrocarbon levels has been underestimated. A well-designed field study is needed to test this hypothesis.

## Air Pollutants and Failures of Electronic Components and Systems

B. Shah, W.J. Fisk, A.J. Gadgil

Much of the U.S. work force relies on electronic equipment and communication systems to maintain a high level of productivity. What is not widely recognized is that air pollution within buildings is a source of failures of electronic systems

Airborne particles appear to play a particularly significant role in electronic equipment failures. Particles can deposit on circuit boards through a variety of mechanisms including gravitational settling, inertial impaction, diffusional deposition, and deposition caused by electrostatic and thermophoretic forces. An accumulation of particles on a circuit board can result in a leakage of current or arcing between conductive paths. The consequence may be a catastrophic circuit board failure or a parametric failure in which the

circuit functions outside of specified tolerances. The deposition of hydroscopic particles, such as nitrate and sulfate salts, is of particular significance. With a sufficient concentration of moisture in the surrounding air, these deposited salts deliquesce and become conductive. Particles can also deposit on electrical contacts and act as an electrical insulator. As contact resistance increases due to the deposited particles, the operation of the circuit can be adversely affected, or a complete open circuit may result. Data storage media, such as magnetic tapes, can also fail due to the deposition of particles. The result may be a loss of valuable data.

Reactive inorganic gases are another source of electronic equipment failures. Ozone can promote cracks in the insula-

tion materials on wires and cables. Failures of insulation can cause short circuits and equipment failure. Ozone can also react with nitrogen dioxide yielding nitric acid aerosols that corrode metallic components in electronic systems.

Volatile organic gases (VOCs) are the third class of pollutants that can cause or contribute to electronic equipment failures. VOCs that adsorb on electrical contacts can increase electrical resistance or cause an open circuit. Sorbed VOCs may also increase the tendency for particles to adhere to surfaces.

In a review of the literature, we identified no estimates of the nationwide economic significance of electronic equipment failures caused by air pollutants within buildings. In addition, the data required to

develop estimates, aside from order-of-magnitude estimates, do not appear to be available. One example of the economic significance of these failures is available from the telephone industry. The annual cost of failures of circuit boards in the approximately 20,000 telephone central offices of the U.S. is on the order of one billion dollars. Roughly 20% of these failures (\$200 million annually) may be attributable to environmental factors despite the maintenance of typical indoor environmental conditions in the telephone central offices. Considering the widespread use of electronic equipment in the U.S. and the reductions in productivity caused by failures in electronic components and sys-

tems, the total nationwide direct and indirect cost of electronic equipment failures is likely to be many times greater than the direct cost of failures within U.S. telephone switching offices. Thus, we suspect that the annual nationwide economic cost of electronic system failures caused by indoor air pollutants is of the order of a billion dollars.

Significant reductions in the rates of failures of electronic systems caused by indoor air pollutants should be feasible using currently available reasonable-cost technologies. The most obvious technology is the use of more efficient particle filters in building ventilation systems. Filtration of the air supplied to the cabinets

housing electronic equipment is another option. Failures due to VOCs may be reduced by decreasing the sources of VOCs within buildings or through the use of sorbent materials to remove VOCs from air. Failures caused by corrosive inorganic gases such as ozone may also be reducible using suitable sorbents and catalysts. Many of the measures for reducing failures of electronic equipment are based on decreasing the concentrations of pollutants within the building air. These measures are likely to simultaneously improve the health and productivity of building occupants, with concomitant large financial benefits.

## Phase 2 of the California Healthy Building Study

*W.J. Fisk, D. Faulkner, M.J. Mendell, D. Sullivan, A.T. Hodgson, J.M. Macher,  
M. Boyle, K. Chow, J. M. Daisey, F.J. Offermann, S. Loiselle*

The California Healthy Building Study (CHBS) seeks to identify the major characteristics of buildings, ventilation systems, jobs, and indoor environments that are associated with the increased prevalence of "sick-building" health symptoms among office workers. The symptoms may include irritation of the eyes, nose, or throat, dry or itchy skin, difficulty breathing, and coughs, headaches, and fatigue. The first phase of the CHBS was a cross-sectional study of 12 office buildings located in the San Francisco Bay area. Health symptom and job data were collected via a questionnaire, buildings and ventilation systems were characterized, concentrations of selected indoor pollutants were measured, and regression models were used to assess associations between the prevalence of symptoms and factors suspected to be associated with increased symptoms.

