LBL-30864
UC-350

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Indoor Environment Program
1990 Annual Report

Applied Science Division

January 1992

Please note name change:

Effective September 1, 1991, the name of the Applied Science Division was changed to *Energy & Environment Division*. Addresses and telephone numbers for the Division remain unchanged.

Available to DOE and DOE Contractors from
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, VA 22161

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098

LBL--30864

DE92 009509

Indoor Environment Program
1990 Annual Report

Joan M. Daisey, *Program Leader*
Anthony V. Nero, *Deputy Program Leader*

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
(510) 486-5001

LBL-30864

Joan M. Daisey, *Program Leader*

Anthony V. Nero, *Deputy Program Leader*

Claus Andersen
Michael G. Apte
Fred Bauman
Frederic Bois
Yves Bonnefous
Gail Brager[*,†]
Remi Carrie
Shih-Chin Chen
Penelope J.E. Compton
Carol Corradi
Lilian deCarvalho
Richard C. Diamond
Darryl J. Dickerhoff
Juergen Dieris
Jonas Engdahl
David Faulkner
Helmut E. Feustel
William J. Fisk[§]
Cynthia Fong
Sharon Fuller
Ashok J. Gadgil
Karina Garbesi
Ted Gartner
David T. Grimsrud
M. Grosso
Lara A. Gundel
Nathan Hamilton
M. Herrlin
Alfred T. Hodgson
Klaus Huber
Nori Hudson
Richard Jansky

Mandy Kamangar
Werner Keilholz
Claude Khalizadeh
Dung Kong
F. Luckau
K.R.R. Mahanama
Pleasant McNeel
Mark Mendell
Mark P. Modera
William Nazaroff[‡]
Matty Nematollahi
Anthony Nero
Timothy Nuzum
Carl Peto
David Pih
Richard J. Prill
Steve Rein
Kenneth J. Revzan
Rosa Rodríguez
Gregory San Martin
Richard Sextro
Max Sherman[§]
Brian V. Smith
Martyn Smith[‡]
Robert Spear[‡]
Carol Stoker
Dean Syn
Gregory W. Traynor
Fritjof Unander
Cynthia Whitfield
John Wooley
Alicia Woods

[*]Participating Guest
[†]Formerly Gail Schiller
[‡]Faculty Scientist
[§]Group Leader

Contents

Introduction

Approximately 38% of the energy consumed in the United States is used in buildings. Because humans spend an average of 85% to 90% of their time indoors, energy usage by the buildings sector can have a significant impact on human comfort, health and productivity. To advance energy conservation technologies while maintaining indoor air quality, research in the Indoor Environment Program (IEP) is directed toward understanding relations between building energy (usage and technologies), indoor air quality, and human health, comfort and productivity.

The IEP addresses the issue of optimizing the health, comfort and productivity of a building's occupants while maintaining the building's energy efficiency. The Energy Performance of Buildings Group within the IEP investigates energy flow through elements of the building's shell. This group measures and models air infiltration and ventilation rates and studies thermal characteristics of the structural elements. Reduction of infiltration holds great potential for saving energy: the heat load associated with natural infiltration is a about 2.5 quads per year, costing about $15 billion dollars annually. Thus, a 25% reduction of infiltration energy losses could save almost $4 billion dollars annually.

However, because ventilation is the dominant mechanism for removing pollutants with indoor sources, reduced ventilation may produce undesirable effects on indoor air quality and on the health, comfort, and productivity of a building's occupants. This issue is an important theme for the research of other research groups and projects within IEP. These groups and projects 1) characterize the emissions of various pollutant classes from their respective sources; 2) study the effectiveness of ventilation in removing pollutants from indoor atmospheres; 3) examine the nature and importance of the chemical reactions and physical removal mechanisms that affect the type and concentration of airborne pollutants; 4) evaluate techniques and strategies for controlling indoor pollutant concentrations; and 5) evaluate the causes of occupant health complaints in office buildings. Development of new measurement techniques is integral to many of these research efforts. The Program has focused on three major pollutant classes: radon and its progeny arising from radium in soils and from building materials (Indoor Radon Group); Combustion products arising from indoor heaters and from combustion appliances (Indoor Air Quality Studies Project); and organic pollutants arising from building materials, consumer products, furnishings, and soil gases (Indoor Organic Chemistry Group).

To understand the relations between these pollutants (i.e. their sources and dynamics) and building energy usage, the IEP is developing models of building energy use and losses, transport of pollutants into and within buildings, exposure to indoor air pollutants, and health risks incident to this exposure. The exposure modeling and analysis integrates much Program research and provides a broad overview of indoor air quality as well as a perspective on associated health risks.

— Indoor Air Chemistry —

Measurement of Vapor-Phase Polycyclic Aromatic Hydrocarbons in Indoor Air: A Pilot Study [1,3,11]

A.T. Hodgson, J.M. Daisey, F.J. Offermann, and S.A. Loiselle**

Volatile polycyclic aromatic hydrocarbons (PAH) have seldom been measured in indoor environments, although there are many known indoor sources of these compounds, including tobacco smoke, wood-burning stoves, and gas stoves. Efforts to measure PAH in indoor environments have been hampered by the lack of sensitive, validated sampling and analysis methods and lack of appropriate sampling equipment. For indoor air, the sampling rate must be substantially lower than the air-exchange rate of the building so that the act of sampling has a minimal impact on the measurements. In this pilot study, a sampler and analytical method suitable for vapor-phase PAH in indoor air were developed and validated.

The new sampler was designed and constructed to collect a 25-m^3 air sample over a 12-hour period. The sampler is contained in an acoustically shielded, fan-cooled enclosure. The sampling train consists of a 47-mm diameter filter (to remove particles) followed by a cartridge containing two 2.5-gm beds of XAD-4 resin to collect the vapor-phase PAH. Before use, the resin beds were spiked with three perdeuterated PAH as internal standards for recovery. After sampling, the front and back sections of XAD-4 resin were ultrasonically extracted with dichloromethane. The extract was filtered, solvent exchanged to benzene and reduced to 500 ml by rotary evaporation. Sample extracts were analyzed by capillary gas chromatography/electron-impact mass spectrometry (GC-MS). Each sample (front and back sections) was analyzed first for naphthalene, its 1- and 2-methyl derivatives, biphenyl, acenaphthalene, acenaphthene and fluorene. The extract is then concentrated tenfold and analyzed for phenanthrene, anthracene, 2- and 9-methyl anthracene, fluoranthene, pyrene, and chrysene. Compounds were identified from their GC retention times and molecular ions and were quantified based on comparison of their integrated ion-current responses to those of internal standards.

The performance of the analytical method was evaluated from the results of the pilot field study. Recoveries of the perdeuterated internal standards averaged 70 to 77%. Breakthrough of the most volatile compounds from the front to the back section of the XAD-4 resin bed was low and generally insignificant. Lower limits of detection were about 0.06 ng/m^3. Analytical precision was estimated to range from about 3 to 24%, depending upon the compound.

*Indoor Environmental Engineering, San Francisco, CA.

Genotoxic Polar Organic Compounds in Airborne Particles[1, 3, 8]

L.A. Gundel, J.M. Daisey, and K.R.R. Mahanama, Lilian R.F. de Carvalho, Norman Y. Kado,† and Dennis Schuetzle‡*

Polar organic matter accounts for 30 to 60% of the organic- solvent extractable mass of airborne particles and 30% to 50% of the direct-acting mutagenic activity in the Ames bioassay with TA-98. More significantly, this fraction has been shown to transform mammalian cells in vitro. Thus, there is reason to suspect that this fraction may be of significance to human health.

Very little work has been done to chemically characterize the polar organic fraction of airborne particles or to identify the subfractions and compounds responsible for its genotoxic activity. The polar properties of this fraction have been a major impediment to their separation and chemical characterization. Because of its polarity, this fraction cannot be analyzed by gas chromatography/mass spectrometry (GC-MS) without derivatization. Preparation of derivatives, however, requires some knowledge of the classes of compounds present. The purpose of this research is to chemically characterize particulate polar organic matter, develop methods for its fractionation, and to identify sub-fractions and compounds responsible for its genotoxicity.

*Instituto de Quimica, Universidade de Sao Paulo, Sao Paulo, Brazil.
†Department of Environmental Toxicology, University of California, Davis, CA.
‡Analytical Sciences Department, Scientific Research Laboratories, Ford Motor Company, Dearborn, MI.

The polar organic fraction is acidic in nature and has a lower percentage of carbon and hydrogen than does the non-polar fraction. Ammonium, nitrate, and several other ions account for about one quarter of the mass. Fourier-transform infrared spectra indicate the presence of carboxylic acids, carbonyl compounds, sulfones and phenols in the acetone extract, and no evidence for anhydrides, peroxides, or esters. Some unique high-molecular-weight compounds (MW > 800 amu) have been found in the polar organic fraction at levels of a few percent. Their infrared spectra resembled those of degraded polyesters.

We have also developed a milligram-scale method for fractionating particulate polar organics. The challenge has been to fractionate the extract based on polarity while obtaining reproducibly good recovery and avoiding addition of water or salts to the fractions. Like salt removal, evaporation of water to concentrate samples for bioassay is difficult. A second objective was to find an alternative to repeatedly collecting fractions as required in preparative-scale HPLC.

The fractionation method employs open-column chromatography with cyanopropyl solid-phase extractions columns. The sample is loaded onto the column in a mixture of solvents and is eluted with a series of organic solvent mixtures of increasing polarity. The mass distribution and recovery are shown for triplicate samples (Figure). Total mass recovery, with blank correction, averaged 96% ± 5%—the highest recovery of particulate polar organic matter reported to date for a fractionation of this type of material. The procedure will next be scaled up to provide sufficient material for bioassay and chemical characterization of fractions.

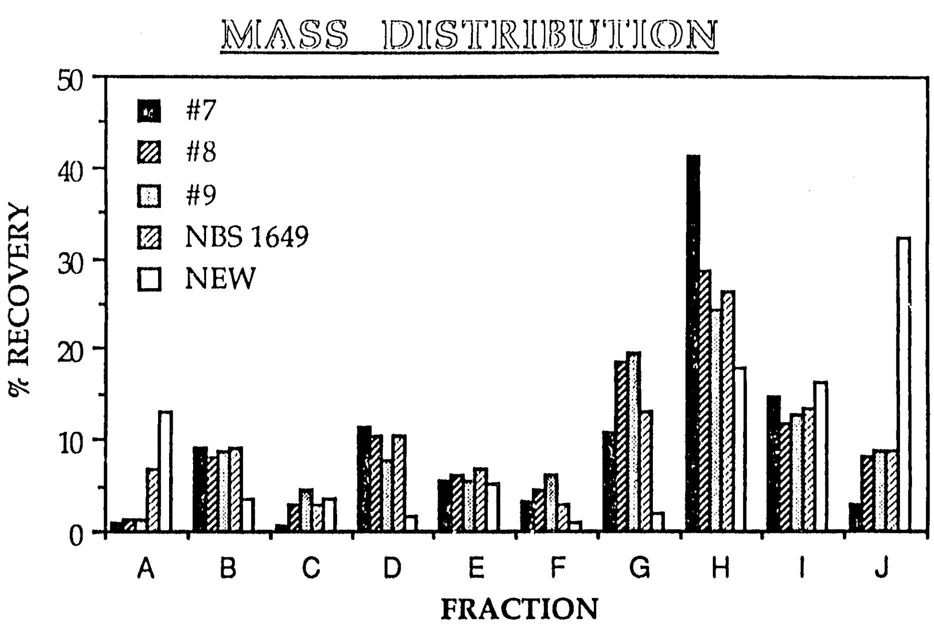

Figure. Mass distribution and recovery for triplicate samples of particulate organics (nos. 7, 8, 9), an acetone extract of standard-reference urban particles (NBS 1649), and scaled-up fractionation of 80 mg of particulate polar organics (NEW).

