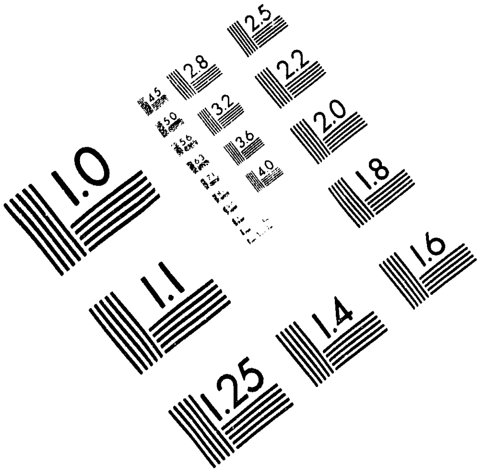

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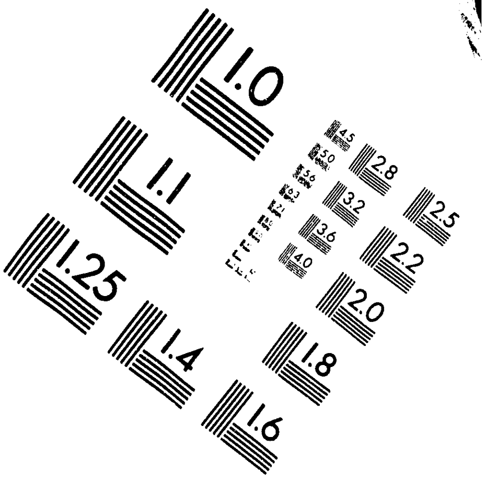

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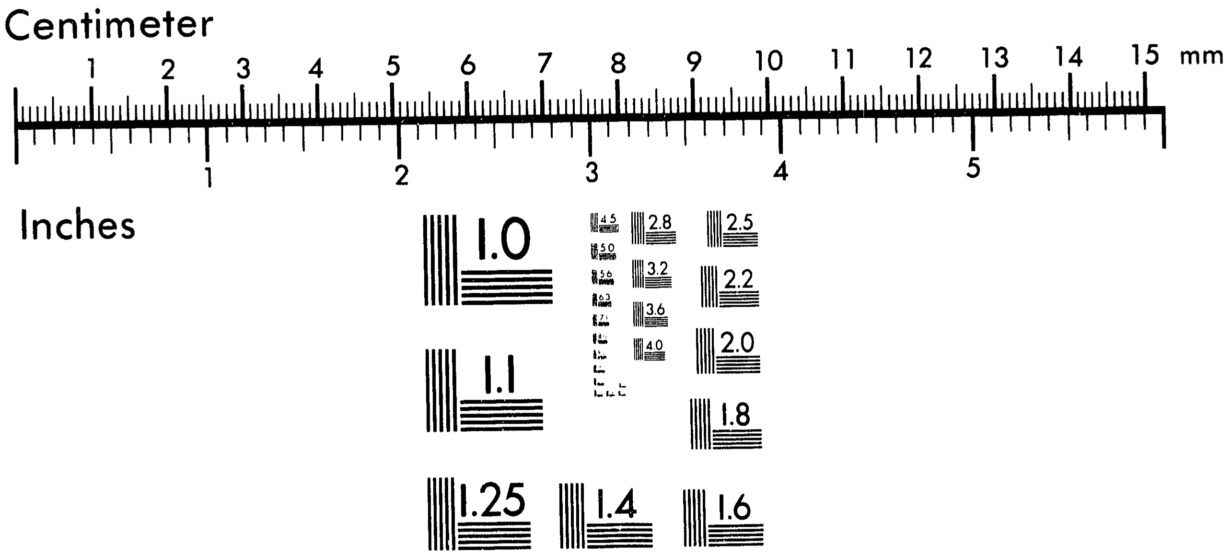

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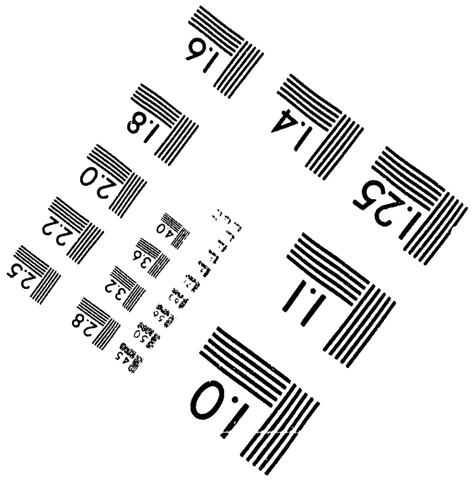

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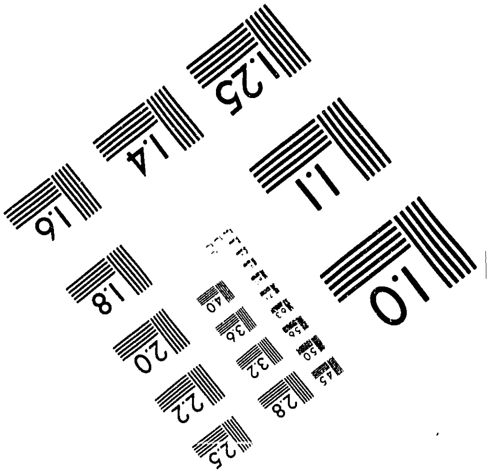

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Indoor Environment Program
1991 Annual Report

Energy & Environment Division

October 1992

Indoor Environment Program

1991 Annual Report

Joan M. Daisey, *Program Leader*

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Introduction

Approximately 38% of the energy consumed in the United States is used in buildings. Much of this energy can be saved by reducing buildings' air infiltration and ventilation, since the heat load associated with these processes is about 13 quads per year. However, because ventilation is the dominant mechanism for removing pollutants that originate indoors, reducing ventilation can cause undesirable side effects such as lowering indoor air quality and adversely affecting the health, comfort and productivity of building occupants.

The Indoor Environment Program at LBL was established in 1977 to conduct integrated research on building ventilation, indoor air quality, and the energy use and efficiency of buildings. The purpose of this research is to increase the energy efficiency of buildings while maintaining or improving occupant health and comfort. The Program is part of the Center for Building Science, a unit of the Energy and Environment Division at LBL. Its research explores energy use and efficiency of buildings; building ventilation and infiltration; the nature, sources, transport, transformation, and deposition of indoor air pollutants; and exposure and risk assessment for indoor air pollutants. Pollutants of particular interest include radon; volatile, semi-volatile and particulate organic compounds; and combustion emissions, including environmental tobacco smoke, CO, and NO_x. The Program also conducts multidisciplinary studies on relationships between occupant health and comfort symptoms and factors within a building's environment.

Air infiltration and ventilation rates are measured and modeled for residential and commercial buildings in order to understand energy transport and thermal losses from various components of building shells and ventilation systems. Methods for reducing energy losses are based on these studies. The effectiveness of various ventilation systems for pollutant removal is also investigated. Methods for characterizing ventilation and building energy use are developed for experimental and applied uses.

Because control of pollutant sources is often the most effective and energy-efficient method for improving indoor air quality, emissions from various types of indoor sources (e.g., combustion sources, building and furnishing materials, consumer products, office equipment) are characterized by determining chemical composition and rate of emission in laboratory and field experiments. The 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 the strengths of pollutant sources and on energy usage are also investigated.

Indoor air quality studies are focused on understanding the dynamic processes within buildings that control pollutant sources, transport, transformation, deposition, re-emission and removal. Spatial and temporal variability of pollutants and pollutant sources and the factors controlling variations in indoor air quality are also characterized. This research provides the basis for models of population exposure to various types of pollutants.

Human exposures to indoor air pollutants and the health risks associated with such exposures are examined in an integrated framework to establish the relative significance of various categories of pollutants. Health endpoints of particular concern include cancer, neurotoxicity, and irritancy. Research has also been initiated to develop exposure metrics and risk assessment methods based on a more fundamental understanding of the biological processes leading to adverse health effects. Analysis of indoor air pollutant exposure and risk integrates much of the Program's research and provides a broad perspective of indoor air quality and its associated health and comfort risks.