Data collection for Phase 2 of the CHBS took place between October 1992 and March 1993. Phase 2 activities included inspections and low-cost measurements yielding additional information that could be used in conjunction with the Phase 1 symptom data. Several measurement and information-collection methodologies were also evaluated during Phase 2. The Phase 2 study included the following components: 1) inspections of HVAC systems to identify and, in some cases, quantify potential sources of volatile organic compounds, fibers, and bioaerosols; 2) evaluation of a protocol

for measuring the concentration of bioaerosols in the air exiting supply air diffusers; 3) interviews with building operators to assess practices related to HVAC inspection, cleaning, and disinfecting; 4) evaluation of a protocol for measuring the extent of microbiological contamination on floors and on upholstered chairs; 5) quantifying the amount of carpet within each study space in order to allow an improved assessment of associations with worker symptoms; 6) interviews with building operators to determine the quality of office cleaning and the nature of office pest-control practices; 7) measurement of the spatial and temporal variations in sound levels within study areas so that a protocol for sound-level measurements could be designed and used in a future study; and 8) measurement of the percentages of lighting flicker in each study space so the association between percent flicker and symptoms could be evaluated.

Evaluation of the Phase 2 data is ongoing. Some findings from analyses to date include:

- Fiberglass duct liner, considered a potential source of fibers and VOCs in the occupied space, was present in 21 out of 27 air handlers. In three air handlers, the duct liner was visibly damaged.
- Microbiological contamination was not observed in any air handler. Concentrations of culturable fungi in supply air samples were typically a factor

of ten to 100 lower than the concentrations in outside air, suggesting that the air handlers were not large sources of culturable fungi during the study period.

- Unadjusted regression analyses thus far indicate that four potential indicators of poor HVAC maintenance are significantly associated with increases in at least some work-related symptoms. Multivariate analyses to confirm these relationships are ongoing.
- Our data suggest that concentrations of fungi and bacteria in dust samples from upholstered chairs exceeded concentrations in samples from floors. However, the convenient method of collecting dust samples from floors and chairs resulted in small numbers of fungal and bacterial colonies and, thus, statistically imprecise data. We concluded that a technique that samples from much larger surface areas, for example, entire chairs or the entire floor in a workstation, should be employed to improve measurement precision and sample representativeness.
- The monitoring protocol for measuring sound-pressure levels (measuring three times per day at four to six sites per study space) yielded mean values of sound pressure level that adequately integrate the temporally- and spatially-variable data within study spaces.

## Indoor Air Quality in New Energy-Efficient Industrialized Housing

A.T. Hodgson

Energy efficiency in housing must be achieved without sacrificing good air quality. When ventilation rates are reduced, acceptable air quality can be maintained only by controlling or eliminating the sources of airborne contaminants. Volatile organic compounds (VOCs) are one important class of contaminants that are typically emitted by building construction and interior finish materials. Therefore, manufacturers, architects, and contractors involved in the construction of energy-efficient houses must be aware of the potential impacts of these sources.

The Department of Energy's Industrialized Housing Program is currently investigating two new houses in Pittsburgh, Pennsylvania. One house was built conventionally; whereas, the other, which is nearly identical with respect to size and major materials, incorporates several innovations. These unoccupied houses are

monitored for energy performance including periodic testing of the building envelop and air distribution system air tightness.

The study of the two houses provided an opportunity to quantify the impacts of VOCs emitted by building construction and interior finish materials on indoor air quality. The objectives of this study were to periodically measure the concentrations of total VOCs (TVOC) and individual VOCs, including formaldehyde, in the conventional house over a period of approximately one year and to compare these values to concentrations measured in the energy-efficient house. Source strengths for TVOC and VOCs were calculated using concurrently measured ventilation rates to see how the emissions from the sources behaved irrespective of the season or operating conditions of the houses at the times of the measurements.