Model Estimates of the Contributions of Environmental Tobacco Smoke to Volatile Organic Compound Exposures in Office Buildings [1,3]

J.M. Daisey, A.J. Gadgil, and A.T. Hodgson

Volatile organic compounds (VOCs) in office buildings originate from multiple sources such as outdoor air, building materials, occupants, office supplies, and office equipment. Environmental tobacco smoke (ETS) in office buildings contains many VOCs, e.g., benzene, toluene, and formaldehyde. Measurements made to date in office buildings have been interpreted by some to imply only small contributions of ETS to VOC exposures in office buildings. We have made a first order estimate of the contributions of ETS to VOC concentrations based on the VOC content of ETS and on a time-dependent mass-balance model. Four different ventilation-infiltration scenarios were modeled for a typical office building.

Our results indicate that, even under moderate ventilation conditions, ETS can contribute significantly to total indoor levels of VOC in office buildings. Concentration ranges for three of the four modeled scenarios substantially overlapped measured ranges of the compounds in office buildings. Average daytime concentrations of benzene from ETS ranged from 2.7 to 6.2 mg m^{-3}, compared to reported measurements of 1.4 to 8.1 mg m^{-3} for four office buildings. Under a "worst reasonable case" scenario, the average modeled ETS-contributed concentration of benzene was 33.9 mg m^{-3} for a 40-hour work week. Levels of other VOC from ETS were similar.

Potential for Ion-Induced Nucleation of Volatile Organic Compounds by Radon Decay in Indoor Environments [3]

Joan M. Daisey

Considerable interest has been shown in the "unattached" fraction of radon progeny in indoor air because of its significance in estimating the risks of radon exposure. Because of its high mobility in air, the unattached fraction—about 0.5 to 3 nm in diameter—is efficiently deposited in the respiratory tract. Variations in the fraction's diameter and in its diffusion coefficient are attributable to clustering of other atmospheric species around the $^{218}PoO_2^+$ ion.

The purpose of this study was to investigate the potential for cluster formation induced by the radon decay in indoor air containing vapor-phase organic compounds and to determine which compounds were most likely to form clusters around the PoO_2^+ ion formed by radon decay. The classical Thomson equation was used to estimate the Gibbs free energy of ion-induced nucleation and to provide an indication of the *relative* potential of various indoor organic compounds to undergo ion-induced nucleation.

Our results indicate considerable potential for formation of ion-induced clusters of organic compounds around the $^{218}PoO_2^+$ ion. Compounds with the greatest potential for cluster formation were largely found in the oxidized hydrocarbon (e.g., n-butanol, phenol, hexanal, nonanal, benzaldehyde, the ketones and the acetates) and in the semi-volatile (pentachlorophenol, nicotine, chlordane, chlorpyrifos) classes. The Thomson theory estimates an average of one VOC molecule per $^{218}PoO_2^+$ ion and cluster diameters of 0.6 to 0.8 nm. Estimated diameters overlap with the measured diameters for the "unattached" fraction.

— Indoor Radon —

Radium Regionalization in California[3,5]

H.A. Wollenberg and K.L. Revzan*

The amount of ^{222}Rn that enters a house depends to a large extent on the concentrations of the radon parent ^{226}Ra in the soil. Surface radium concentrations are one indicator of the local or regional radon potential of soil. One source of radium data covering most of the conterminous United States is the National Aerial Radiometric Reconnaissance (NARR) database, based on country-wide aerial surveys conducted by the U.S. Department of Energy in the mid-to-late 1970's, primarily to evaluate uranium resources.

Assuming that radium is in radioactive equilibrium with its ultimate parent, ^{238}U, we have used the NARR data and a database covering the concentration and distribution of uranium in California rocks to estimate the regional distribution of radium. A north-to-south increase in radium concentration occurs between 42°N and 36°N, then the concentration decreases further southward (Figure).

*Earth Sciences Division, Lawrence Berkeley Laboratory.

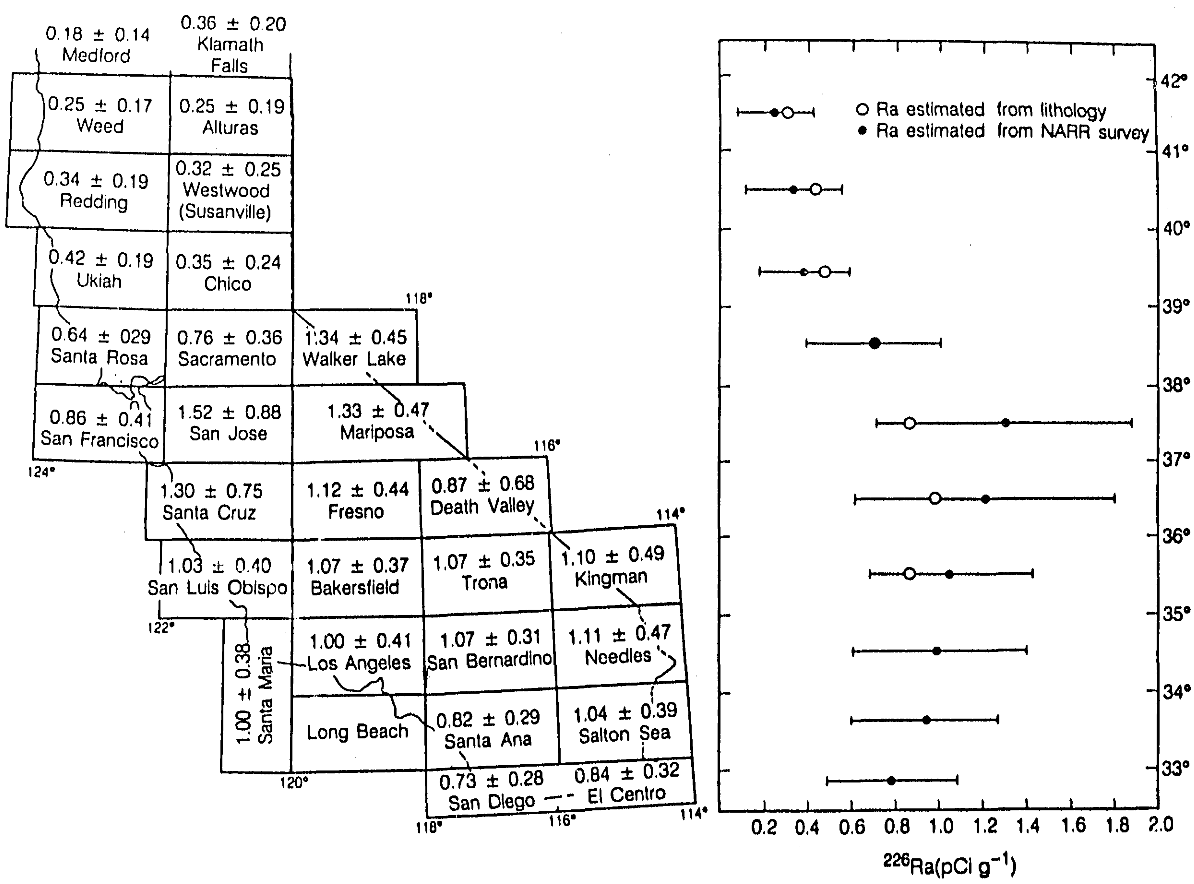

Figure. A map of California showing the mean and standard deviation of the quad-wide ^{226}Ra concentration for each 1° ± 2° quadrangle, determined from the NARR data. The adjacent plot shows the same data, as a solid circle and error bar, compared with Ra concentration estimates based on lithology (open circles). These data are based on a 4° longitude-wide band between 43°N and 33°N. Below 35°N, the Ra-lithologic database is not sufficient for estimating the Ra concentration.

The pattern is explained by the distribution of rock types. The overall mean radium concentrations estimated from the aeroradiometric and lithologic data are similar, but there is a significant discrepancy between aeroradiometric and lithologic-estimated radium concentration in central California. We have made additional ground measurements in a region where the NARR data show considerable variation. These measurements suggest that the radium values from the NARR measurements in that area are erroneously high, pointing out the necessity of verifying radium estimates based on aeroradiometric data before they are used as indicators of radon potential.

Modeling Unattached Radon Progeny Deposition Under Natural Convection in Enclosures[3, 5, 13]

A.J. Gadgil, W.W. Nazaroff, and D. Kong

Airborne radon progeny is often classified according to whether the atoms are attached to pre-existing airborne particles. Unattached radon decay products possess a much larger health hazard, per atom inhaled, than the attached species. Although radiological dose assessment from exposure to radon is often based on radon concentration measurements, the rate of deposition of unattached decay products onto surfaces is an important factor governing relationship between exposure to indoor radon and radiological dose to tissues in the respiratory tract. Detailed understanding of the mass transport aspects of radon decay products is needed as a basis for evaluating the effect on human exposure that would result from changes in building design and operation, including the use of filtering devices and other control measures.

The rate of deposition to a surface of a pollutant is often described in terms of a deposition velocity. The deposition velocity equals the flux of the pollutant to the surface normalized (i.e., divided) by the concentration of the pollutant at a far enough distance away from the surface. We investigated numerically the deposition velocities of unattached ^{218}Po and ^{212}Pb to the surfaces of square and rectangular two-dimensional enclosures under laminar natural convection flow with Grashof numbers in the range 7 ± 10^7 to 8 ± 10^{10}. The predictions are based on an existing finite difference model of fluid flow that has been extended to simulate the behavior of indoor radon decay products.

For the cases considered, the deposition velocity averaged over the enclosure surface was found to be in the range $(2\text{-}4) \pm 10^{-4}$ m/s for ^{218}Po and $(1\text{-}3) \pm 10^{-4}$ m/s for ^{212}Pb. In each simulation the deposition velocity varied with position by an order of magnitude and was found to be a sensitive function of position (Figure). We can explain the variations in the deposition velocity in terms of the fluid entrainment (or its absence) that brings fluid from the core of the space bearing fresh supply of decay products, into the boundary layers lining the surfaces of the enclosure.