Thermal-Energy Distribution Systems

M. Modera

Thermal-energy distribution systems represent the vital link between heating and cooling equipment and conditioned building spaces. In the United States, approximately 10 quads of primary energy annually pass through generally inefficient thermal distribution systems in buildings. Moreover, the load shape due to inefficient distribution systems is often more peaked than general cooling demand, 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, on direct cold-air distribution systems (summarized separately within this document), and on friction-reducing additives for hydronic distribution systems in commercial buildings (performed at UC Santa Barbara).

Impacts of Residential Air-Distribution Inefficiencies

In 1991 our research on residential air-distribution efficiency in California (i.e., attic and crawlspace ducts) focused on:

- completion of a 31-house field study of duct-system performance based on a two-day air-distribution diagnostic measurement protocol; and
- improvement and application of an integrated airflow/thermal-performance simulation tool.

Some highlights of the field results are:

- Building envelopes appear to be approximately 30% tighter for houses built after 1979.
- Duct system tightness showed no apparent improvement in post-1979 houses.
- Distribution-fan operation added an average of 0.45 ACH to the average measured air-change rate of 0.24 ACH.
- An average of 20% of the heat provided by the furnace was lost due to duct conduction losses alone.

To obtain credible estimates of air distribution system performance, the hourly simulation tool developed in 1990 was streamlined and improved this year to provide quicker, more accurate results. The modified tool is based on a multizone flow simulation (COMIS) for a residential air distribution system in a typical California house, coupled to a thermal simulation of the same house (DOE-2) via a heat and mass transfer model of the air distribution system. The simulation tool was applied this year to the simulation of indoor radon concentrations in Florida houses with attic ductwork, the details of which are summarized separately within this document. In the year to come, the simulation tool will be used for:

- simulating annual energy, peak-load and ventilation implications of residential air distribution; and
- simulating the effectiveness of alternative distribution technologies and retrofit options.

In 1991, an evaluation of the potential for energy savings available by improving thermal distribution systems in residential and small commercial buildings was also completed. This evaluation was divided into four stages:

- a breakdown of buildings into categories relevant to thermal distribution issues;
- an estimation of space-conditioning energy use per building for each category;
- a projection of the building stock to the year 2020 in order to compare the savings potential in new and existing buildings; and
- an estimation of energy savings from improved thermal distribution within each category.

These numbers were used to project national energy savings: 0.87 quads based upon current technologies and market information, 2.11 quads based upon achievable efficiency improvements, and an additional 0.27 quads in small-building market segments whose energy savings potential was not examined in detail.

Thermal Performance of Nonresidential Buildings

H.E. Feustel, J. Dieris, R. Meierhans, R. Meldem, A. Theiss, B. Wildmoser

Cooling of nonresidential 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 improves indoor air quality and the control and zoning of the system. Because of 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 by approximately 25% of the original load.

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

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

Hydronic cooling systems together with heavy construction can significantly reduce peak cooling power demand. Furthermore, the thermal storage effect of high structural mass helps to reduce compressor cooling by using alternative cooling strategies.

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 (temperature or enthalpy) 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 well 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 may become obsolete if the envelope is improved, if the thermal storage performance is increased, and if the air-handling system is equipped with an economizer.

Existing Building Efficiency Research

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

As architects and contractors respond to higher energy prices and stricter energy codes by constructing more energy efficient buildings, existing buildings remain as 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. Although the emphasis in past years has been on coordinating research in this sector, we continue to work in single-family and commercial buildings.

Competitive Solicitation for Existing Buildings

In 1990 the U.S. Department of Energy awarded 10 proposals designed to save energy in existing buildings. Two of the ten proposals are receiving technical assistance from LBL in the form of design projects and evaluation. The first project is the retrofit of 350 units of multifamily housing in Burlington, Vermont. A local non-profit housing organization (Northgate Housing) and the local electric utility (Burlington Electric Department) conceived the project and are implementing it. The apartments have been converted from electric baseboard heating to gas-fired hydronic systems, with additional retrofits made to the building shell and equipment.

Computer simulation of the units shows an energy savings of nearly 20% from the shell retrofits. Preliminary analysis of utility bills shows energy savings lower than 20%, but this discrepancy is accounted for by the tenants' heating more rooms and keeping them warmer. These findings have been supported by the data from the tenant surveys. Tenant satisfaction with the retrofits has been extremely positive, and the average utility bill is nearly 50% lower. A final report will be available in Spring, 1992.

The second project is being conducted in collaboration with the New York State Energy Office and involves two retrofit strategies in 30 New York City apartment buildings. The retrofits replace central boilers and add new windows. Energy consumption will be monitored for two years to examine whether the savings last. The worsening budget situation in New York State has caused a reduction in the scale of the project.

The DOE-HUD New Initiative

A New Initiative was created in 1990 by the U.S. Department of Energy and the U.S. Department of Housing and Urban Development to improve energy efficiency in the federally-assisted housing sector. We have been active in the initial planning and development of the Initiative. We started work in 1990 on five projects to address energy-efficiency in HUD-owned and HUD-mortgaged multifamily buildings by revising HUD statutes and guidelines and by conducting collaborative demonstration projects.

Work to date has included review of the energy characteristics of HUD housing for the elderly in New England and identification of one site in Worcester, Massachusetts where the utility agreed to finance retrofits. We will monitor the energy consumption at the site and survey the tenants and managers' satisfaction with the retrofits. This work is planned to continue in FY92.

Standards for Infiltration, Ventilation, and Leakage

M. Sherman and M. Modera

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

The American Society of Testing and Materials (ASTM) through its committee on Infiltration Performance of Building Constructions (E6.41) has several standards relevant to air infiltration. In November 1975 ASTM decided to develop standard practices relating to air infiltration: one on measurement of infiltration using tracer gases and one on the measurement of airtightness using fan pressurization. The current versions of these standards are Standard Test Method for Determining Air Leakage by Tracer Dilution (E741-83), and Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (E779-87). Standard E741 was reapproved in 1990 and is currently being revised significantly.

Since those two fundamental standards were completed, ancillary standards have been written: Standard Practice for Air Leakage Site Detection in Building Envelopes (E1186-87), and Standard Test Method for Airflow Calibration of Fan Pressurization Devices (E1258-88). 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 and publishing symposia proceedings on air infiltration. Mark Modera is chairman of the next such symposium scheduled for 1993.

In process are relevant ASTM 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 standard E779.

The International Standards Organization (ISO) is using some of these ASTM standards as a basis for similar international standards. Currently standards for airtightness and tracer dilution measurement techniques are being developed.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) is concerned with good practice as far as the HVAC engineering community is concerned. Two relevant standards have been approved: Ventilation for Acceptable Indoor Air Quality (ASHRAE 62-1989), and Air Leakage Performance for Detached Single-Family Residential Buildings (ASHRAE 1191-1988). LBL is presently participating in the revision of Standard 62.

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 the effective ventilation rate appropriate to indoor air quality concerns.

In addition to our participation in these societies, we have been using our experience to support regional agencies in setting building standards. We have advised the State of Florida through the Florida Radon Research Program (FRRP), 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).

Advanced Techniques for Measuring Airtightness

M. Modera

Air leakage is the process of air flowing through unintended apertures. 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 airtightness (the fan pressurization technique or 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 multifamily buildings) have only recently begun to be examined. For all three types of air leakage, the measurement and study of airtightness allow us to characterize buildings, to better understand ventilation and space conditioning, to evaluate the performance of mechanical systems, and to estimate the effectiveness of airtightness retrofits.

Our advanced airtightness measurement research in the past year was focused in two areas:

- fan-pressurization measurements of residential air-distribution tightness.
- experimental examination of a envelope tightness technique based on a building's response to an impulsive change in pressure (pulse pressurization).

Measuring Leakage in Air Distribution Systems

An automated airtightness measurement system based on a blower door was used in FY91 to measure the envelope leakage and duct leakage of 31 houses. Results of these measurements were consistent with earlier studies showing that duct leakage is approximately 15% of overall envelope leakage. That field study also included measurements of the pressures driving air leakage in air distribution systems during fan operation; the average pressure differential across supply leaks was 30 Pa, and the differential across return leaks was 60 Pa. By comparison, the average pressure differential across building envelope leaks is approximately 4 Pa. In the coming year, a fan pressurization device that connects directly to the ducts will be tested in houses under construction; which are unsuitable for blower-door testing. Such a device will allow ducts to be sealed while they are more readily accessible.