To date, air samples have been collected in the conventional house on three occasions over a period of eight months with the first samples collected approximately one month after completion of construction. A single set of air samples has been collected from the energy-efficient house shortly after its completion. The ventilation rates for the conventional house at the times of sample collection ranged from 0.08 to 0.22 per hour. An exhaust fan operates continuously in the other house giving a ventilation rate of 0.38 per hour. Concentrations of TVOC and formaldehyde were respectively 1.7 - 4.4 mg/m<sup>3</sup> and 15 - 74 µg/m<sup>3</sup> in the conventional house and 2.8 mg/m<sup>3</sup> and 49 µg/m<sup>3</sup> in the energy-efficient house. There was less than a factor of two decline in the source strengths of TVOC and formaldehyde in the conventional house over the eight months.

## Indoor Air Exposures and Risks

### Associations of Measured Temperatures and Carbon Dioxide Concentrations to Sick Building Symptoms in the California Healthy Building Study

M.G. Apte, W.J. Fisk, M.J. Mendell

Over the last decade, episodes of Sick Building Syndrome (SBS), incidents where outbreaks of illness in office buildings cannot be readily explained by a recognized disease or environmental exposure, have become an important issue both in public health and building energy management. Typical symptoms of SBS include mucosal irritation of the eyes, nose, or throat, headache, fatigue, dry or itchy skin, and chest tightness or difficulty breathing. These symptoms are building-related since they tend to ameliorate when the affected individuals are absent from the building. Several studies (most conducted in Europe) have attempted to determine the prevalence of SBS symptoms expressed by individuals working within the normal or "healthy" building population. These studies have shown that occupants within these so-

called healthy buildings report frequent work-related symptoms of the same non-specific type as those working in buildings with acknowledged SBS problems. Analyses have identified a fairly consistent pattern of increased prevalence of SBS symptoms in air-conditioned buildings relative to those that are naturally ventilated.

We conducted Phase 1 of the California Healthy Building Study (CHBS) between June and September of 1990 in 29 distinct spaces within twelve office buildings located in the San Francisco Bay Area in California. Buildings were selected without regard to SBS complaint status; they were either ventilated naturally, mechanically, or with air conditioning. A cross-sectional study design was used to learn about risk factors for building-related health symptoms. A self-adminis-

tered questionnaire of 880 occupants of the 12 buildings provided data about the prevalence of symptoms, demographic information, and job and workspace characteristics. Inspections were used to collect data on the physical characteristics of the buildings. Indoor (and ambient) pollutant concentrations, temperature, and humidity were characterized during a one-week measurement period. Details of this study including statistical analyses have been described fully in previous reports.

We recently focused on investigating associations between measured environmental parameters and the prevalence of reported SBS symptoms in the CHBS dataset. In particular, two hypotheses, based on a review of the literature, are being tested: 1) indoor temperature is associated with an increase in symptoms

of mucosal irritation, and 2) higher indoor carbon dioxide ( $\text{CO}_2$ ) levels are associated with an increased prevalence in symptoms of headache, fatigue, and difficulty breathing. Multiple logistic regression models have been developed to test these hypotheses on the CHBS data.

A risk variable for temperature was constructed that reflects the proportion of time the indoor temperature was above  $23^\circ\text{C}$  (reference  $<23^\circ\text{C}$ ). Similarly a  $\text{CO}_2$  risk variable was constructed that reflects average indoor concentrations above 500 ppm (reference  $<500$  ppm). Logistic models containing these main risk variables were constructed. Co-variables were added to adjust for environmental/building, demographic, and psychosocial parameters.

Preliminary results from the logistic models indicate that after adjustment, the prevalence of irritated eyes and irritated throat are elevated (odds ratios 2 to 3,  $p<0.1$ ) for spaces with temperature below  $23^\circ\text{C}$  (but above about  $18^\circ\text{C}$ ) more than half the time. They also suggest that the prevalence of headache and fatigue is

elevated in spaces where weekly average  $\text{CO}_2$  concentrations are above 500 ppm (odds ratio 2,  $p<0.1$ ).

The finding for temperature is consistent with certain similar research found in the literature; however, it contradicts other published work indicating that increased temperatures are associated with increased symptoms. It is possible that this contradiction is due to the differing climatic conditions in Northern California (especially moderate ambient relative humidity and temperature) compared to those in the Eastern United States and northern Europe. It is also possible that certain interactions with volatile organic compounds may be present in some studies and not others. The finding for  $\text{CO}_2$  is consistent with other published data, although most researchers have not seen health effects associated with such low indoor concentrations.