Our careful calculations undertaken from first principles yield values of average deposition velocities that are about a factor of 6 smaller than the deposition velocities suggested on the basis of experiments. The source of this persistent discrepancy should be investigated further. New experimental work and more theoretical work will be needed to resolve this issue.

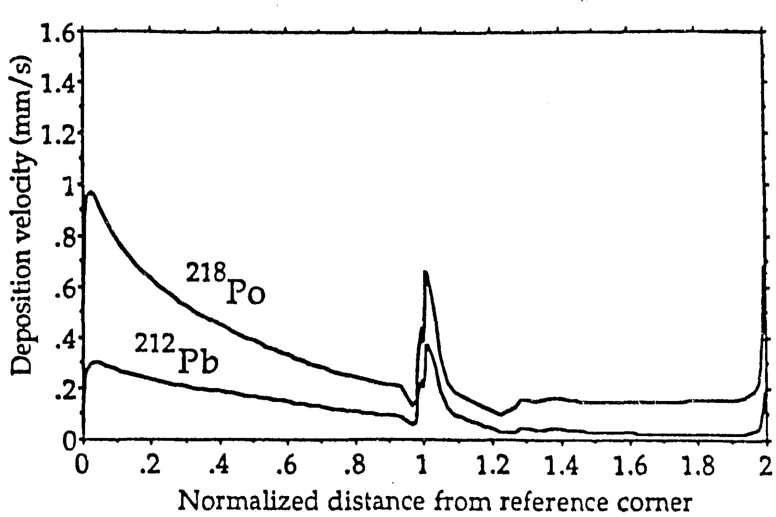

Figure. Deposition velocity as a function of position for the two radionuclides of interest. The model assumptions include a two-dimensional square enclosure (3 m on a side), differentially heated vertical sides ($\Delta T = 4^0$ K), and adiabatic top and bottom. The initial difference in the deposition velocities for these two species is due to the differences in the radioactive half-lives compared with the characteristic time required for air within the boundary layer to travel the length of the enclosure. The initial reference corner (0) is the bottom of the hot wall. Airflow proceeds up the hot wall, across the top of the enclosure, down the cold wall, and across the bottom of the enclosure, so that position 1 in the figure is the top of the hot wall and position 2 is the top of the cold wall.

Indoor Radon: A Critique of U.S. Federal Policy[3, 5]

W.W. Nazaroff

Exposure to the radioactive decay products of radon in homes is thought to be a leading cause of lung cancer. Risk estimates suggest that radon exposure contributes to the incidence of 16,000 cases annually in the United States. The average lifetime risk of lung cancer from radon exposure is of the order of 0.001. Furthermore, radon concentrations vary over a wide range; many individuals receive exposures that are an order of magnitude or more larger than the average.

In the United States, the Environmental Protection Agency and the Centers for Disease Control (CDC) have issued recommendations for citizens to undertake monitoring and remediation to limit radon concentrations below 4 pCi/l in their residences. An amendment to the Toxic Substances Control Act (TSCA) establishes a long-term national goal of reducing indoor radon concentrations to outdoor levels (approximately 0.25 pCi/l).

The best available information suggests that successful implementation of the EPA/CDC recommendations in the current housing stock would cost $20 billion (net present value), reduce the population exposure to radon by an estimated 17%, and lead to an ultimate avoidance of 2500 lung cancer cases per year. Compared with the costs of controlling exposures to other environmental carcinogens, radon mitigation appears attractive for the population as a whole. But, because of the apparent synergism between smoking and radon as causes of lung cancer, the EPA/CDC guidelines may not be attractive to most individuals.

The cost of attaining the TSCA long-term goal in the present housing stock is estimated at $1 trillion. If achieved, population exposure to radon in the United States, and the corresponding health risk, would be 75% less than current values.

Achieving the EPA/CDC recommendations, or the long-term national goal, will require that corrective measures be applied in millions of homes. In a small fraction of these, the radon concentrations are extraordinarily high. The objective of reducing radon-related health risks at reasonable cost is more likely to succeed if the primary short-term goal is to identify and apply remedial measures in houses having unusually high indoor concentrations.

Lumped Parameter Modeling of Soil Gas and Radon Entry Dynamics[3, 5]

C.E. Anderson, A.J. Gadgil, and R.G. Sextro

Indoor radon concentrations have been predicted and measured under a range of static conditions and for a variety of relevant parameters. However, the driving forces for radon entry, such as the indoor-outdoor pressure difference or the atmospheric pressure, and parameters such as the soil permeability and emanating fraction of radon, change with time. We have developed a simple lumped parameter model that describes the basic physical behavior of the soil gas and radon entry dynamics into basements of houses. The model is mainly based on analytical solutions to the transport equations under simplified boundary conditions, and is formulated in terms of electrical circuit analogs.

The model has two parts. The first deals with the soil gas entry dynamics in response to driving forces that vary sinusoidally in time. The dynamics arise due to the structure of the porous medium and the compressibility of soil gas. This gives rise to a pressure diffusion equation in the soil, in response to changes in the pressure at soil boundaries (i.e., the basement or the atmosphere). The second part of the model, which deals with radon dynamics, is coupled to the first but has its own electrical circuit analog. Here the dynamics arise because of the interplay between the finite rate of radon generation in the soil, and the variable time of travel for air-parcels that get transported under basement depressurization from the atmosphere to the basement.

A lumped parameter model that couples soil gas and radon entry permits additional insights into the physical processes involved in radon transport. A model that is based on simple set of measurements, or easily-inferred parameters, can also be applied to the design and application of new diagnostic techniques or more efficient mitigation techniques for reducing radon entry into houses.

Modeling Radon Entry into Florida Houses Built with Concrete Slabs and Concrete-Block Stem Walls[1, 3-5, 9]

K.L. Revzan, W.J. Fisk and R.G. Sextro

Entry of soil gas and radon into structures depends upon a number of variables, including driving pressures, the air permeability and geometry of the building substructure and any adjacent soil or gravel layers, and the radon generation rate in the soil. Residential building substructures in many areas of Florida often consist of a perimeter stem wall constructed of hollow-core concrete blocks and an above-grade floor slab resting on backfill. When the building is depressurized with respect to the ambient pressure, radon-bearing soil air flows through various combinations of soil, backfill and blockwall components, entering the house through perimeter slab-stem wall gaps or interior cracks or openings in the floor slab.

We have modeled convective radon entry through soil into a house whose configuration is typical of these Florida construction practices. The Laplace equation, based on Darcy's law and the continuity equation, and the mass-transport equation are solved using a steady-state finite-difference model to determine the pressure and radon concentration fields in the soil. The house and soil are represented as cylindrically-symmetric in order to increase resolution and computing efficiency without significant loss of generality. From the pressure and concentration fields, we determine soil gas and radon entry rates 1) through openings in the slab; 2) through gaps between the stem wall and slab, and between the stem wall and footer; and 3) through the permeable stem wall. We use the model to examine the influence of a number of parameters on radon and soil gas entry, including variable soil, backfill, and stem wall permeability, slab opening width and position, soil radium content, and water table depth. We also consider the effect of a gap that restricts the passage of soil gas from the interior of the stem wall into the house.

Under base case conditions, approximately 98% of the soil gas entry occurs through the stem wall and only 2% through an interior slab opening. In contrast, 77% of the radon entry rate occurs through the stem wall and 22% through the interior slab opening. This reflects the fact that the soil-gas radon concentrations are higher below the slab than at the edge of the slab and in the region of the stem wall.

The model further predicts that radon entry is relatively low unless the soil or backfill permeability or radium content is high. Apart from soil characteristics, the backfill permeability is the major factor determining radon entry rates. Stem wall permeability is a relatively unimportant factor in radon entry when small openings through the slab into the house are also present. Radon entry through the stem wall may be controlled by ensuring that the pressure in the interior is very nearly atmospheric, but entry through slab openings increases when this is done, so that the net reduction in radon may be only a factor of 2-3. Some of these results are illustrated in the Figure, which shows that the largest reductions in radon entry rate occur when the backfill permeability is reduced. On the other hand, changes in the stem wall permeability show little overall effect.

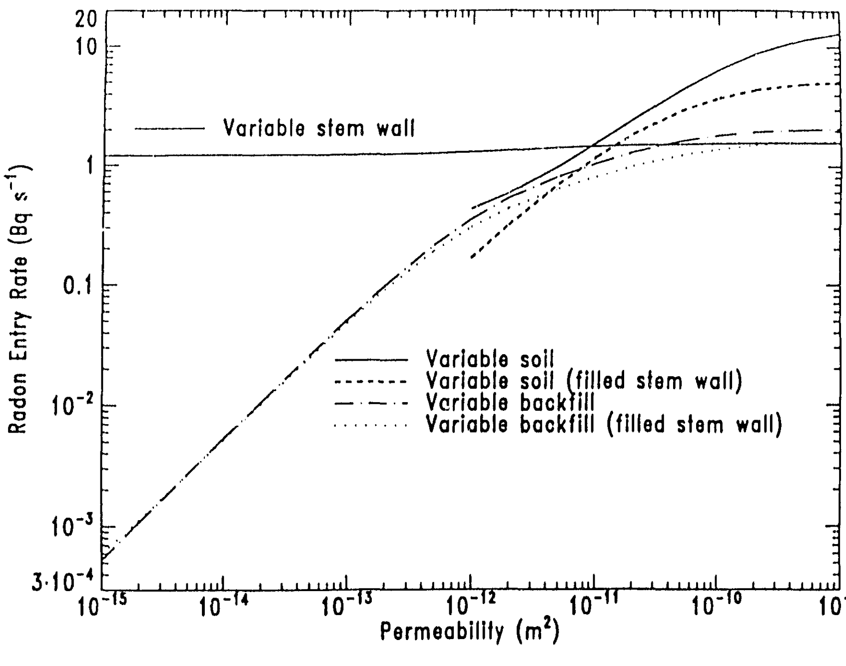

Figure. Range of radon entry rates produced by variations in the soil, backfill and stem wall permeabilities for open and concrete-filled stem walls. Also shown are entry rates when the stem wall-footer gap is eliminated. In each case, all other parameters have the base case value.

Reduction of Indoor Particle and Radon Progeny Concentrations with Ducted Air-Cleaning Systems[3, 5-7, 9]

*R.G. Sextro and F.J. Offermann**

Four categories of in-duct air-cleaning devices have been evaluated for control of indoor concentrations of respirable particles and radon progeny. Changes in particle and radon progeny concentrations were measured with and without air cleaner operation in a three-room experimental facility. Respirable particle concentrations were measured for total number concentration and for number concentration by particle size.