Pulse Pressurization

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. We have 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 yielded three principal findings:

- Joule-Thomson heating or cooling of the expanding gas can play an important role in the measured pressure response of the structure;
- inertial effects in flows through internal doorways cannot be eliminated simply by increasing the length of the pulse;
- successful implementation in a single-family residence with typical doorways will require multipoint injection of the expanding gas flow.

Ventilation Modeling and Measurement in Single-Zone Buildings

M. Sherman, D. Dickerhoff

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

Virtually all ventilation measurements use a diluted tracer gas. Most such measurements have been made for a single zone using a single tracer gas. In recent years, the need to determine ventilation rates/airflows 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 indicated an opportunity to improve 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 our motivation was to advance the LBL infiltration model, the results are generally useful and explain puzzling data seen in the literature.

Future work will focus on the parts of single-zone modeling that have not yet been addressed and on comparison of measured and predicted ventilation rates.

International Studies in Ventilation

H.E. Feustel, B.V. Smith, W. Brown, J. Dieris, A. Klingler, K. Nitta, U. Riemann, and B. Stracke

The COMIS project at LBL is a multinational collaborative effort of a team of experts to develop a modular model of multizone airflow. The LBL effort has focused on 1) developing output routines that maximize the final program's ease of use and 2) developing a Time Management System (TMS). The program has been linked to a spreadsheet program to use graphics capabilities available for IBM-compatible personal computers. Macros were developed to allow use of available output options without the user having to learn a spreadsheet program. We also installed additional output options to create tables for selected parameters.

Within the framework of an annex adopted by the Energy Conservation in Buildings and Community Systems program of the International Energy Agency, we have begun studying physical phenomena causing airflow and pollutant transport (e.g., moisture) in multizone buildings. Special emphasis is being given to providing data necessary to use the COMIS model (e.g., wind pressure distribution, default values for leakage of building components, material properties such as absorption and desorption). An important goal 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.

Annex participants will undertake 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 into three subtasks:

Subtask 1: System development

A multizone airflow 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. Coupling with the thermal building simulation model will be demonstrated.

Subtask 2: Data acquisition

Data sets are being obtained for evaluation purposes and as input for the model.

Subtask 3: System evaluation

The model will be evaluated using data obtained from subtask 2. Sensitivity of the model to the quality of input data will be determined.

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

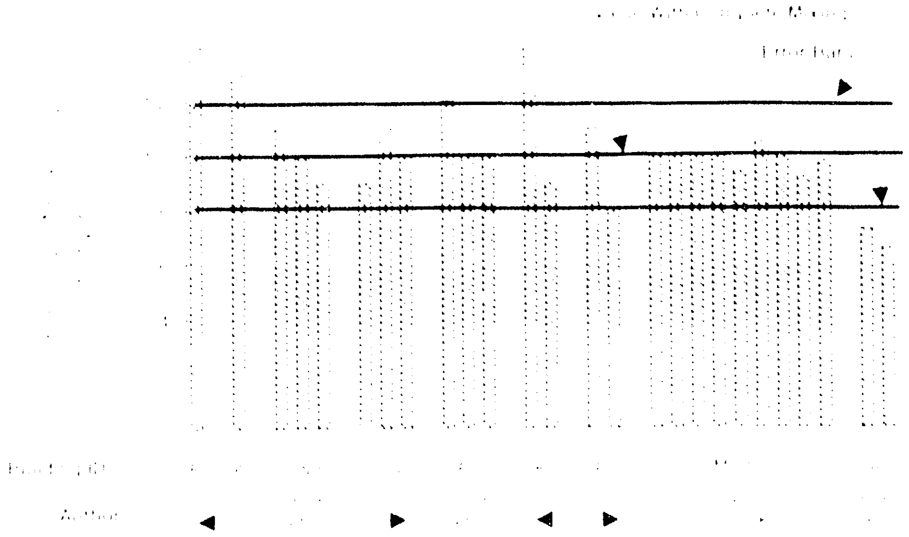
Close cooperation is envisioned, mainly with regard to state-of-the art reviews, data collection, and coordination of work (e.g., defining cases for evaluation with other pertinent projects). As part of its ongoing work plan, the Air Infiltration and Ventilation Centre (AIVC) will disseminate the results of this annex. A database for evaluation purposes has already been prepared by AIVC.

Lawrence Berkeley Laboratory is managing the annex on behalf of the U.S. Department of Energy. By the end of FY91, Canada, France, Italy, Japan and the United States officially committed to the annex. The Netherlands and Switzerland have indicated a strong interest in joining the annex.

VENTILATION AND INDOOR AIR QUALITY CONTROL

Air Exchange Effectiveness of Conventional and Task Ventilation Systems for Offices

W.J. Fisk, D. Faulkner, and R. Prill



Performance of a Task Ventilation System with Air Supply at the Desktop

*D. Faulkner, W.J. Fisk, D. Sullivan, and F.S. Bauman**

In today's typical office buildings, occupants usually cannot control the ventilation and thermal conditions of their environments. Most office buildings have sealed windows and use a central heating and ventilation system to control the temperature and flow rate of air supplied to occupants.

Experiments were carried out in the University of California's Controlled Environment Chamber (CEC) to study the effects of a task ventilation system on indoor ventilation and thermal comfort. 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—typical of real offices—i.e., overhead lights, task lights, and a personal computer. Two of the workstations were occupied by a heated, seated mannequin.

The task ventilation system consists of a mixing box connected by flexible duct to two air supply nozzles on the desktop. The supply nozzles may be rotated in the horizontal plane and contain movable outlet vanes in the vertical plane. The mixing box uses a small, variable-speed fan that pulls supply air from the main air handling unit ducting under the floor, pulls room air from beneath the desk, and directs the mixture out from the nozzles. The unit has a desktop control panel that allows occupants to adjust the speed and temperature of air emerging from the vents, temperature of a 200 W radiant heating panel, task lighting, and a white-noise generator. The control panel also contains an infrared occupancy sensor that shuts the unit off when the workstation has remained unoccupied for a few minutes. Experiments were designed to evaluate this system over a range of conditions.

Using steady-state temperatures and ventilation flow rates, a tracer gas was injected into the supply air and multipoint measurements of tracer-gas concentrations, air velocity, and air temperature were made inside the chamber. Comfort indices were calculated and were compared to standards such as those published by the American Association of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Local ventilation rates were computed from the tracer concentrations.

At most conditions tested, the whole area was adequately ventilated; and the local ventilation rate, at the breathing area of a seated occupant in the workstations with task ventilation was approximately 20% higher than at other locations in the room. At the highest flow rate tested, with nozzles pointed directly at the occupant, the local ventilation rate at the breathing level was higher by approximately 60%. Improvements in local ventilation rates during actual use will depend on occupants use patterns.

This task ventilation system was capable of controlling the air velocity from a barely noticeable level to an uncomfortably drafty one. The temperature of the supply air could be controlled from a relatively low value (typically 18 °C) when coming directly from the main air handling unit to a temperature warmer by a few degrees; the supply air consisted of an equal mix of recirculated room air and air from the main air handling unit. Thus, this system could be controlled over a wide range, giving occupants the ability to adjust their local environment with some precision. Comfort indices were within acceptable standards for most test conditions (i.e., except for the high flow rates with small nozzle openings).

Future studies must determine whether task ventilation saves energy. We plan to conduct field studies to collect data on energy performance and to assess usage patterns and thermal comfort.

*University of California Berkeley, Center for Environmental Design Research

Mixing Rate of a Pollutant from a Point Source Within a Single Room

A.V. Baughman, W.W. Nazaroff, A.J. Gadgil, and R.G. Sextro

Studies of contaminant dynamics in indoor environments have commonly utilized single or multizone models based on an underlying assumption that the zones are well mixed. This assumption, however, is not always appropriate. For example, when considering the effectiveness of segregating smokers from nonsmokers in public buildings investigators must take into account the rate at which the smoke mixes within the room. Our experimental study quantitatively characterizes the rate at which smoke from a cigarette disperses within a single room under typical residential conditions. The room used was 31 m^3 and had a deliberately low air-exchange rate of 0.03 to 0.08 ACH. A smoldering cigarette was simulated using an electrical resistance coil-which generated heat at the same rate as the idling cigarette-and a tracer gas (a neutrally buoyant mixture of about 18% SF_6 in He) that was released in a pulse about 1 cm above the coil. The source was located approximately 1 m from two of the interior walls, and about 0.8 m above the floor.