In addition to the modeling efforts just discussed, a series of analyses have been conducted using an exploratory method to adjust for hypothesized reporting bias due to dissatisfaction with

the overall work environment. The hypothesis is that overall dissatisfaction with work, caused by psychosocial or physical stressors, is reflected in an heightened awareness and intolerance of symptoms leading to increased reporting of a variety of SBS symptoms. Dissatisfaction irrespective of environmental conditions would lead to falsely increased symptom reporting and reduce our ability to detect real relationships between environmental conditions and symptoms. A question from the study, designed to elicit the respondents' level of satisfaction with the overall physical environment, is used as a co-variable in regression models similar to those discussed above. Consistent with the hypothesis, after adjustment using this method, the odds ratios for the associations between the above mentioned symptoms and environmental parameters increase and the associated  $p$ -values decrease. Thus, this exploratory analyses suggests that adjustment for overall dissatisfaction may increase our ability to detect true associations between symptoms and environmental parameters.

## Reducing SBS Symptoms in Office Workers: Progress in The Design of Experimental Intervention Studies

W.J. Fisk and M. Mendell

Public health officials, researchers, as well as the general public all recognize the phenomenon of "sick building syndrome" (SBS) as a significant problem. Incidents of SBS within specific buildings (often office buildings) are characterized by an unusually high prevalence of health symptoms and health complaints among the building's occupants. The symptoms may include irritation of the eyes, nose, or throat, dry or itchy skin, difficulty breathing, coughs, headaches, and fatigue. These symptoms could have many potential causes and, therefore, do not generally indicate a specific disease or specific pollutant exposure. Recent research indicates that a significant percentage of occupants in most office buildings report frequent building-related SBS symptoms.

The primary approach for learning about the risk factors for SBS symptoms has been to perform multi-building surveys. Questionnaires collect data about health symptoms and data on demographics and jobs. The buildings are characterized and relevant indoor environ-

mental conditions (e.g., pollutant concentrations) may be measured. Multivariate regression models are then used to assess relationships between various factors and symptoms. While these studies have been informative, because a large number of inter-related factors potentially affect symptoms, this type of study cannot clearly identify causes of SBS symptoms nor definitively find or identify methods to reduce symptoms.

LBL's Indoor Environment Program and the National Institute for Occupational Safety and Health (NIOSH), drawing upon a few prior studies in office buildings and on well-established clinical research methods, are developing protocols for controlled experimental intervention studies in office buildings. These intervention studies will provide data on the effectiveness of different interventions in reducing symptoms and, eventually, will increase our knowledge of causal exposures and mechanisms involved. In these experimental studies, a single factor (such as ventilation rate) that is ex-

pected to affect symptoms is improved. Symptom data, before and after repeated interventions, are compared within occupants. This approach reduces much of the potential for confounding, which is characteristic of the cross-sectional survey approach. We are focusing on three types of interventions: increases in outside air ventilation, improved air filtration, and improved cleaning of indoor surfaces (e.g., carpets).

In addition to conducting experimental interventions in our future research on SBS symptoms, we plan to incorporate improved methods of measuring health status. Questionnaires will collect data on current symptom intensity, as well as on symptoms during a previous period (the typical practice). Greater accuracy is expected in the assessments of current symptoms because the subjects do not have to recall the past. We are also exploring the potential to include more objective health measurements, such as of nasal congestion or eye dryness, in future studies.

The steps in an intervention study would be as follows:

1. At least two populations (P1 and P2) of approximately 100 workers within a suitable building are selected. Air flow between the two populations must be limited so that an intervention affects only the desired population. In other respects, the populations should be as similar as possible. In the building selection process, calculations and pilot studies are employed to ensure that the intervention parameter can be varied over the range of interest.
2. All workers (P1 and P2) initially complete a long questionnaire, providing demographic and job data and gaining experience with the health symptom portion of the questionnaire.
3. In P1, the intervention is implemented blind to the occupants and, if possible, also blind to those in contact with occupants. If the intervention can not be blind, a mock intervention is simultaneously implemented in P2. After approximately three weeks, health data are collected from both P1 and P2 on a short questionnaire.
4. The intervention parameter is returned to the initial condition in P1 and simultaneously modified in P2. After approximately three weeks, health data are collected from both P1 and P2, again on the short questionnaire.
5. Steps 3 and 4 are repeated at least once.