Particle removal rates were found to be negligible for two types of panel-filters, and one type of electrostatic precipitator. Similarly, low removal rates were observed for air circulation through the duct and furnace system without a filter device. Significant particle removal rates were measured for a second type of electrostatic precipitator and for two types of extended surface filters: a bag filter and a HEPA filter. These results are summarized in the figure. This evaluation of radon progeny control produced similar results; the air cleaners which were effective in removing particles were also effective in removing radon progeny. At low particle concentrations deposition of the unattached radon progeny on room surfaces is an important removal mechanism, although the fraction of airborne radon progeny that are not attached to particles increases.

*Indoor Environmental Engineering, San Francisco, CA

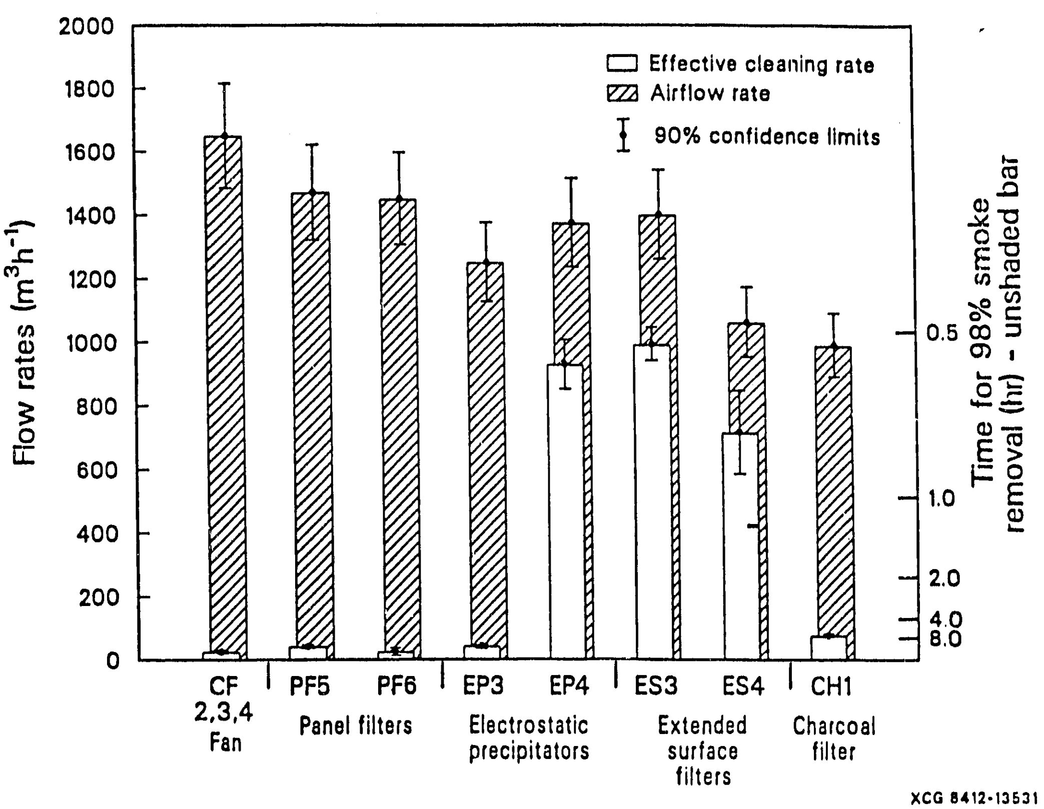

Figure. Effective air cleaning and air flow rates measured for several types of ducted air cleaning systems. The right axis indicates the time required for a 98% reduction in particle concentration for each device when operated in the 140-m^3 test space.

Experimental and Theoretical Investigations of Radon Entry Into Basements[1,4]

W.J. Fisk, R.G. Sextro, H.A. Wollenberg, T.N. Narasimhan,* K. Garbesi, A.J. Gadgil, K.L. Revzan, Y.T. Tsang*, S. Flexser*, and A.R. Smith†*

Radon concentrations in houses vary widely, primarily because of variations in the rate of radon entry from the surrounding soils. We are undertaking experimental and theoretical research to improve our understanding of the mechanisms of radon entry into basements and the dependence of radon entry rates on climatic conditions, steady and time varying indoor-outdoor pressure differences, and characteristics of the soil and structure.

For the experimental component of this project, we are constructing room-size basements at sites with different soil characteristics and climates. The unique structures have adjustable-size openings to the soil, are otherwise very airtight, and are mechanically ventilated using a system that also controls the indoor-outdoor pressure difference. Core samples of soil are analyzed to determine porosity, permeability, radium content, radon emanation coefficient, and the microscopic sites of emanating radium. Numerous probes are installed in the soil around the structures to permit multipoint periodic monitoring of soil moisture, soil temperature, soil permeability, soil gas pressure, and soil gas radon concentration. Structure ventilation rate, indoor radon concentration, the concentration of radon in the entering soil gas, and meteorologic parameters are also measured. We have constructed two structures at the first site and completed numerous experiments with steady and time-varying indoor-outdoor pressure differences.

Two current modeling efforts are coupled to the experimental research. In the first approach, a steady- state finite difference model is used to study steady-state radon entry, the impact of soil and structural characteristics on entry rates, and the impact of buoyancy forces (caused by heat loss from the basement) on entry rates. The second approach, is an investigation of transient soil gas and radon entry driven by time varying pressure differences such as those associated with atmospheric pressure. An integrated finite difference model is used.

The most significant findings and accomplishments are as follows:

- Modeling indicates that a layer of high permeability aggregate or soil adjacent to a substructural surface containing cracks or holes can increase radon entry rates by a factor of five.
- Modeling indicates that buoyancy forces can increase entry rates by approximately 40%.
- Transient modeling indicates that transient radon entry, driven by atmospheric pressure fluctuations, may be a dominant process of radon entry into basements surrounded by low permeability soil and an important process with soil permeabilities as high as 10^{-11} m^2.
- The experiments have yielded detailed, high-quality steady state and transient data suitable for model validation. Previously, such data have not been available.
- The first comparisons between measured and predicted steady-state radon entry rates indicate that the model underpredicts by approximately a factor of five. Investigations of the causes of the underprediction should substantially advance our understanding of radon entry.

*Earth Sciences Division, Lawrence Berkeley Laboratory.
†Engineering Division, Lawrence Berkeley Laboratory.

— Energy Performance of Buildings —

International Studies in Ventilation[1, 20-22]

H.E. Feustel, M. Grosso, M. Herrlin, W. Keilholz, and J. Dieris

The COMIS workshop held at LBL has been using a multinational team of experts to develop a multizone airflow model on a modular basis. During the second year of the workshop, we gave special emphasis to the output routines in order to maximize the final program's ease of use. The program has been linked to a spreadsheet program to use the graphics capabilities available for PC-type computers. Macros were developed which allow use of the available output options without the user having to learn a spreadsheet program.

Within the framework of an annex adopted by the Energy Conservation in Buildings and Community Systems program of the International Energy Agency, we have been studying physical phenomena causing airflow and pollutant transport (e.g., moisture) in multizone buildings. Special emphasis is given to providing data necessary to use the COMIS model (e.g., wind pressure distribution, default values for leakage of building components, material properties like absorption and desorption). An important part of this annex is the comparison between model results and results from in-situ tests. Before these data sets can be used for model evaluation, however, internal model comparisons based on benchmark buildings must be performed.

The COMIS participants have undertaken this task-sharing project involving model development, data acquisition and analytical studies. The annex is scheduled to span a four-and-a-half year period. To reach these objectives, the project is structured in three subtasks:

- *System development (subtask 1):*
  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 (e.g., results from Annex XX), and developing user-friendly interfaces for input and output. The coupling with thermal building simulation model will be demonstrated.

- *Data acquisition (subtask 2):*
  Data sets are being obtained for evaluation purposes and as input for the model. Sensitivity of the model to the quality of input data will be determined.

- *System evaluation (subtask 3)*
  The model will be evaluated using data obtained from subtask 2.

Results of these subtasks are addressed to researchers and consultants and will promote an energy-efficient design.

Close cooperation is envisioned, mainly with regard to state-of-the art reviews, data collection, coordination of work, e.g., defining cases for evaluation purposes 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 will be prepared by AIVC, which has already started to collect data on wind pressure and air leakage.

Codes and Standards Support[1]

M.H. Sherman and M.P. Modera

Consensus standards play an important role in technology transfer. By incorporating research results into such standards, we can transfer the techniques and practices developed at LBL to practitioners and can thus incorporate them into standard engineering practice. From inception to acceptance of a standard the process takes many years; several standards are at various stages of progress.

Through its Committee on Infiltration Performance of Building Constructions (E6.41), the American Society of Testing and Materials (ASTM) has set several relevant standards for air infiltration. In November 1975, ASTM decided to develop standard practices relating to air infiltration: one for infiltration measurement using tracer gases, and one for airtightness measurement using fan pressurization. At this writing, current versions of these standards are E741-83 (Standard Test Method for Determining Air Leakage by Tracer Dilution), and E779-87 (Standard Test Method for Determining Air Leakage Rate by Fan Pressurization). Since these fundamental standards were completed, ancillary standards have been written: E1186-87 (Standard Practice for Air Leakage Site Detection in Building Envelopes), and E1258-88 (Standard Test Method for Airflow Calibration of Fan Pressurization Devices). The consensus process in this area is continuing, and a revision of E741 is currently underway. ASTM has actively supported technical efforts surrounding its standards by sponsoring symposia on air infiltration and by publishing a book based on the symposia.

Relevant ASTM standards in process include standards for determining leakage in residential air-distribution systems (i.e., duct leakage) and standards for determining leakage between zones of a building. Both of these standards use blower-door technology and the E779 standard.

The International Standards Organization (ISO) is using some of these ASTM standards as a basis for similar international standards. Standards for air tightness and tracer dilution measurement techniques are under development.

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) is concerned with practices acceptable for the HVAC engineering community. Two relevant standards have been approved: ASHRAE 62-1989 ("Ventilation for Acceptable Indoor Air Quality") and ASHRAE 119-1988 ("Air Leakage Performance for Detached Single-Family Residential Buildings").

Relevant ASHRAE standards in progress involve ventilation efficiency and the estimation of infiltration (for use in indoor air-quality calculations). The latter standard, 136P, involves use of the LBL infiltration model to estimate effective ventilation rates appropriate to indoor air quality concerns.

In addition to interacting with these societies, we have been using our experience to help regional agencies to set building standards. We have advised the State of Florida through the Florida Radon Research Program (FRRP), and the State of California through the California Institute of Energy Efficiency (CIEE); and the Pacific Northwest through agencies such as the Bonneville Power Administration (BPA) and the Washington State Energy Office (WSEO).