A grid of 27 sampling points was established in the core of the room; the exterior sampling points in this grid were 0.5 m from the nearest wall. The lowest 9 points were 76 cm from the floor; the 9 points at the mid-level were 1.6 m above the floor, while the highest level points were 2 m above the floor. Sampling sites were also positioned at each of the eight room corners and at approximately the center of the face of each of the six room surfaces. Samples from each of the 41 locations were remotely collected nearly simultaneously using gas-tight syringes through 1/8-inch copper tubing at 2- to 20-minute intervals. Following the experiment these samples were analyzed for SF_6 content using a gas chromatograph with an electron capture detector. The experiment was carried out three times under the following thermal conditions: nearly isothermal surfaces; convection from a 500-watt heat source placed on the room floor along a wall; and convection from the solar radiation that came through an unshaded window and struck the floor and adjacent wall. The characteristic mixing time was defined as the period required for the relative standard deviation of the concentrations to become less than 10%. Strong convection from the solar radiation yielded the fastest mixing time, (about 18-20 minutes). The heater experiment yielded similar mixing times (about 21 minutes). Data from this experiment are shown (Figure). The slowest mixing time occurred for the case with the nearly isothermal surfaces; almost 80 minutes was necessary to achieve mixed conditions.

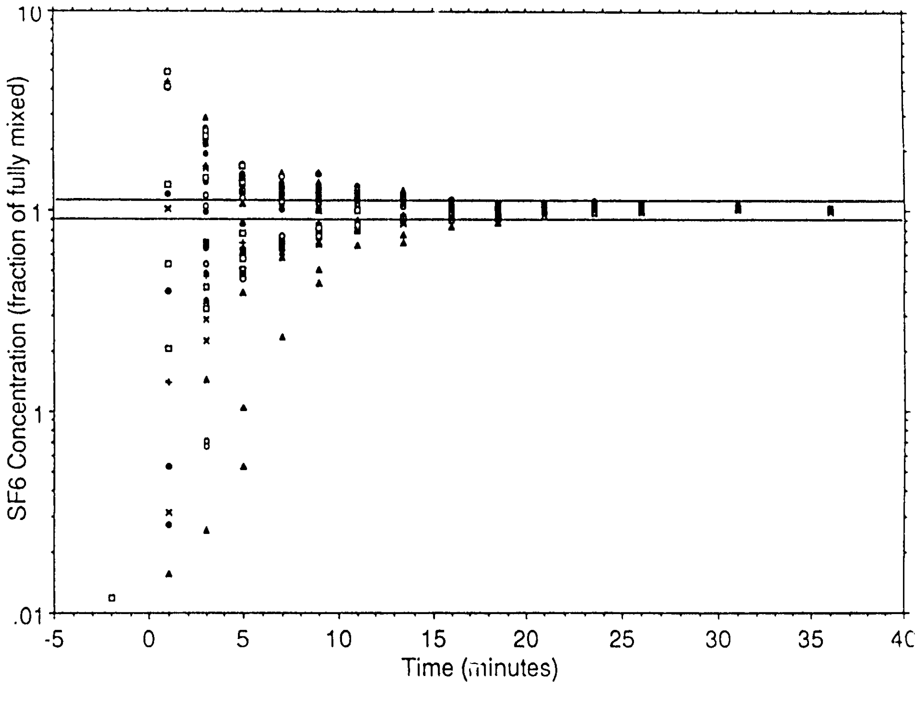


Figure. *SF_6 concentration, relative to the fully mixed concentration, for groups of sampling points as a function of time. Different symbols represent different locations in the room. The horizontal lines indicate the range where the relative standard deviation is within 10%. For this experiment, the time required to achieve this degree of mixing is about 21 minutes.*

Modeling Radon Entry and Concentrations in Crawlspace Houses

R.G. Sextro, H.E. Feustel, M.P. Modera, K.L. Revzan, and M.H. Sherman

We have combined a model for radon migration through soil with a multizone airflow model to predict radon entry and concentrations in crawlspace houses typical of those constructed in Florida. Radon entry into a crawlspace with an open unvented soil floor is governed by both advective and diffusive migration through the soil. We have assumed that wind is the only source of pressure differences between the crawlspace and the adjacent soil; therefore, predicted [illegible] conditions differ [illegible] the [illegible] radon entry rate of [illegible] radium concentration of [illegible] permeability of [illegible] pressure differences [illegible] wind speed [illegible]

We used the COMIS multizone airflow model to calculate pressure differences between [illegible] (Feustel, 1990) [illegible] the living space [illegible]

The building energy and airflow [illegible] Florida [illegible] temperature [illegible] wind speed and direction for a typical [illegible] year (TMY). [illegible] results were obtained for each hour of the year and consisted of flows between the crawlspace and the outside, flows between the crawlspace and the living space of the house in either direction (Figure, part a) and flows between the living space and the outside. The hourly flows were then averaged for each of four seasons and for the entire year. Combining these results with the predicted radon entry rates into the crawlspace yields seasonal and annual radon concentrations for the crawlspace and living space (Figure, part b).

As shown in the Figure, radon concentrations in the crawlspace are highest for the summer season; however, the living-space radon concentrations for this season are quite low. This situation is caused in part by the reverse stack effect when the indoor temperatures are cooler than those outdoors. Thus, the net airflow will be directed primarily from the living space to the crawlspace, thereby minimizing the transport of radon from the crawlspace into the house.

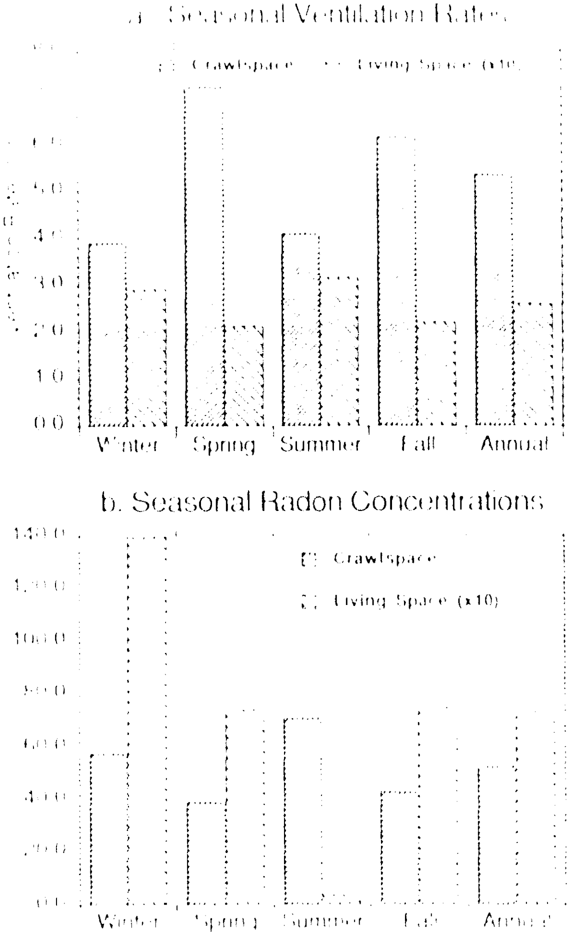


Figure. [illegible]

The Small Structures Project: Experimental and Theoretical Studies of Soil Gas and Radon Entry

W.J. Fisk, R.G. Sextro, K. Garbesi, H.A. Wollenberg, Y.T. Tsang,* S. Flexser,* A.J. Gadgil, T.N. Narasimhan,* K.L. Revzan, 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, two room-size basements were constructed at a site in northern California. 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. 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. During the past year, we have completed numerous experiments with steady and time-varying indoor-outdoor pressure differences. In the course of these experiments, soil properties have been tracked over time.

Two current modeling efforts are coupled to the experimental research. In the first approach, a 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. A transient integrated finite difference numerical model is used. The predictions are described elsewhere in this annual report.

We highlight here a major finding from the past year's research: the measured soil gas and radon entry rates during periods of steady depressurization of the structure are larger—by approximately a factor of six—than the entry rates predicted with a numerical model assuming a homogeneous soil. The measured pressure field in the soil also differs substantially from the predicted pressure field (Figure). Numerical modeling that accounts for the general features of the soil permeability distribution at the site does not yield predictions that are substantially closer to measurements. Resolution of this discrepancy is a major focus of our present research.