During the study period, the parameter that is intentionally varied is measured. In addition, other uncontrolled

and potentially unstable parameters that are thought to affect symptoms are also measured.

Data are analyzed to determine the effect of the intervention on SBS symptoms. Because of the availability of simultaneous data from the two populations and the within-subject comparisons of symptoms, the crude effect of the intervention on symptoms can be adjusted for extraneous factors such as individual differences, placebo responses, and time.

We hope to undertake intervention studies in a number of buildings during the next few years. The first study will probably involve improved filtration and is tentatively scheduled for the summer of 1995.

## Improved Productivity and Health from Better Indoor Environments\*

W.J. Fisk

The economic incentives for investments that improve productivity are unquestionable. Worker salaries exceed building energy and maintenance costs by a factor of 100 and exceed annualized construction or rental costs by almost as much. Thus, from the viewpoint of an employer, even a 1% increase in productivity, if really tangible, should be sufficient to justify an approximate doubling of energy or maintenance costs or large increases in construction costs or rents. Productivity increases of 1% correspond to reduced sick leave of two days per year, reduced breaks from work (or increased time at work) of 5 minutes per day, or a 1% increase in the effectiveness of physical and mental work.

Evidence from a variety of research areas suggests the potential for substantial improvements in human health and productivity, as well as a reduction in health care costs, from improvements in the quality of indoor environments. Five links between the quality of the indoor environment and health and productivity are identified in the following paragraphs:

**Infectious Disease Transmission:** Numerous infectious diseases are, at least in part, transmitted through airborne routes. In a large study by the U.S. Army, rates of acute respiratory disease with

fever were 50% higher among recruits housed in barracks with closed windows, low rates of outside air supply, and extensive air recirculation compared to recruits in barracks with frequently open windows, more outside air, and less recirculation. Several potential, but largely unproved, methods exist to reduce the transport of infectious aerosols between people in buildings. These methods include high efficiency filtration, reduced air recirculation, increased outside air ventilation, and disinfection of air with ultra-violet light. The potential productivity gains from reduced disease transmission are huge. For example, reducing respiratory disease by one-third in U.S. office workers (equal to the observed decrease in the Army study) translates into a nationwide annual productivity gain of approximately \$16 billion.

**Allergies and Asthma:** Approximately 20% of the U.S. population has environmental allergies. Approximately 10% have asthma. Allergies and asthma increase health care costs and reduce productivity. The estimated cost of asthma-related illness in the U.S. during 1990 was \$6.2 billion. The symptoms of allergies and asthma can be triggered by indoor pollutants including fragments of house dust mites, animal dander, fungi, irritat-

ing chemicals, and pollens from outdoor air. Infectious respiratory diseases can also cause the symptoms of asthma. Improving the indoor environment should reduce allergic and asthmatic symptoms. Potential measures to reduce the symptoms include better filtration to prevent the entry of pollens from outdoors, reduction of microbiological growth (e.g., fungi, bacteria, mites) on indoor surfaces, reduced emissions of irritating chemicals from indoor materials, consumer products, and equipment, and better building-cleaning practices. Measures that reduce transmission of infectious respiratory diseases should also reduce symptoms of asthma. The potential annual benefit in reduced health care costs alone (neglecting productivity gains) is billions of dollars.

### Acute Sick-Building Symptoms

Some characteristics of buildings and indoor environments have been linked to increased prevalences of acute health symptoms among office workers. These symptoms, often called sick building syndrome symptoms, include eye, nose, and skin irritations, headaches, fatigue, and difficult breathing. They affect a substantial fraction of workers in many buildings. Sick building symptoms distract people at

\* This article is based on a document prepared for the Subcommittee on Construction and Building, Committee on Civilian Industrial Technology, National Science and Technology Council. A formal citation is not presently available.