Existing Buildings Efficiency Research[1]

R.C. Diamond, M.H. Sherman, and M.P. Modera

As new buildings, both residential and commercial, respond to higher energy prices and stricter energy codes by becoming more energy efficient, the existing stock represents a large untapped area for energy conservation activity. The Existing Building Efficiency Research Program was initiated to address these problems in all three building sectors: single-family, multifamily, and commercial. The U.S. Department of Energy has designated LBL as the primary laboratory for conducting research in the multifamily sector, and while the emphasis in the past years has been on coordinating research in this sector, we continue to work in single-family and commercial buildings.

We have reviewed more than 100 proposals submitted to the DOE competitive solicitation for improving energy efficiency in existing buildings. Two proposals will receive technical assistance from LBL in projects design and evaluation.

The first project is the retrofit of 350 units of multifamily housing in Burlington, Vermont. The project was conceived and is being carried out by a local nonprofit housing organization (Northgate Housing) and the local electric utility (Burlington Electric Department). The apartments have been converted from electric-baseboard heating to gas-fired hydronic systems, with additional retrofits to the building shell and equipment.

The second project, with the New York State Energy Office, involves two retrofit strategies in 30 apartment buildings in New York City. The retrofits will involve replacement of central boilers and installation of new windows. Energy consumption will be monitored for two years to examine the persistence of savings.

A New Initiative was created in 1990 between the U.S. Department of Energy and the U.S. Department of Housing and Urban Development to improve the energy efficiency in the federally-assisted housing sector. We were active in the initial planning and development of the Initiative, and in 1990 started work on five projects to address energy efficiency in HUD-owned and HUD-mortgaged multifamily buildings. Three large multifamily buildings in Washington DC will be retrofitted as case studies, and a small sample of HUD housing for the elderly in New England will be evaluated as part of utility-sponsored retrofit programs. We will also be active in planning and carrying out new projects for the remaining three years of the Initiative.

Our most successful technology transfer has been through collaborative projects, where information is exchanged between researchers and practitioners. In addition to collaborative monitoring and demonstration projects, we publish our research results in both professional and trade journals.

Our current efforts are directed at providing technical support to groups funded under the competitive solicitation, and through projects in the DOE/HUD New Initiative. We plan to make the results of these projects available to our wide network of practitioners.

Ventilation Research[1]

M.H. Sherman and D.J. Dickerhoff

Mass transfer caused by pressure-driven airflow is a process important for determining environmental quality as well as energy requirements of buildings. Heat, moisture, and contaminants are all transported by air movement between the indoors and the outdoors as well as between different zones within a building. Appreciation of these airflows is critical to understanding the performance of buildings. Although direct measurement of airflows can be made, it is more practical to use diagnostic properties of the house (such as leakage from building envelope) to calculate airflows of interest.

Virtually all ventilation measurements use dilution of a tracer gas. The majority of such measurements have been made for a single zone using a single tracer gas. In recent years, the need to determine ventilation rates/air flows in complex buildings has become more acute, and many researchers have been devoting effort to the problem. LBL uses its MultiTracer Measurement System (MTMS) to make such measurements.

As part of a research project sponsored by the Electric Power Research Institute (EPRI), LBL has been measuring interzonal airflows in single-family homes in the Pacific Northwest. Results of this study have shown that the LBL infiltration model is a reasonably good predictor of the infiltration, but deviations in the wind, stack, and superposition parts of the standard models can be seen from the detailed tracer measurements. These measurements have shown that an opportunity exists to improve the state of the art in residential ventilation modeling.

We began improving the modeling by investigating the interaction between stack effect, wind effect, and mechanical ventilation. Various models handle this superposition in different ways; the models were surveyed and then compared with an improved superposition method suitable for general use. Although motivation for the improvement lay in the context of the LBL infiltration model, the results are generally useful and explain many puzzling data seen in the literature.

Future work will focus on the remaining parts of single-zone modeling and on comparison of measured and predicted ventilation rates.

Thermal Performance of Non-Residential Buildings[1, 22, 23]

H.E. Feustel, J. Dieris, K. Huber, F. Luckau, and R. Meierhans

Cooling of non-residential buildings contributes significantly to consumption of electrical power and to peak power demand. Energy consumption can be reduced several ways: by reducing the cooling load of the building, by reducing the requirements of mechanical cooling, or by improving thermal distribution within the building.

A significant amount of electrical energy used to cool buildings is drawn by the fans used to transport cool air through the ducts. If ventilation and thermal conditioning of buildings are separated, the amount of air transported through buildings can be reduced significantly. In this case, the cooling would be provided by radiation, using water as the transport medium, and the ventilation must be provided by outside air systems without the recirculating air fraction. Not only does this improve comfort conditions, it increases indoor air quality and improves the control and zoning of the system. Due to the physical properties of water, radiant cooling systems can remove a given amount of thermal energy using less than 5% of the otherwise necessary fan energy. Although the supply air necessary for ventilation purposes will still be distributed through ducts, the electrical load for transportation can be reduced approximately to 25% of the original number.

Review of the literature shows several advantages for hydronic cooling systems:

- Due to the large surfaces available for the heat exchange, the coolant temperature is only marginally lower than the room temperature. This allows the use of either heat pumps with high COP values or indirect evaporative cooling to further reduce the electricity power requirements.
- Hydronic cooling systems reduce problems caused by duct leakage, as the ventilation air is significantly reduced and is conditioned to meet room temperature only rather than that of the cooling supply air. Compared with cold-air distribution systems, condensation is less of a problem, due to the higher surface temperatures of the cooling medium.

A different approach for reducing the energy consumption in non-residential buildings is to use an economizer. Air economizers decrease the requirements of mechanical cooling by using cool outdoor air instead of mechanically cooled air. If ambient-air properties are below certain limits, outdoor air and recirculated air are mixed to maintain the desired supply-air temperature necessary to remove the cooling load. If the desired supply-air temperature cannot be maintained by mixing the two airstreams, the supply air must be cooled mechanically. Outdoor airflow is reduced to its minimum if the properties of the outside air exceed those of the return air.

Our work has shown that the use of an air economizer is beneficial for conventional air handling systems that supply constant airflows; however, no economizer control strategy works best under all circumstances. For dry climates, the lockout control should be based on the temperature difference between the return air and the outdoor air, whereas humid climates call for a differential enthalpy controller to maximize energy savings.

Detailed studies involving moderate climates show that mechanical cooling might become obsolete if the envelope is improved, the thermal storage performance is increased, and the air-handling system is equipped with an economizer.

Thermal-Energy Distribution Systems[1, 14]

M. Modera

Thermal-energy distribution systems represent the vital link between heating and cooling equipment and conditioned building spaces. In the United States, approximately 4 quads of primary energy annually passes through thermal distribution systems in buildings. Based on an efficiency of 75% for existing systems, a 50% reduction in the inefficiency of those systems represents an annual savings of more than 0.5 quads of primary energy, or an annual cost savings of over 4 billion dollars. Moreover, the load shape due to inefficient distribution systems is even more peaked than general cooling demand (due to the increased fractional on-times of distribution systems during peak periods), implying that efficiency improvements can provide even larger savings in peak electricity demand.

In 1990, we initiated a three-year research program that focused on improving the efficiency of thermal energy distribution systems. Co-sponsored by the California Institute for Energy Efficiency and by the Department of Energy, this program consists of research projects focusing on residential air distribution systems (summarized below), on localized distribution systems (summarized separately within this document), on direct cold-air distribution systems, and on friction-reducing additives for hydronic distribution systems in commercial buildings (the latter project being performed at the University of California, Santa Barbara).

Impacts of Residential Air-Distribution Inefficiencies

In 1990, a three-component research effort was initiated to estimate the energy-savings potential of efficiency improvements to thermal distribution systems in California single-family residences. The focus on California residences is essentially a focus on crawlspace and slab-on-grade houses, for which the distribution system typically passes through unconditioned spaces (attics or crawlspaces), and which are common throughout most of the U.S. sunbelt. This year's research included three components :

- a telephone survey of HVAC contractors;
- development and use of a two-day air-distribution diagnostic measurement protocol; and
- development of an integrated air-flow/thermal-performance simulation tool.

Some of the more salient indications for California from the HVAC-contractor survey were that

- the vast majority of new duct systems are installed in attics;
- the vast majority of ducts installed are R-4 insulated flexible plastic;
- approximately three quarters of the ducts are sealed with cloth duct-tape only; and
- more than half of the contractors said they would be interested in being paid to make post-installation performance checks, and are capable of installing water/refrigerant distribution or conditioned-space air distribution systems.

The objectives of the field diagnostic measurement program are to compile high-quality data for characterizing the California residential air-distribution stock (including its retrofit potential), to gather defensible input data for performance-simulation efforts, and to refine measurement tools for use in larger-scale projects.

The two-day diagnostic measurement protocol includes measurements of several quantities:

- supply and return-duct leakage to outside by three independent techniques;
- supply and return-duct pressures and overall building air infiltration with and without distribution-fan operation;
- interzonal and envelope pressure differences created by distribution-fan operation with interior doors closed, including measurements of the driving flows;
- temperature variations between the supply plenum and several registers to characterize the duct conduction losses;
- crawlspace and attic temperature changes due to system operation;
- documentation of house and equipment conditions, including duct-system leakage sites.

An automated data-acquisition system was developed to complete these measurements within a two-day period while minimizing instrumentation- and operator-induced uncertainties. This protocol was successfully applied in six houses this year and will be applied to at least 24 more houses in the coming year.

To obtain credible estimates of air distribution system performance, an hourly simulation tool was developed. This tool is based on a multizone flow simulation (MOVECOMP) for a residential air distribution system in a typical California house, coupled to a thermal simulation of the same house (DOE-2). The long-term objectives of developing this tool are to provide the capability for 1) simulating annual energy, peak-load and ventilation implications of residential air distribution; and 2) simulating the effectiveness of alternative distribution technologies and retrofit options. The airflow simulation portion of this tool is operational and will be combined with the thermal simulation model and applied in the coming year. The coming year will also see the initiation of research to develop novel duct-sealing technologies and complete retrofit protocols.

Advanced Techniques for Measuring Airtightness[1]

M. Modera

The process of air flowing through unintentional apertures is called air leakage. In buildings, air leakage occurs through apertures in the building envelope, in mechanical systems, and between building zones. Air leakage depends both on the airtightness of the building component and on the pressures driving the flow. For building envelopes, the technique used for measuring and characterizing air tightness (the fan pressurization technique, i.e., blower-door technique) has evolved over the past ten years. The airtightness of residential-building mechanical systems (e.g., central furnace ducts) and the airtightness of internal partitions between zones (e.g. in multi-family buildings) have only recently begun to be examined. For all three types of air leakage, the measurement and study of airtightness allows us to characterize buildings, to better understand ventilation and space conditioning, to evaluate the performance of mechanical systems, and to estimate the effectiveness of air-tightness retrofits.

Our advanced airtightness measurement research in the past year was focused in two areas: 1) higher-accuracy fan-pressurization measurements of residential envelope and air-distribution tightness; and 2) experimental examination of an envelope tightness measurement technique based on a building's response to an impulsive change in pressure (pulse pressurization).