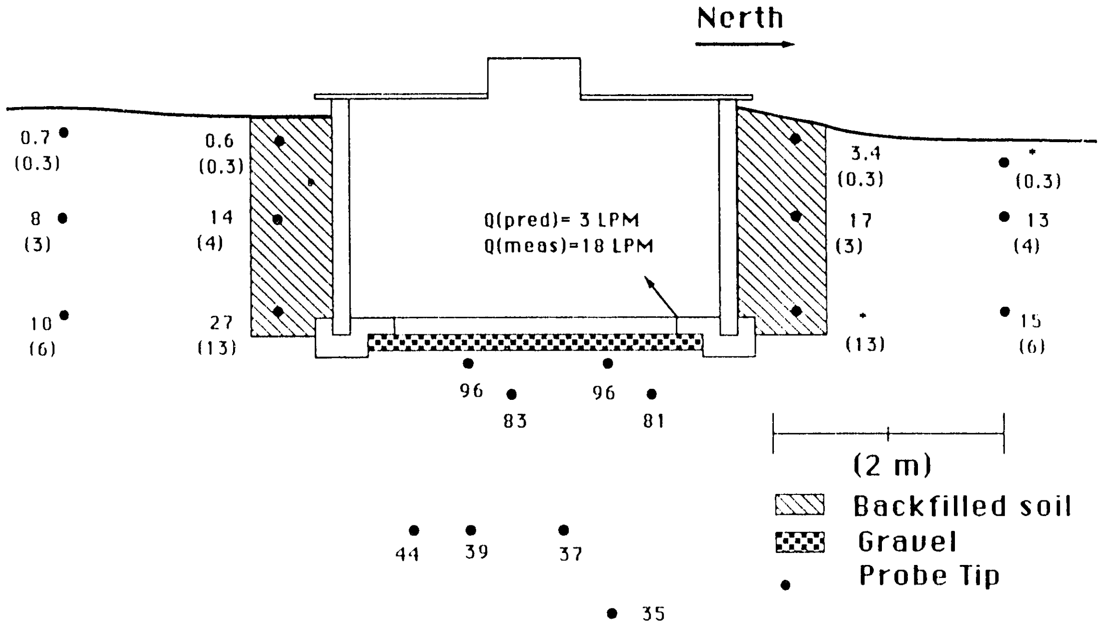


Figure. *Comparison of measured (not in parentheses) and predicted (in parentheses) pressure coupling expressed as a percentage, and measured and predicted soil-gas entry rates. The percent pressure coupling is the pressure decrease in the soil divided by the depressurization of the structure. Q(pred) and Q(meas) are the measured and predicted soil-gas entry rates.*

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*Earth Sciences Division, LBL

†Engineering Division, LBL

Radon Entry into Basements Driven by Fluctuations in Atmospheric Pressure

Y.W. Tsang and T.N. Narasimhan**

Using a mathematical model, we have investigated temporal variations in radon entry rates into a house basement subject to both time-dependent periodic variations in barometric pressure and a small, steady-state depressurization between the basement and outside. Our investigation uses a transient integrated finite-difference model that can solve for both diffusive and advective flux of radon in the soil gas, which is treated as a slightly compressible fluid. Two different boundary conditions in the house basement are considered: 1) a dirt-floor basement, through which diffusion is equal to or more important than advective transport; and 2) a concrete basement floor which is impermeable to radon migration except for a 1-cm-wide crack near the perimeter of the basement floor through which advective transport of radon dominates. Based on a Fourier decomposition of barometric pressure data, two frequencies of barometric pressure fluctuation, each having representative amplitudes, were chosen for this study. One has a short period of 0.5 hour with a pressure amplitude of 50 Pa, while the other is diurnal, with a 24-hour period and a typical pressure amplitude of 250 Pa.

For a homogeneous soil medium with soil air permeability between 10^{-13} m^2 and 10^{-10} m^2, we predict that barometric pressure fluctuations can increase the radon entry rate into the basement by as much as 120% of the steady-state entry caused by a steady depressurization of 5 Pa. The presence of a thin layer of higher-permeability aggregate immediately below the basement floor further enhances the radon entry rate. Effects of this barometric pressure pumping on radon entry are also compared to radon transport by diffusion only, i.e., transport in the absence of steady depressurization. The pressure pumping effect on radon entry is found to be significant for the case of a concrete basement floor and a perimeter crack. In particular, for pressure pumping at a 0.5-hour period and for a homogeneous soil permeability of 10^{-10} m^2, the radon entry rate is a factor of 10 larger than that caused by diffusive transport. This finding may help explain indoor radon concentrations during periods when the steady-state driving force is small.

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*Earth Sciences Division, Lawrence Berkeley Laboratory

Deposition of Unattached Radon Progeny Under Natural Convection: Effect of Progeny Lifetimes

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

The deposition rate of unattached progeny is a governing factor in determining the radiological dose to the lungs from exposure to indoor radon. Our research was undertaken to investigate mass-transport aspects of unattached progeny in rooms. Numerical solutions were obtained for the equation governing the flow of air caused by natural convection in room-size enclosures as well as for those governing the generation, transport, deposition and decay of the two unattached radon progenies of importance ^{218}Po and ^{212}Pb. We used two-dimensional solutions to the equations to obtain generally valid results without excessive computational demands. The deposition of a species onto walls is commonly characterized by "deposition velocity," defined as the mass flux of the species per unit surface area onto the walls, divided by concentration of the species at regions far away from the surfaces.

Deposition velocities are calculated for various locations on the enclosure surface for two different thermal boundary conditions. For the cases considered, the surface-averaged mean deposition velocity was found to be in the range (2-4) × 10^{-4} m/s for ^{218}Po and (1-3) × 10^{-4} m/s for ^{212}Pb. The local deposition velocity is observed to depend strongly upon the position of the surface with respect to the flow. An order of magnitude difference between the maximum and minimum values of the deposition velocities for both species is seen.

The production and decay of ^{218}Po affects the spatial distribution of its concentration, the magnitude of its deposition velocity and its dependence on location compared to that of ^{212}Pb, which behaves almost as a stable species with respect to the time scale of convective motion. Because the production and decay rates of ^{218}Po are significant on the time scale of air motion, the boundary layers are continuously replenished with a fresh supply of the species. This increases the deposition of ^{218}Po relative to its core concentration, compared to the deposition rate of ^{212}Pb relative to its core concentration. This effect seems to have been overlooked by other investigators.

The results have significance for assessing the health risk associated with indoor exposure to ^{222}Rn and ^{220}Rn decay products and for investigating mass-transport aspects of the more general problem of the interaction of air pollutants with indoor surfaces.

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*Department of Civil Engineering, University of California

We thank D. Gobin of CNRS (France) for assistance with reinstalling the numerical fluid mechanics software at Lawrence Berkeley Laboratory during the early stages of this work.

Performance of Subslab Ventilation Systems for Indoor Radon Mitigation

W.J. Fisk, Y.C. Bonnefous, A.J. Gadgil, R.J. Prill, and A. Nematollahi*

In houses having elevated indoor radon (Rn) concentrations, the primary source of Rn is usually the surrounding soil where Rn is generated by the radioactive decay of trace amounts of radium. The predominant process of Rn entry into these houses is pressure driven flow of high-Rn soil gas into the structure through small cracks, joints and holes. Subslab ventilation (SSV) is one of the most effective and common methods of reducing indoor Rn concentrations in houses that have basements. Two basic methods of SSV are used in subslab depressurization (SSD), a fan exhausts soil gas from beneath the slab floor to the outside. The fan usually draws air through one or more plastic pipes that penetrate the slab floor. This process decreases the pressure beneath the floor and therefore reverses the pressure difference that normally causes soil gas and Rn to flow into the structure. In subslab pressurization (SSP), outdoor air is forced beneath the slab using a fan (i.e., the direction of air flow is reversed compared to that in a SSD system). SSP ventilates the soil beneath the slab floor, thus reducing radon concentrations within the soil near the slab. Soil-gas entry into the structure continues, but the concentration of Rn in the entering soil gas is decreased.

SSV for limiting radon entry into basements was investigated through complementary experimentation and numerical modeling. Determination of the impact of subslab aggregate permeability on SSV performance was a primary objective. Subslab pressure fields resulting from SSV were measured in six well-characterized basements, each with a different combination of soil and aggregate permeability. The relationship between air velocity and pressure gradient within the three types of aggregate installed beneath the basement slabs was measured in the laboratory. A new numerical model of SSV was developed and verified with the field data. This model simulates non-Darcy flow in the aggregate. We demonstrate that non-Darcy effects significantly affect SSV performance.