work, contribute to time away from work, increase visits to a doctor, and can lead to litigation. Characteristics of buildings and indoor environments known or suspected to influence these symptoms include the type of building ventilation system, the type or existence of humidification equipment, the rate of outside air ventilation, the chemical and microbiological pollution in the indoor air and on indoor surfaces, and indoor temperatures and humidities. In experiments, such practical changes in the environment as increased ventilation, decreased temperature, and even improved cleaning of floors and chairs have reduced symptoms. In a large Dutch study of office workers, absenteeism attributed to sick building symptoms was significantly lower among workers who could adjust the temperature in their workspaces. Potentially very large financial benefits are anticipated from increases in productivity due to reduced absences or distractions from work caused by sick building symptoms. If reduced sick building symptoms resulted in a 1% increase in productivity of U.S. office workers, the estimated annual benefit would be \$25 billion.

#### Direct Impacts of Environment on Human Performance

Specific indoor environmental conditions may adversely affect the performance

of physical and mental work without causing health symptoms. Substantial existing data only detail the connection between temperature and work performance. These data, while limited, suggest an important link between temperature and selected measures of performance (e.g., accident rates, manual dexterity, signal recognition, and response time). It seems plausible that some chemical pollutants, such as selected volatile organic compounds that affect the central nervous system, may also have a direct impact on work performance. Even very small increases in performance (e.g., 1%) would translate into annual productivity gains of billions of dollars.

**Electronic Equipment Failures:** The productivity of the U.S. work force increasingly depends upon fast and dependable electronic communication and electronic equipment. Failures of electronic equipment can impede job performance and bring about costly repairs. Substantial evidence shows that deposition of aerosols on circuit boards (leading to electronic short circuits) and the action of corrosive gases on electronic circuits and electrical contacts are major causes of failures in electronic equipment. The annual cost of failures of circuit boards in the 20,000 telephone switching offices across the U.S. is on the order of \$1 billion and about 20% (\$200 million) of the failures are traceable to

indoor air pollution. Considering the widespread use of electronic equipment in the United States and the reductions in productivity caused by failures in electronic components and systems, the total nationwide direct and indirect cost of electronic equipment failures is likely to be many times greater than the direct cost of failures within U.S. telephone switching offices. Thus, we suspect that the annual nationwide economic cost of electronic system failures caused by indoor air pollutants is of the order of a billion dollars. Possible methods for reducing failures include improved filtration, reduction of indoor pollutant sources, and automatic control of ventilation based on outdoor particle concentrations.

#### Proposed Initiative

Previous studies have suggested the potential to improve productivity and health by improving indoor environments. However, existing data are too sparse and current knowledge is inadequate to stimulate widespread adoption of measures to improve the indoor environment. Consequently, we have proposed a multi-disciplinary, multi-institutional research program with the primary goal of evaluating the health and productivity gains associated with practical methods of improving indoor environments.

## Energy Conservation and Environmental Quality in Developing Countries

### Ethical Dimensions of Biodiversity Prospecting

*A.J. Gadgil*

The regions of the world with a rich biodiversity generally tend to be economically poor, while most of the rich industrial countries have a smaller biodiversity. At present substantial interest exists in exploring, identifying, sampling, cataloguing, and commercially exploiting the threatened or rapidly vanishing biodiversity resources on the Earth. Considerable effort is directed to this end by ethnobotanists, foresters, entomologists, and various academics, as well as by experts from museums, botanical gardens,

and large pharmaceutical corporations.

The present effort to conserve the world's biodiversity is motivated by strong commercial reasons. With appropriate investments in research, raw materials can be turned into lucrative pharmaceutical products. Such materials would certainly be prospected and extracted by large multinational corporations, which is actually what is increasingly occurring in most biodiversity prospecting. In addition, related anthropological and ethnobiological research is undertaken to in-

quire into folk remedies based on local resources. Such knowledge has been developed during many centuries of experience by the indigenous communities who have been stewards for these ecosystems. These poor tribal communities usually receive no compensation for such "prospecting" for highly profitable pharmaceuticals.

An ethical issue arises centered on whether (and how) these indigenous communities should be compensated. There is also a practical issue; that is, the

communities are left with no incentive for conserving their folk knowledge or for maintaining their stewardship of the local biodiversity. Thus a practical reward-sharing system and a code of ethics, if accepted by the relevant academic communities (e.g. by editorial policies of relevant journals), professional societies (e.g., the Ethnobotanical Society), government, private sponsors of research, and by the corporate sector, would not only be ethically warranted, but also would strengthen the continued preservation of biodiversity for the future.