Because fan pressurization involves measurement of the fan flows that maintain measured indoor-outdoor pressure differences, wind-induced pressure variations add uncertainty to the measurement.

The pulse pressurization technique determines leakage characteristics of a building envelope by determining the decay of its pressure from an elevated value down to its steady-state value. During 1990, we conducted an experimental examination of a pulse-initiating device designed to implement this technique. The device tested consists of a standard compressed-air cylinder that exhausts to the building via a pneumatically actuated valve whose opening time can be adjusted (this device was loaned by Professor Gren Yuill of Pennsylvania State University). This study had two principal findings: 1) Joule-Thomson heating or cooling of the expanding gas can play an important role in the measured pressure response of the structure; and 2) successful implementation in a single-family residence with typical doorways will require either multi-point injection of the expanding gas flow or significantly extended injection times (and subsequently larger cylinder volumes). In the coming year, these findings will be published and a new prototype constructed.

— Ventilation & Indoor Air Quality Control —

Indoor Airflow and Pollutant Removal in a Room with Task Ventilation[1, 14]

W.J. Fisk, D. Faulkner, D. Pih, P.J. McNeel, F.S. Bauman, and E.A. Arens**

Using an experimental facility consisting three workstations enclosed by partitions, we studied the performance of a task ventilation system designed for use in office buildings. With this system, occupants can use floor-mounted supply grills to adjust the volume and direction of air supplied to their workspace. Air typically leaves the building through ceiling-mounted return grills. Because occupants can to some extent adjust their local thermal environment, the potential for improved thermal comfort, is a major impetus for using task ventilation. Improved indoor air quality is another potential benefit: freshest (i.e., least polluted) air can be supplied directly to the region surrounding the occupant.

To study indoor airflow patterns and check for enhanced ventilation at the occupant's location, we used the tracer gas stepup procedure to measure the age of air at multiple indoor locations. (The age of air is the time elapsed since the air entered the building, the reciprocal of the age of air can be considered a local ventilation rate.) To study the transport of tobacco-smoke particles between workstations, we measured particle concentrations at multiple indoor locations after a cigarette was smoked in one workstation. Test variables included furnishings in the chamber, location(s) of air supply, supply flow rates, temperatures, directions, and internal heat loads. During most tests, the air supplied by the task ventilation system was 100% outside air.

*University of California Berkeley, Center for Environmental Design Research.

Our major findings were as follows:

- In most tests, we found less than 30% deviation from uniform age of air and from uniform particle concentration. We suspect that entrainment of room air in the high-velocity supply jets was a major source of mixing of the indoor air.

- Some supply air short circuits to the return grill when the air is directed toward the return grill with a high velocity. This type of flow pattern is generally undesirable.

- Low supply velocities resulted in a floor-to-ceiling displacement (i.e. piston-like) flow pattern. Such a pattern is generally desirable because the oldest (usually the most polluted) and warmest air leaves the room through the ceiling-mounted return grills.

- Directing the supply air either toward the occupant or in an outward direction typically yielded an age of air that was 15 to 25% lower where occupants breathe, compared to the age at other indoor locations. Consequently, this mode of operation results in an increased local ventilation rate at the occupant's breathing level.

- With low supply velocities and air directed toward the occupant, concentrations of tobacco smoke particles in a ventilated, nonsmoking workstation were 50% of the chamber-average concentration. This tentative finding, based on only one test, suggests that task ventilation may be effective in reducing occupant exposure to tobacco smoke generated in nearby workstations.

In summary, our research indicates that this type of task ventilation system can result in significantly enhanced ventilation around the occupant, but only during some operating conditions. The direction and velocity of air supply seem to be the most important operating parameters.

Air Movement, Comfort, and Ventilation in Workstations[1, 24]

D. Faulkner, F.S. Bauman, W.J. Fisk, and P.J. McNeel IV*

In today's typical open-plan office building, the design and layout of workstation furniture and partitions can play an important role in determining many environmental conditions, including temperature, airflow, noise, spatial privacy, and the functionality of the workplace. Some people have been concerned that partitioned workstations may restrict the flow of air so that the workstations themselves are not well ventilated.

A series of experiments were carried out in the University of California's Controlled Environment Chamber (CEC) to study the effects of office partitions on ventilation efficiency and thermal comfort. Types of partitions tested included a new prototype "airflow" partition with a 15-inch-high gap at the base, as well as partitions 42, 65, and 75 inches high. Each partition configuration was subjected to ventilation changes such as: supply air volume, differences in room/supply air temperatures, supply diffuser location, heat load density (heat output per workstation area), and workstation size.

The CEC was designed to emulate an interior region of a typical open-plan office. Three workstations of different sizes and furniture configurations contained sources of heat and air motion—i.e., overhead lights, task lights, and a personal computer—typical of real offices. One or two of the workstations was occupied by a heated, seated mannequin.

With steady-state temperatures and ventilation flow rates, a tracer gas was injected into the supply air and multipoint measurements were made inside the chamber. Factors measured included: tracer-gas concentrations, air velocity, and air temperature. From the air velocity and temperature values, comfort indices were calculated and compared to standards such as those published by ASHRAE (American Association of Heating, Refrigerating, and Air-Conditioning Engineers). Local ages of air (i.e., time elapsed since air entered the chamber) were computed from the tracer concentrations, indicating the spatial uniformity of ventilation.

In tests in the heating mode (supply air used for heating), we noted a slight tendency for supply air to short-circuit from the supply diffuser directly to the return grill and thus bypass the occupied region. Based on previous experiments, the partitions may not have caused the short-circuiting. Short-circuiting was not evident in the cooling mode—the mode in which buildings usually operate.

Experimental results showed that in general, ventilation in the chamber was uniform within 20%, and thus not substantially preferential to any location. In particular, the measurements did not indicate that the partitions caused any decreased or poor ventilation within the workstations. Comfort indices were within acceptable standards for most of the test conditions. The only effect of the "airflow" partitions was to increase the air velocity slightly near the floor, but this increase was not enough to bring conditions beyond the comfort range.

*University of California Berkeley, Center for Environmental Design Research.

— Indoor Air Pollution Exposure & Risks —

Concentrations of Indoor Pollutants (CIP) Database[1, 16, 17]

M.G. Apte, C.A. Corradi, S.P. Felix, G.W. Traynor, and A.L. Woods

In the last decade, air pollution in the indoor environment has emerged as an important environmental issue. Research has shown that people spend 60-80% of their time indoors. In many cases, a significant if not dominant portion of people's exposure to air pollution is likely to occur while they are indoors, especially when an indoor pollutant source exists and energy conservation measures have been taken which reduce building ventilation. A proliferation of research has been conducted on the subject of indoor air pollution, and with it a large base of literature has been generated. We started the "Concentrations of Indoor Pollutants Database" (CIP Database) in 1983 as a bibliographic management tool to track the rapidly expanding amount of literature being generated in this field. The CIP Database contains references to articles explicitly reporting concentrations of pollutants measured indoors.

Activity on this project in FY90 includes the release of CIP Database Version 4.0, which includes literature references current up to March 1990 and contains 443 references (205 more references than were contained in Version 3.0). The database was provided at no cost to the 239 users of Version 3.0 who requested the software.

Mechanism-Based Risk Assessment for Indoor Air Exposure

F. Bois, R. Spear, M.T. Smith, J. Compton, and J.M. Daisey

Current methods for determining risks from exposure to toxic chemicals at levels found in indoor air are scientifically flawed and may over- or underestimate risk by orders of magnitude. Human health risk assessment would be much improved if mechanism-based models, based on fundamental biology, could be used to extrapolate data from exposures to toxic chemicals at high concentrations or data from laboratory experiments to predict adverse health effects at the low concentrations typically encountered in indoor environments. An interdisciplinary and UC inter-institutional research project has been initiated for this purpose as a joint project of the Indoor Environment Program at LBL and the Biomedical and Environmental Health Sciences Department at UC.

The specific objective of the exploratory research in progress is to develop an integrated pharmacokinetic-cancer model to predict cancer risk from human exposure to benzene. The model for benzene is being developed as a "proof of principle." Benzene was selected as the model compound for this work because much is known about benzene and because it emerged as one of the high-risk indoor pollutants from previous work here at LBL.

We have successfully linked a physiologically-based pharmacokinetic (PBPK) model and a simple cancer model into an integrated model for benzene. A new method, employing global optimization and Monte Carlo simulations, was used to incorporate distributions of input variables rather than a single value for each of the 29 parameters of the coupled physiological pharmacokinetic and multistage cancer model. This new approach incorporates biological variability into PBPK modeling for the first time and allows a distribution of probabilities to be estimated for low-level exposures. The results of the modeling demonstrate the limited value of the common animal cancer experiments for quantitative extrapolations to humans and indicate the need for more biological information relevant to the identificaton of the parameters of the multistage models of carcinogenesis.

Work is now in progress to incorporate benzene metabolites into the model, to modify the pharmacokinetic part of the model for humans, and to incorporate a biologically-based cancer model. For the cancer (leukemia) part of the model, we will apply a new human, somatic mutation assay, the HLA-A assay on white blood cells, to provide input data for the model. The assay can be used for monitoring exposed human populations and can also be used *in vitro* to provide mutational rates, information on mechanisms and spectra of mutations for chemical carcinogens. We also plan to use this assay to investigate mutation spectra for other important indoor toxic compounds.

The California Healthy Building Pilot Study[1, 12]

W.J. Fisk, M.J. Mendell, A.T. Hodgson, J.M. Daisey, D.T. Faulkner, A.R Nematollahi, J.M. Macher, and J.R. Girman*†*

Developing scientifically-defensible recommendations for maintaining a healthy indoor environment in office buildings requires a greatly improved understanding of the building and environmental factors that result in healthy, satisfied, and productive occupants. Prior U.S. research relevant to this issue has focused on self-defined sick buildings, and most research efforts have involved only one, or a few, disciplines. To determine the factors that make buildings healthy and to determine background symptom levels in healthy buildings requires research in healthy and sick buildings. This research must be multidisciplinary if, as is currently believed, occupant health and satisfaction depend on many factors.

As a first step toward this type of research, we have conducted the California Healthy Buildings Pilot Study in twelve San Francisco-area office buildings selected without considering prior complaints. To assess the associations between symptoms and method of ventilation as indicated in European studies, we divided the buildings into three groups: naturally ventilated; mechanically ventilated with operable windows and no air conditioning; and mechanically ventilated with air conditioning and sealed windows. Eight hundred and eighty occupants reported their health symptoms and provided demographic data on self-administered questionnaires. The questionnaires also included measures of "environmental worry" and a scale of job stress and satisfaction. Indoor and outdoor concentrations of CO_2, CO, volatile organics (including aldehydes), fungi, and bacteria were measured along with indoor temperatures and humidities.