Field data and numerical simulations indicate that increasing the aggregate permeability within the investigated range (2×10^{-8} m^2 to 3×10^{-7} m^2) substantially improves the extension of the subslab pressure field caused by SSV operation. Subslab pressure field extension also improves as soil permeability decreases between 10^{-9} m^2 and 10^{-10} m^2. With a 1-mm-wide gap at the junction of the slab and basement walls and aggregate permeabilities between 2×10^{-8} m^2 and 3×10^{-7} m^2, we have found that further reductions in soil permeability do not significantly improve the subslab pressure field extension. Sealing of cracks in the slab and excavation of a small pit where the SSV pipe penetrates the slab also dramatically improve this pressure-field extension. A large ratio of aggregate permeability to soil permeability reduces the need for a large depressurization at the SSV pit.

Our findings are consistent with the results of prior field studies; however, our understanding of SSV has been improved by this research, and the dependence of SSV performance on the relevant parameters can now be quantified with the model.

*Washington State Energy Office, Washington Energy Extension Service

Finding Areas of High Indoor Radon in the United States: A Design Study

A.V. Nero, A.J. Gadgil, S.M. Leiden, D. Nolan, and S. Rein

Developing a methodology for identifying high-radon areas of the United States continues to be a major need in indoor radon research. With such a methodology, homes having genuinely high radon concentrations can be found and the problem remediated rapidly. In perhaps 50,000 to 100,000 homes, for example, occupants are exposed to 20 pCi/l (740 Bq/m^3) or greater, thereby accumulating exposures at or above the occupational radiation limit.

Previous research efforts have aimed to characterize the causal chain between the parent radium in the soil and the indoor concentration. However, the details of this chain are very complex, and—even if known—nation-wide data for directly calculating area-by-area indoor concentrations in the United States for the U.S are lacking. Still, substantial information exists for most regions, both on indoor levels and on some of the causal factors, such as radium concentrations and permeabilities of soils. Using Minnesota as a test case, we have undertaken examination of such regional data, to determine the extent to which a correlation analysis can provide estimators of the indoor concentration distribution at a scale (e.g., county or smaller) where monitoring data alone are not sufficiently accurate.

Initial results for Minnesota are encouraging. Using the short-term "screening" data from the survey conducted by Minnesota in cooperation with the Environmental Protection Agency, we have examined the extent to which three soil-related parameters (indicators, respectively, of radium concentration, radon emanation, and soil-gas permeability) can predict the county-to-county variance in the geometric mean (GM) indoor radon concentration. For the 28 counties where 10 or more homes were monitored, the multiple regression yields an R2 of 0.5 (Figure). Further, part of the unexplained variance is due purely to the uncertainty arising from modest numbers of measurements (such as 10) in each county. A modification of R2 to measure the capability of predicting only the explainable variance yields values exceeding 0.5 for either the 28 counties or for the full set of 87, including counties with fewer than five data points. These results thus indicate that soil information provides substantial power for estimating GMs and therefore for finding the areas with most of the high indoor concentrations.

Continuing efforts in collaboration with the U.S. Geological Survey are devoted to archiving three major goals:

- develop a more flexible and comprehensive analytical treatment of soil-related and other information;
- include other influencing variables, e.g., meteorology and housing characteristics, in the analysis; and
- frame a methodology that can sweep the entire country and also that can utilize for any region the predictive power arising from the analysis of national data.

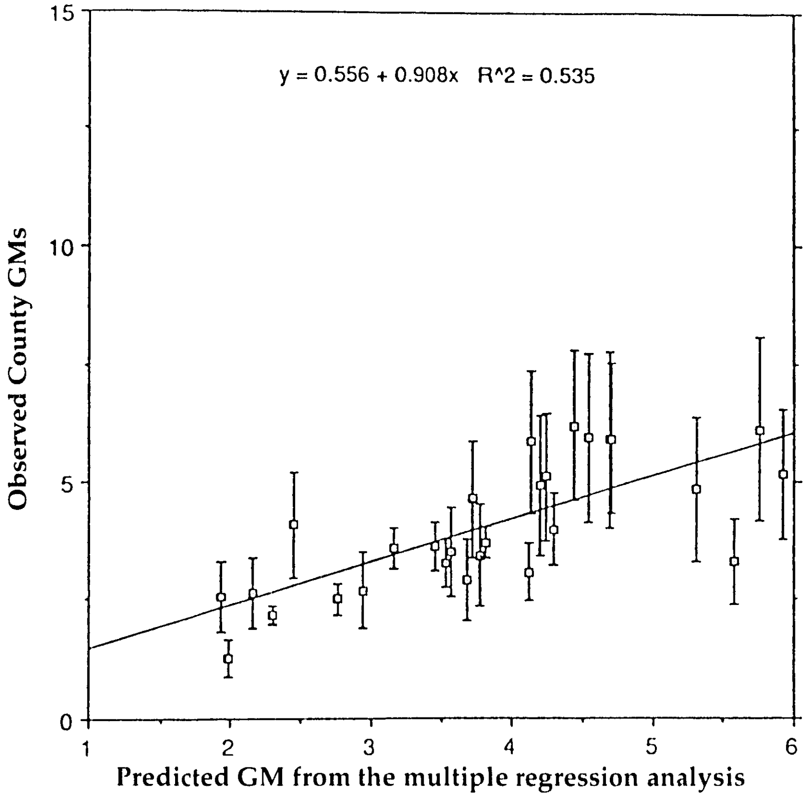

Figure. *Multiple regression results indicate capability of predicting county geometric mean (GM) indoor radon concentrations in Minnesota using indicators of soil radium concentration, permeability, and emanation fraction, for counties with 10 or more indoor radon measurements.*

Emissions of Volatile Organic Compounds from New Carpets

A.T. Hodgson and J.D. Wooley

Emissions of volatile organic compounds (VOCs) from new carpets allegedly cause complaints of discomfort and may cause adverse health effects among building occupants. This study was undertaken to qualitatively and quantitatively investigate the emissions of VOCs from representative samples of new carpet.

Carpets were collected directly from manufacturers' mills and were packaged and shipped to preserve their integrity. VOCs emitted from the samples were [illegible]

[illegible] relative humidity, and a loading ratio of 0.4 m²/m³. Samples for the analysis of low molecular weight aldehydes, VOCs, and total VOC were collected throughout the first day and on each subsequent day of an experiment.

In general, the carpet backing materials were the primary sources of the compounds that were emitted. Dominant compounds emitted by the various carpets included vinyl acetate, 2-butanol, 1,2-propanediol, 4-ethenylcyclohexene, styrene, 4-phenylcyclohexene, and 2,6-di-tert-butyl-4-methylphenol (BHT). One carpet was a source of formaldehyde emissions. The shapes of the concentration profiles over one week were related to compound volatility. Concentrations of the more volatile compounds decayed rapidly to relatively low values over the first 12–24 hours after installing the carpets in the chamber. Concentrations of the less volatile compounds did not decay rapidly and remained high at the end of the week-long period. Carpets are complex materials, and generally the concentration profiles did not fit simple mathematical models describing changes in emission rates over time.

Ozone and Carpets: Chemistry with Implications for Indoor Environments

C. J. Weschler, A. T. Hodgson, and J. D. Wooley*

[illegible]

VOCs increased by almost a factor of two at 50 ppb ozone concentration. The latter observations indicate that reactions between ozone and relatively nonvolatile compounds (e.g., unsaturated polymers or other chemicals) may be significant sources of VOCs.

The results of this research have implications for investigations of indoor air quality in buildings. The concentrations and types of VOCs measured in a building in the absence of ozone or at low ozone levels may differ significantly from those measured at higher ozone levels. Consequently, [illegible] under one set of conditions may not be adequate to characterize indoor air quality or to associate indoor air pollutant chemical concentrations with occupant complaints.