With the aim of developing a guideline for ethical conduct in biodiversity prospecting, several Pew Scholars launched an initiative on this topic in late 1993. At LBL, we first assembled and assessed the existing guidelines for prospecting biodiversity required by universities, societies, grant agencies, foundations, botanical and zoological gardens, gene banks, non-profit organizations, research institutions, and business corporations. We then reviewed and critiqued these guidelines to identify their shortcomings and suggest remedial changes.

During the summer of 1994 we prepared a first draft, which is presently being critically reviewed by the Pew Scholars who are active researchers in relevant organizations. The coordinating center for the next phase of this activity has been purposely selected to be in a developing country location: Ahmedabad, India. In this next phase, we will obtain and incorporate comments from selected organizations, including those of indigenous communities, and then present the draft for discussion to various interested and relevant entities.

## Advanced Windows for Hot-Climate Commercial Buildings in Developing Countries

A.J. Gadgil

Air conditioning energy consumption in commercial buildings in some of the rapidly urbanizing developing countries represents a significant portion of the overall growth in electricity demand. Although indoor-outdoor temperature differences can be as high as 20 °C, windows in the air conditioned buildings usually have single-pane glass, permitting large conductive and radiative heat gains.

In an earlier thermal and economic analysis of a hospital building in Bangkok Thailand, we discerned that advanced windows, used in place of the single-pane gray-glass windows, would significantly decrease both the peak and the annual heat gains. Such a reduction in peak heat gains would permit significant downsizing of the cooling plant of the building. The economic savings from the downsizing of the air conditioning plant would offset approximately the incremental cost of the advanced windows. Thus the electricity savings (and the savings in associated CO<sub>2</sub> emissions) would be approximately "free."

This project aims to verify these predictions with experiments and consequently to convince decisionmakers in selected developing countries about the viability of this strategy to save energy and reduce CO<sub>2</sub> emissions. For this purpose, we have initiated field tests of advanced windows at two locations in Bombay, India, and will also conduct similar field tests at one location to be selected in Thailand or Malaysia. At each field site we will monitor the electricity consumption of air conditioners

in two matched offices that are cooled to the same temperature. One office is fitted with an advanced window; the other has the standard single-pane glass common to developing country office buildings. The room air conditioners used in the two matched offices are carefully selected to have as similar performance characteristics as possible. During the 1994 fiscal year one of the two Bombay

sites was fitted with an advanced window and data-collection instrumentation. The second Bombay site and the Southeast Asian site will be instrumented during the 1995 fiscal year. Preliminary results of the data analysis are expected to become available in late 1995. At each site, care is being taken to inform local decisionmakers in building technologies of the project's progress.

## Ultraviolet Disinfection of Drinking Water for Villages in Developing Countries

A.J. Gadgil, D. Yegian

According to UNICEF estimates, approximately two out of every three persons in the world do not have water piped into their homes and must fetch water from a community source. UNICEF also estimates about a billion people do not have access to safe drinking water. These conditions lead to the deaths of more than 400 children per hour worldwide from water-borne diseases. The specific incentive for launching this research effort was the outbreak of a new (so-called "Bengal") strain of cholera in India, Bangladesh, and now Thailand, for which there is no available vaccine.

We proposed and investigated a simple and rugged method (Figure) for disinfecting drinking water at the point of end use with shortwave ultraviolet "C" light. Such light can be easily produced with an electrical discharge in a low-pressure mercury arc (the same tech-

nology used inside a fluorescent lamp). Furthermore, because the light irradiates the DNA of bacteria and viruses at their resonant frequency, very little energy is necessary for disinfection—about 40,000 times less primary energy than would be used in boiling that water over a traditional cookstove. This irradiation method would kill off the pathogens causing cholera, hepatitis, dysentery, and diarrhea. Once we convinced ourselves that this device appeared feasible, we developed a simple design that would use 40 watts of electricity, could disinfect 40 liters (about 10 gallons) of water per minute, and would cost only 2 US cents to operate per hour. Such a device could serve a community of 2000 persons. We developed a prototype for the device and obtained satisfactory hydrodynamic performance for the design. Convinced of the significance of this effort, Philips (Holland), and General

Electric (U.S.) donated UV "C" lamps for use in field trials.