We are currently analyzing the resultant data. The analyses include use of a new method of estimating the irritancy of the mixture of indoor volatile organic compounds. A thermal comfort model is being used to evaluate the temperature and humidity data and to estimate the fraction of occupants expected to be dissatisfied with the thermal environment. The effective ventilation rate per occupant is indicated by the difference between indoor and outdoor CO_2 concentrations.

Preliminary analyses of questionnaire data has been completed; however, simultaneous adjustment for multiple confounders and correlations of questionnaire data to measured data have not been completed. Therefore, we have compiled the following tentative findings.

In our study population, the prevalence of work related symptoms (reported as occurring often or always at work in the previous year, and improving when away from work) ranged from 3% (for chest tightness) and 4% (for chills or fever) to 24% (for stuffy nose and fatigue/tiredness). Women, clerical workers, and those with high job dissatisfaction were associated with increased symptom prevalence. In a preliminary analysis that does not control for confounders, we found that buildings with mechanical ventilation, relative to buildings with natural ventilation, were associated with significantly increased odds ratios (ORs) for some work-related symptoms (upper respiratory symptoms, OR 1.7; lower respiratory symptoms, OR 3.3; skin symptoms, OR 4.4). We saw no apparent differences in work-related symptoms between mechanically ventilated buildings with and without air conditioning. We are currently analyzing the data in greater detail and are developing plans for additional research to better understand the causes of differing symptom prevalences.

*Indoor Air Quality Program, Air and Industrial Hygiene Laboratory, California Department of Health Services, Berkeley, CA.
†Analysis Branch, Indoor Air Division, U.S Environmental Protection Agency, Washington, DC.

Release of Ethanol to the Atmosphere During Use of Consumer Cleaning Products[1, 3, 18]

J.D. Wooley, W.W. Nazaroff, and A.T. Hodgson

Liquid laundry and hand dishwashing detergents contain volatile organic compounds (VOC; the include ethanol) that may be liberated during use. Use of these detergents may thus contribute to increased indoor concentrations of ethanol and other VOC and to photochemical air pollution in outdoor air.

The purpose of this study was to measure the release of ethanol to the air during simulated household use of liquid detergents. Three replicate experiments and a blank were conducted in a 20-m^3 environmental chamber for each of four conditions: "typical" dishwashing (DT), "high-release" dishwashing (DH), "typical" laundry (LT), and "high-release" laundry (LH).

Average amounts of ethanol transferred to the atmosphere per use (and the fraction of ethanol used so liberated) were 32 mg (0.038) for DT, 100 mg (0.049) for DH, 18 mg (0.002) for LT, and 110 mg (0.011) for LH. Thus, a large fraction of the ethanol added to wash solutions with liquid detergents is discharged to the sewer rather than transferred to the air during use. The contribution of this source to photochemical air pollution is, consequently, much less than estimates based on 100 percent release to the atmosphere.

Another potential concern is the impact of ethanol emissions on indoor air quality. Although there are no guidelines for residential indoor exposures to ethanol in air, the significance of the exposure resulting from washing activities appears to be small. For the experimental protocols used in this study, the measured concentrations reflect levels that might be obtained during ordinary use of the products. The average ethanol levels measured were on the order of 1 ppm or less—i.e., 1000 times lower than the threshold limit value of 1000 ppm (time-weighted average, based on occupational exposure during a 40-hour work week).

Macromodel for Assessing Residential Concentrations of Combustion-Generated Pollutants[1, 6, 10]

G.W. Traynor, M.G. Apte, and B.V. Smith

We have developed a simulation model (a *macromodel*) to predict distributions of indoor air pollutants in specified homogeneous residential housing stocks. Initial research has focused on predicting indoor concentrations of combustion-generated pollutants (CO, NO_2, and respirable suspended particles). This effort is part of a project to predict indoor air pollutant concentrations for all key indoor pollutants including radon, volatile organic compounds, and other hydrocarbons (e.g., carcinogenic polycyclic aromatic hydrocarbons).

Research in the past year has concentrated on conducting sensitivity analysis on the macromodel. We chose a general nonparametric sensitivity analysis technique using the Kolmogorov-Smirnov test as the most applicable method for the combustion macromodel.

The advantages of this method are that

- it is consistent with intuition regarding sensitivity analyses;
- it does not depend on linear relationships or normal distributions;
- its results are easily interpreted.

In general, results of the sensitivity analysis demonstrated the importance of indoor pollutant source emission rates and usage rates in determining which houses have high levels of indoor air pollutants and which populations groups are therefore at greatest risk. In addition, the reactivity rate of NO_2 was identified as a very important factor in determining indoor levels of NO_2. The most critical factor for houses with vented gas space heaters was the appliance venting factor (the fraction of pollutant emissions directly injected into the indoor environment), yet very little is known about this parameter. Many important causal parameters identified in this report have been ignored in past indoor air quality field studies, and this trend must be reversed.

Residential Energy Use and Indoor Air Quality in Developing Asian Countries[19]

M.G. Apte, K.R. Smith[a], A. Kulkarni[b], Y. Ma[c], F. G. Manegdeg[d], and W. Wathana[e]

Indoor and outdoor exposures to air pollutants are much higher in developing countries than in industrialized countries. LBL's Indoor Environment Program (IEP) is involved in an international project measuring indoor and outdoor air pollutants in developing Asian countries. This project is being conducted in collaboration with the East-West Center in Honolulu, Hawaii, and with research institutions in China, Philippines, Thailand, and India. The project is part of a study examining trends in residential energy usage and is designed to assess the changes in air pollution exposure that accompany increased urban development.

In FY90 a one-week indoor air pollution survey training workshop was taught by staff from LBL, the East-West Center, the U.S. Environmental Protection Agency, and WESTAT, Inc. (Rockville, MD). The workshop served to transfer essential technical information on environmental monitoring to these institutions in developing countries. A statistical design and sampling strategy for monitoring indoor, outdoor, and personal pollutant concentrations in 60 homes in urban centers in each of the four Asian countries (Beijing, Manilla, Bangkok, and Pune) were developed. Pollutants measured include respirable suspended particles (RSP), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). Miniaturized instrumentation packages for measuring the above pollutants were assembled and provided to the Asian research groups. IEP provided one-week of on-site training in each of the Asian countries at the commencement of the monitoring project.

Monitoring in all of the countries was successfully completed by December of 1990. We expect sample and data analysis to be completed during FY91.

[a]East-West Center, Honolulu, HI.
[b]Systems Research Institute, Pune, India.
[c]Tsinghua University, Beijing, China.
[d] University of Philippines, Manilla, Philippines.
[e] Chulalongkorn University, Bangkok, Thailand.

Behavior of Particle-Phase Environmental Tobacco Smoke Indoors: A Comparison of Predictions and Experiments[3, 5, 15]

R.G.Sextro, E. Gross, and W.W.Nazaroff

Particle size influences the behavior of particles indoors, especially coagulation and deposition on surfaces. The distribution of particle sizes is in turn affected by characteristics of the indoor environment, including filtration and ventilation. Ultimately, this particle-size distribution is an important determinant of the deposition and retention pattern of particles in the lung, which then affects the lung dose of the constituent chemicals.

We have used a previously developed model to examine experimental data on the size distribution of environmental tobacco smoke (ETS) obtained as a function of time in a series of chamber studies. This model describes the time-dependent behavior of particles in indoor air. It explicitly accounts for the effects of filtration and ventilation, and predicts deposition and coagulation rates as a function of particle size. We then compared the model predictions and the experimental results: in general, the model results agreed well with the experimental data (Figure).

These comparisons have also been used to estimate the effective initial size distribution of the ETS emissions. Such distributions are experimentally difficult to obtain because of mixing effects. The emissions profile estimated on the basis of the experimental data where then used as the initial condition for the model. The subsequent time-dependent behavior of ETS was successfully predicted, including the case where sequential cigarette smoking occurred over a period of time.

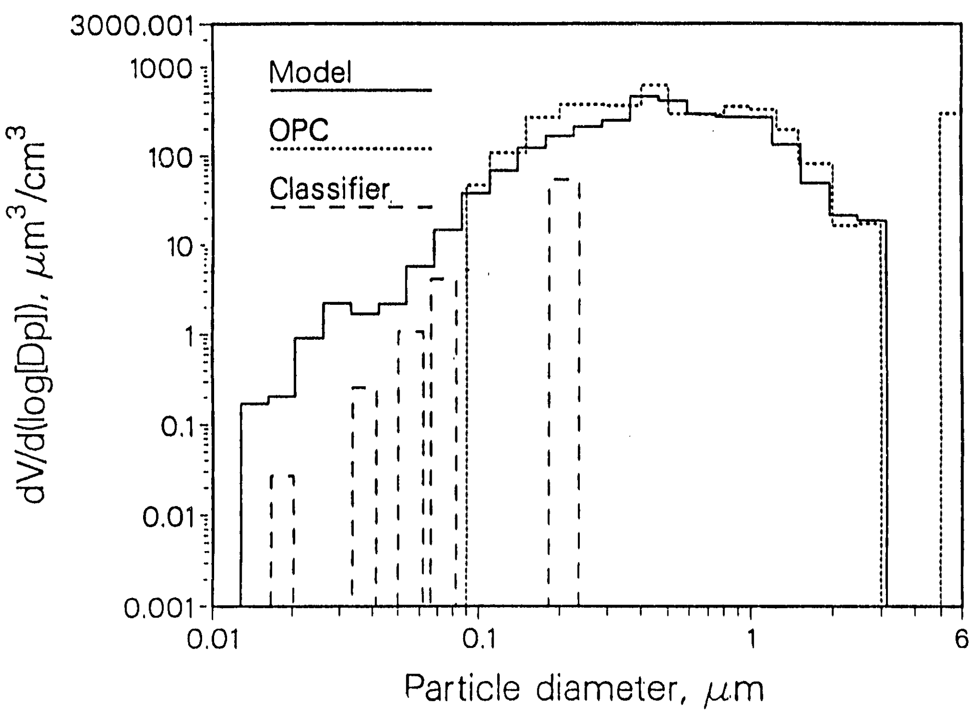

Figure. Comparison of predicted and experimental size distributions for environmental tobacco smoke, approximately 4.5 h after smoking of one cigarette. Experimental data were obtained using an optical particle counter (OPC) and with a differential mobility analyzer (electrostatic classifier).

References

Apte MG, Brown SR, Corradi CA, Felix SP, Grimsrud DT, Smith BV, Traynor GW, Woods AL. *Concentrations of Indoor Pollutants (CIP) Database User's Manual, Version 4.0.* Lawrence Berkeley Laboratory Publication No. Pub-3083, 1990.

Bois F, Smith M, Spear RC. Mechanisms of benzene carcinogenesis: Application of a physiological model of benzene pharmacokinetics and metabolism. *Toxicology Letters* (In press, 1990).