Genotoxic Polar Organics in Airborne Particles

L.A. Gundel, J.M. Daisey, K.R.R. Mahanama, L.R. de Carvalho, and N. Kado†*

Most chemical characterization research that done on particulate organic matter in the atmosphere has focused on nonpolar and moderately polar organics that are soluble in solvents such as cyclohexane and dichloromethane. Much less investigation has been done on particulate polar organic matter that is soluble only in acetone or methanol. This material 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. Bioassay-directed fractionation and chemical analysis are needed to focus attention on the polar organic matter fractions and compounds likely to be of most significance to human health. Any fractionation method developed must give high mass and mutagenicity recoveries, and the recovered fractions must be in solvents that can be easily evaporated or solvent-exchanged for compatibility with bioassay and chemical characterization methods.

Our research has three major goals: 1) to develop a milligram-scale fractionation method for particulate polar organics; 2) to chemically characterize the resulting fractions; and 3) to test the mutagenicity of the fractions. Using open-column chromatography with cyanopropyl-bonded silica and elution solvent mixtures of increasing polarity (hexane, dichloromethane and methanol), acetone extracts of airborne particles have been separated into twelve fractions. Recovery of mass was 96% and 100% for extracts of ambient particles from Elizabeth, New Jersey, and NIST standard reference SRM material 1649, respectively, when 87 and 40 mg were applied to 12.5-mg packing material.

The acetone extracts and fractions were characterized by mass determination, high-performance liquid chromatography with absorbance and fluorescence detection, Fourier-transform infrared spectroscopy, chemical class tests, and ion chromatography. Unfractionated extracts contained 20% (Elizabeth, NJ) and 7% (SRM 1649) inorganic material by mass. Elemental analysis indicated that the acetone extracts were highly oxygenated. The major inorganic species in the acetone extracts were ammonium nitrate and sodium chloride. Chemical class (spot) tests and infrared analyses of the extracts and fractions showed evidence for a variety of organic functional groups, including polycarboxylic acids, aldehydes, ketones, phenols, and nitrous esters. Class tests of the unfractionated extract of Elizabeth, New Jersey, also indicated the presence of alcohols and sulfones. The characterization results showed that the fractionation procedure separated the acetone extracts into fractions of increasing polarity as elution solvent polarity increased, but particular organic functional groups did not concentrate in individual fractions. The results are consistent with the presence of bi- or polyfunctional organic compounds.

The acetone extracts and fractions were subjected to a microsuspension version of the Ames test for mutagenicity using *Salmonella* typhimurium (± S9). Revertant yield per unit mass was generally higher for the less polar than for the more polar fractions, but substantial activity was seen in one of the more polar fractions (eighth of twelve) for both types of acetone extracts. Differences in mutagenic activity for the fractions presumably reflect differences in the chemical compositions of the fractions, but specific mutagenic compounds have not been identified. Levels of fluorescence correlated with revertant yield, suggesting that polar aromatic compounds such as azarenes may account for appreciable mutagenicity in the acetone extracts of airborne particles.

Analysis of Environmental Tobacco Smoke for Polycyclic Aromatic Hydrocarbons

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

Determination of polycyclic aromatic hydrocarbons (PAHs) in environmental tobacco smoke (ETS) requires a method both extremely sensitive and selective. Our earlier work showed that determination of particulate PAHs in environmental tobacco smoke by high-performance liquid chromatography (HPLC) with fluorescence detection was complicated by the presence of interferences and high background when no sample cleanup was used. The objectives of this study were to develop a cleanup scheme and to devise a wavelength-programmed fluorescence detection method for HPLC analysis of environmental tobacco smoke.

Without cleanup, individual PAH peaks appeared as a fringe atop a high background of unresolved fluorescence, and signals from semi-volatile PAHs at short retention times (naphthalene through chrysene) were obscured by large and often non-reproducible interferences from other, probably more polar, species. These features were also seen in indoor particulate samples containing woodsmoke, but not in outdoor particulate matter. Use of dichloromethane extracts also led to peak distortion in reverse-phase HPLC with acetonitrile and water.

Removal of fluorescing interferences and reduction of the fluorescing background from ETS were accomplished by a combination of solvent choice and silica cleanup. Cyclohexane at 72 C extracted PAHs with fewer polar species than did dichloromethane, a solvent frequently used for PAH extraction. Silica cleanup of dichloromethane extracts did not remove enough of the interferences. Good-quality chromatograms were obtained when cyclohexane extracts of ETS were passed through silica solid-phase extraction (SPE) columns before evaporation and dilution with tetrahydrofuran and acetonitrile. More concentrated extracts were also prepared by drying the cleaned cyclohexane extract on a second silica SPE column and eluting with acetonitrile for subsequent evaporation to approximately 200 microliters. Fluoranthene-D_{10} was used as an internal standard to correct for losses of PAH during the workup.

Two wavelength-programmed fluorescence detectors were used in series in the determination of polycyclic aromatic hydrocarbons (PAHs) and their methyl derivatives in complex environmental samples by high-performance liquid chromatography. With simultaneous detection at two sets of excitation and emission conditions, co-eluting pairs of PAHs could be quantitated from a single injection. Several sets of fluorescence conditions have been developed for determination of parent PAHs and their methyl derivatives in environmental tobacco smoke: benzo(a)pyrene, chrysene, pyrene and the benzofluoranthenes, among others.

The method was used to determine particulate PAHs in National Institutes of Standard and Technology (NIST) standard reference material SRM-1649, urban dust/organics. PAH concentrations for ten compounds (for which data is available from NIST) averaged 104 ± 24% of the published values, for six replicate analyses of 15-mg aliquots of the standard.

Volatilization from Contaminated Water in Showers

J.C. Little

In this work, the classic two-resistance mass-transfer theory is applied to the volatilization of contaminants from showers. Reported experimental data from two experimental and two residential full-scale shower systems were used to calculate mass transfer coefficients using transient mass-balance models. These models account for variation in volatility, mass-transfer driving force, water and air flowrates, and volume of the shower stall and bathroom. The simultaneous volatilization of VOCs of widely varying volatility in the two experimental systems enabled individual liquid- and gas-phase mass-transfer coefficients to be determined. This provides a means of accounting for variation in contaminant volatility more accurately than has been achieved previously. Results from the four studies are compared, and measured mass-transfer coefficients are used to predict shower stall and bathroom exposures during a typical shower.

Measured liquid-phase mass transfer coefficients, $K_l A$, range between 8 and 28 L/min whereas the gas-phase coefficients, $K_G A$, vary from 130 to 380 L/min. Until more reliable data become available, a ratio of gas-phase to liquid-phase mass-transfer coefficients of 17 is recommended for shower systems. This ratio can be used to estimate $K_G A$ when only $K_l A$ is known. The mass transfer coefficients appear to vary strongly with water flowrate, but variation among the four shower systems prohibits firm conclusions from being drawn. The influence of water temperature on the mass-transfer coefficients is smaller than the observed experimental precision.

A set of reference parameters taken from a study conducted in a residential bathroom has been used to estimate the average shower-stall exposure during a ten-minute shower. These reference conditions represent an upper bound for potential exposure because they include the highest water flowrate and mass-transfer coefficients found in the four shower systems. The influence of decreasing the water flowrate, Q_L, from 13.7 to 5 L/min is also examined. Average exposure is calculated for a range of volatilities representative of VOCs found in water-supply systems (Figure). Shower-stall exposures for the most volatile VOCs are higher by a factor of 3 than those for the VOCs of lowest volatility. For the most volatile compounds, the inhalation exposure in the shower stall is equivalent to about 1.5 times that incurred through ingestion of 2 L of the same water. Decreasing the water flowrate to 5 L/min results in an exposure about one third as high as that found at the higher flowrate.