We also organized a workshop on the topic in the city of Bhubaneswar, India (bordering on the Bengal cholera zone) in spring of 1994. This workshop attracted more than 50 participants from the central and state government, universities, government enterprises, the private sector, and voluntary agencies. We transferred the design for the device to two of the attendant organizations that showed an interest in commercial production. Based on the workshop discussions, UNESCO (New Delhi) funded one of these organizations to perform field trials in the state of Orissa. Last year these two organizations already sold a few devices to non-governmental organizations for field testing. We also initiated dialogues with interested groups in Mexico and Brazil for possible applications of this technology in these countries.

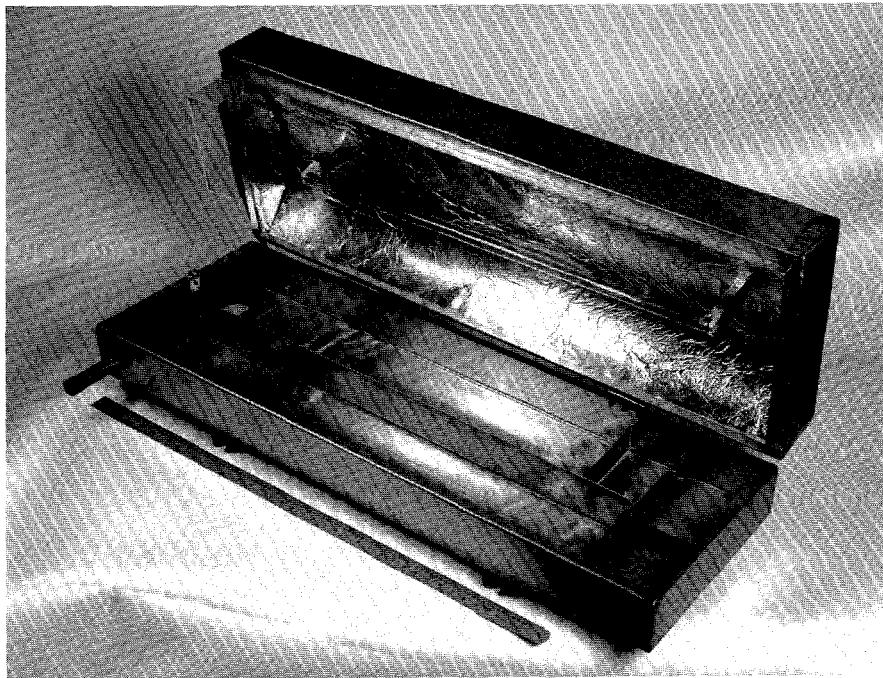


Figure. An early prototype of the irradiation device built and tested at LBL and also in Bombay, in mid-1994.

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## Sponsors

Support from the following sources was provided through the U.S. Department of Energy under Contract No. DE-AC03-76-SF00098:

- U.S. Department of Energy:
  - Assistant Secretary for Conservation and Renewable Energy:
    - Office of Building Technologies
    - Building Systems and Materials Division
    - Building Equipment Division
  - Assistant Secretary for Environment, Safety and Health, Office of Environmental Analysis
  - Director, Office of Research:
    - Office of Health and Environmental Research
    - Energy Research Laboratory Technology Transfer Program
- National Institute of Environmental and Health Sciences (NIEHS), National Institutes of Health through the University of California at Berkeley
- National Heart, Lung and Blood Institute, National Institutes of Health
- U.S. Environmental Protection Agency
- U.S. Food and Drug Administration
- U.S. Consumer Product Safety Commission
- California Institute for Energy Efficiency (CIEE), a research unit of the University of California  
(Publication of research results does not imply CIEE endorsement or agreement with these findings, nor that of any CIEE sponsor.)
- Cigarette and Tobacco Surtax Fund of the State of California, through the Tobacco-Related Disease Research Program of the University of California
- Electric Power Research Institute, Palo Alto, California
- California Air Resources Board
- PEW Charitable Trusts
- Battelle Pacific Northwest Laboratories
- National Institute of Environmental Health Sciences through the University of California at San Francisco and Thomas Jefferson University