Bois F, Spear RC. *Analysis of Parametric Uncertainty in Physiological Pharmacokinetic and Multistage Cancer Models.* Lawrence Berkeley Laboratory Report No. LBL-28631, 1990.

Bois F, Woodruff TJ, Spear RC. Comparison of three physiologically-based pharmacokinetic models of benzene disposition. *Toxicology Letters* (In press, 1990). (Also published as Lawrence Berkeley Laboratory Report No. LBL-29970, 1990.)

Boone PM, Rossman TG, Daisey JM. The genotoxic contribution of woodsmoke to indoor respirable suspended particles. *Environment International* 1990; 15: 361-368.

Daisey JM, Fisk WJ, Hodgson AT, Mendell MJ, Faulkner D, Nematollahi M, Macher JM. *The California Healthy Building Pilot Study. I. Study Design and Protocols.* Lawrence Berkeley Laboratory Report No. LBL-29851, 1990.

Daisey JM, Hodgson AT, Grot RA. Sources and source strengths of volatile organic compounds in a new office building. *Journal of the Air and Waste Management Association* (In press, 1991).

Feustel HE. The COMIS Air Flow Model: A tool for multizone applications. In: *Proceedings of the Fifth International Conference on Indoor Air Quality and Climate, Toronto, Canada.* 1990; 4: 121-126.

Feustel HE, Allard F, Dorer VB, Garcia ER, Grosso M, Herrlin MK, Mingsheng L, Phaff HC, Utsumi Y, Yoshino H. *COMIS Fundamentals.* Lawrence Berkeley Laboratory Report No. LBL-28560, 1990.

Fisk WJ, Faulkner D, Bauman FS, Arens EA, Pih D, McNeel PJ. *Indoor Air Flow and Pollutant Removal in a Room with Task Ventilation.* Lawrence Berkeley Laboratory Report No. LBL-29505, 1990.

Gadgil AJ, Najita JS, Revzan KL, Harrison J, Turk BH, Fisk WJ. *An Experiment with Depressurization Tests as Indicators of Radon Availability in 6 New Jersey Houses.* Lawrence Berkeley Laboratory Report No. LBL-28690, 1990.

Gundel LA, Daisey JM, Offermann FJ. Development of an indoor sampling and analysis method for particulate polycyclic aromatic hydrocarbons. In: *Proceedings of the Fifth International Conference on Indoor Air Quality and Climate, Toronto, Canada.* 1990; 2:299-304.

Hodgson AT, Daisey JM, Offermann FJ. A sampling and analytical method for gas-phase polycyclic aromatic hydrocarbons in indoor air. In: *Proceedings of the Fifth International Conference on Indoor Air Quality and Climate, Toronto, Canada.* 1990; 2: 719-724.

Loureiro CO, Abriola LM, Martin JE, Sextro RG. Three-dimensional simulation of radon transport into houses with basements under constant negative pressure. *Environmental Science & Technology* 1990; 24: 1338-1348.

Miguel AG, Daisey JM, Sousa JA. Comparative study of the mutagenic and genotoxic activity associated with inhalable particulate matter in Rio de Janeiro air. *Environmental Molecular Mutageneses* 1990; 15: 35-43.

Narasimhan TN, Tsang YW, Holman HY. On the potential importance of transient air flow in advective radon entry into buildings. *Geophysical Research Letters* 1990; 17: 821-824.

Nazaroff WW, Cass GR. Protecting museum collections from soiling due to the deposition of airborne particles. *Atmospheric Environment* (In press, 1990).

Nazaroff WW, Ligocki MP, Ma T, Cass GR. Particle deposition in museums: Comparison of modeling and measurement results. *Aerosol Science and Technology* 1990; 13: 332-348.

Nazaroff WW, Salmon LG, Cass GR. Concentration and fate of airborne particles in museums. *Environmental Science & Technology* 1990; 24: 66-77.

Nazaroff WW, Teichman KY. Indoor radon: Exploring U.S. federal policy for controlling human exposures. *Environmental Science & Technology* 1990; 24: 774-782. (Also published as Lawrence Berkeley Laboratory Report No. LBL-27148 Rev., 1990.)

Nero AV, Gadgil AJ, Nazaroff WW, Revzan KL. *Indoor radon and decay products: Concentrations, causes and control strategies*. Washington, DC: U.S. Department of Energy Report DOE/ER-0480P, November 1990. (Also published as Lawrence Berkeley Laboratory Report No. Report LBL-27798, 1990.)

Offermann FJ, Loiselle SA, Daisey JM, Gundel LA, Hodgson AT. A pilot study to measure indoor concentrations of polycyclic aromatic compounds. *Proceedings of the Fifth International conference in Indoor Air Quality and Climate, Toronto, Canada.* 1990; 2: 379-384.

Revzan KL, Fisk WJ. *Modeling Radon Entry into Houses with Basements: The Influence of Structural Factors*. Lawrence Berkeley Laboratory Report No. LBL 28109, 1990.

Revzan KL, Fisk WJ, Sextro RG. *Modeling Radon Entry into Florida Houses with Concrete Slabs and Concrete-Block Stem Walls*. Lawrence Berkeley Laboratory Report No. LBL-30005, 1991.

Revzan KL, Gadgil AJ, Fisk WJ. Modeling radon entry into houses with basements: Model description and verification. *Indoor Air* 1(2): 173-189, 1990.

Schuetzle D, Daisey JM. Identification of genotoxic agents in complex mixtures of air pollutants. In: Waters MD et al, eds. *Genetic Toxicology of Complex Environmental Mixtures*. New York: Plenum Press, 1990; 6: 11-32.

Sextro RG. Issues in the use of short-term radon concentration measurements for estimating long-term exposures. In: *Proceedings of the 1990 Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 1990.*

Sherman MH. *A Multitracer System for Multizone Ventilation Measurements*. Lawrence Berkeley Laboratory Report No. LBL-29010, 1990.

Sherman MH. *A Power-Law Formulation of Laminar Flow in Short Pipes*. Lawrence Berkeley Laboratory Report No. LBL-28505, 1990.

Sherman MH. Superposition in infiltration modeling. *Building and Environment* (In press, 1990). (Also published as Lawrence Berkeley Laboratory Report No. LBL-29116, 1990.)

Sherman MH. Tracer gas techniques for measuring ventilation in a single zone. *Building and Environment* 1990; 25(4): 365-374. (Also published as Lawrence Berkeley Laboratory Report No. LBL-29328, 1990.

Traynor GW, Apte MG, Smith BV, Porter WK. *Macromodel for Assessing Indoor Concentrations of Combustion-Generated Pollutants: Empirical Evaluation of Key Assumptions and Sensitivity Analyses*. Lawrence Berkeley Laboratory Report No. LBL-27652, 1990.

Traynor GW, Apte MG, Smith BV, Porter WK. *Macromodel for Assessing Residential Concentrations of Combustion-Generated Pollutants: Model Development and Selected Sensitivity Analyses*. Lawrence Berkeley Laboratory Report No. LBL-28450, 1990.

Traynor GW, Apte MG, Sokol HA, Chuang JC, Mumford JL, Tucker G. Selected organic pollutant emissions from unvented kerosene heaters. *Environmental Science & Technology* 1990; 24: 1265-1270. (Also published as Lawrence Berkeley Laboratory Report No. LBL-21355, 1990.)

Tuluca AN, Sherman MH, Krarti M. Reduction of the effective leakage areas of single-section HUD-code manufactured homes due to air infiltration barriers. In: *ASHRAE Transactions* 1990; 96 (Pt. 1).

Turk BH, Harrison J, Prill RJ, Sextro RG. Developing soil gas and radon entry potentials for substructure surfaces and assessing radon control diagnostic techniques. *Health Physics* 1990; 59: 405-419. (Also published as Lawrence Berkeley Laboratory Report No. LBL-27319, 1990.)

Turk BH, Harrison J, Sextro RG. Soil gas and radon entry potentials for substructure surfaces. In: *Proceedings of the 1990 Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 1990.*

Turk BH, Prill RJ, Grimsrud DT, Moed BA, Sextro RG. Characterizing the occurrence, sources and variability of radon in Pacific Northwest homes. *Journal of the Air and Waste Management Association* 1990; 40: 498-506.

Wallman PH, Fisk WJ. Exhaust-air heat pump performance with unsteady state operation. *Journal of Heat Recovery Systems & CHP* 1990; 10(3): 231-241. (Also published as Lawrence Berkeley Laboratory Report No. LBL-27705, 1990.)

Wollenberg HA, Revzan KL. Radium regionalization in California. *Geophysical Research Letters* 1990; 17: 805-808.

Wooley J, Hodgson AT, Nazaroff WW. Release of ethanol to the atmosphere during use of consumer cleaning products. *Journal of the Air & Waste Management Association* 1990; 40:1114-1120.

Projects described in this report were supported by the following sources (funding sources for individual projects are keyed to this list; see superscript numbers following the project titles):

U.S. Department of Energy:

1 Assistant Secretary for Conservation and Renewable Energy, Office Building Technologies, Buildings Systems and Materials Division

2 Assistant Secretary for Conservation and Renewable Energy, Office Building Technologies Buildings Services Division

3 Director, Office of Energy Research, Office of Health and Environmental Research Human Health and Assessments Division

4 Director, Office of Energy Research, Office of Health and Environmental Research Ecological Research Division

5 Director, Office of Energy Research, Office of Health and Environmental Research Pollutant Characterization and Safety Research Division

6 Assistant Secretary for Environment, Safety and Health, Office of Environmental Analysis

7 Bonneville Power Administration

8 U.S. Environmental Protection Agency, Exploratory Research Grant No. R-815755-01

9 U.S. Environmental Protection Agency through Interagency Agreements DW89934620-0; or AD-89-F-2A-062 (with the U.S. Department of Energy)

10 U.S. Consumer Product Safety Commission, under Contract No. CPSC-IAG-87-1282

11 California Air Resources Board, under Contract No. A732-106

12 California Department of Health Services:
- Environmental Epidemiology and Toxicology Branch
- Indoor Air Quality Program, Air and Industrial Hygiene Laboratory

13 Universitywide Energy Research Group, University of California

14 California Institute for Energy Efficiency (CIEE)*

15 Tobacco-Related Disease Research Program, University of California

16 Electric Power Research Institute

17 Gas Research Institute

18 Soap and Detergent Association

19 East-West Center, Honolulu, HI

20 Polytechnico di Torino, Italy

21 Swedish Council for Building Research, Sweden

22 Carl-Duisberg-Gesellschaft, Federal Republic of Germany

23 Meierhans & Partner A. G., Switzerland

24 Generous donations of furniture and partitions from Steelcase, Inc., Grand Rapids, MI

*Publications of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor.

This support was provided through the U.S. Department of Energy under Contract No. DE-AC03-765F00098.

END

DATE
FILMED
4/22/92