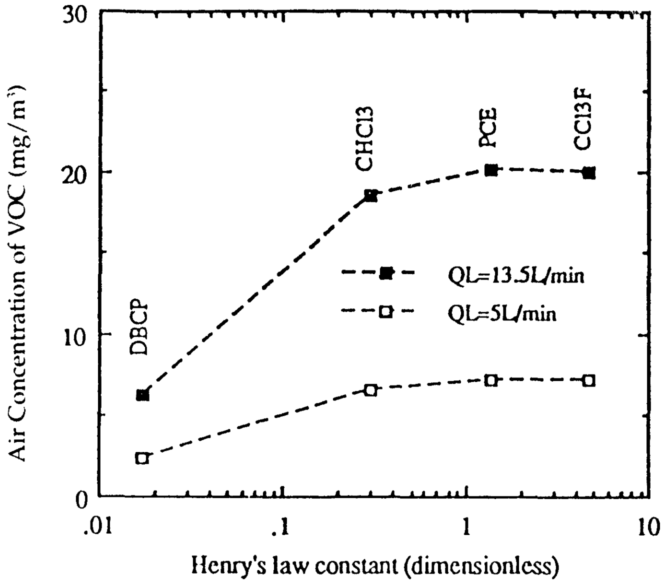

Figure. *Average concentration of volatilized contaminants in shower stall air (inlet water concetration = 1mg/L).*

Development Research on Carbon Monoxide Passive Sampler

G.W. Traynor and M.G. Apte

An annual total of 15,000 to 20,000 carbon monoxide (CO) poisonings are reported in the United States. Hundreds of these poisonings result in death and thousands result in some type of physical or mental damage. In addition, exposures to high concentrations of CO can cause fetal and cardiac damage, including heart attack. High concentrations of CO can be caused by a wide variety of residential combustion appliances, including the following: unvented kerosene and gas space heaters; malfunctioning combustion space and water heaters; indoor use of charcoal; and indoor operation of an internal combustion engine (e.g., operating cars or generators in a garage). Some poisonings can be avoided by better education, whereas others (e.g., those caused by malfunctioning vented appliances) can be avoided only by an active mitigation program. Groups of individuals especially at risk are the poor and the elderly, who often do not have the resources for routine inspection and maintenance of their gas appliances.

There is a critical need for an inexpensive CO sampling device that could be used 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 primary goal of the CO passive-sampler development research is to develop a passive sampler that requires no power, can be deployed through the mail, is stable for several weeks before and after deployment, and is accurate and precise within a 20% margin of error.

Recent research has concentrated on modifying a commercially available disk (Quantum Group Inc., San Diego, CA) that changes its transmission of near-infrared radiation in the presence of CO. Working closely with the staff at Quantum Group, we have tested many new formulations of the disk to increase the sensitivity of the disks, to reduce the batch-to-batch variations, and to reduce the reversibility of the disks. Further refinements of the CO-sensing disk and the passive sampler configuration are planned.

The California Healthy Building Pilot Study

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

Distribution of Radon Exposure: Effects of Population Mobility

A. Gadgil, S. Rein, T. Nero, and H. Wollenberg*

Estimates of the distribution of radon exposure dose to the population are required for assessing the fraction of population at high health risk from such exposure. Such estimates would be useful for assessing the costs and health risk reduction impacts of different strategies for radon mitigation in the U.S. housing stock. Such estimates would also be useful for establishing a U.S. public health policy on mitigation of indoor radon, consistent with the treatment of other public health risks.

The distribution of human exposure to radon is different from the distribution of indoor radon concentrations because most people live in several houses during their lives. Their lifetime exposures thus arise from the average of radon concentrations in these houses. For estimating distribution of radon exposure dose to populations, it is therefore insufficient to know the distribution of radon concentrations in the housing stock; we must also know how the population moved within this stock.

The problem is carefully posed in terms of estimating the distribution of the exposure *rate* to radon; results are then not strongly affected by the current age distribution of the population. More specifically, we here define the problem as estimation of the distribution of the time-averaged rate of exposure.

We have developed an approach to estimating the distribution of population exposure to radon using existing data from diverse sources. For illustration, we demonstrated its preliminary application to the data for Minnesota.

In essence, our approach was to construct the exposure rate distribution using a Monte Carlo method. We first constructed (or derived) regional distributions of residential living-level radon concentration, and a transition probability matrix for moves between and within regions and also for in- and out-migration across Minnesota boundaries. Simulations for 10,000 lives are then carried out. Simulation of each life evaluates the radon dose-rate experiences over the lifespan. In- or out-migration is included in the simulation as necessary. At the end of the 10,000-lives simulation, the distribution of exposure rates is obtained and analyzed.

A useful result (Figure) compares the annual distribution of average living-level radon concentrations adjusted for occupancy (smooth curve) to the radon exposure rate distribution of the current Minnesota residents (histogram). The latter distribution—which has a lower tail—would allow us to compare effects of undertaking mitigation measures of various costs (in terms of number of houses mitigated, various methods of mitigation implemented, their effectiveness, and their cost per house) on reducing the number of persons (or fraction of the population) exposed to high health risk from radon exposure.

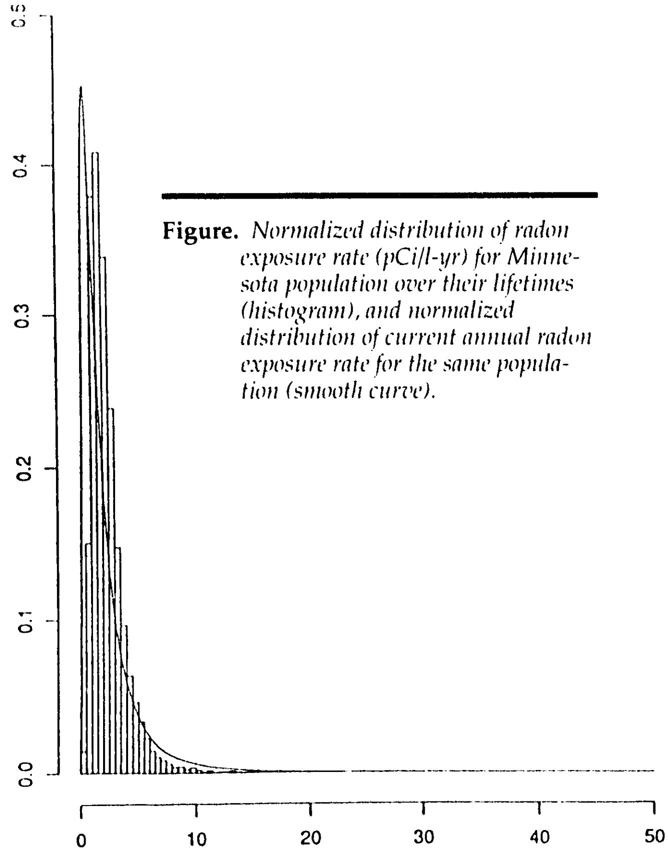

Figure. *Normalized distribution of radon exposure rate (pCi/l-yr) for Minnesota population over their lifetimes (histogram), and normalized distribution of current annual radon exposure rate for the same population (smooth curve).*

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Indoor Exposure to Volatile Organic Compounds from Soil Gas

J.C. Little, J.M. Daisey and W.W. Nazaroff

Assessments of exposure to volatile organic compounds (VOCs) for populations living near hazardous waste sites and landfills typically focus on ingestion of contaminated water, inhalation of contaminated outdoor air, and, more recently, inhalation of VOCs transferred from water to air during household water use. In this work, we evaluate the transport of VOC-contaminated soil gas into building substructures as an additional exposure pathway. Simple transport models are combined with various VOC source strengths to obtain order-of-magnitude estimates of the potential ranges of exposure.

Four possible sources of VOCs in the subsurface are spilled liquid solvents such as perchloroethylene (PCE), leaking liquid gasoline (Benzene is a component of particular interest), contaminated landfill gas, and contaminated groundwater. The vapor in equilibrium with liquid PCE has a concentration of about 130,000 mg/m^3 whereas the benzene vapor concentration in equilibrium with a typical fresh gasoline (assuming application of Raoult's law) is about 7,000 mg/m^3. In a survey of 20 municipal landfills, a maximum landfill gas concentration for PCE of about 1,300 mg/m^3 was found, whereas the maximum PCE groundwater concentration found in a survey of California wells was 170 mg/m^3. Using Henry's law, this result translates into an equilibrium air concentration of about 90 mg/m^3. These four sources are ranked by source strength (Table).

In studies of radon entry into buildings, the average ratio of resulting indoor radon concentration to soil-gas radon concentration is $a = C_{indoor}/C_{source} = 0.0016$. For VOCs, however, this "attenuation factor" will most likely represent an upper bound, since radon generally emanates in the soil immediately adjacent to the building whereas VOCs are transported some distance before entering the building. To account for the additional attenuation resulting during transport between source and building, some simple models are invoked. A steady-state diffusion model which depends mainly on the effective diffusion coefficient of the VOC and the distance between source and building (L) gives a range of a from 0.00003 to 0.003 as L varies from 100 m to 1 m. A steady-state landfill-gas advection model based on a landfill located 100 m from the building and a typical landfill pressure of 1,500 Pa gives values of 0.00008 to 0.008 as the permeability of the surrounding soil varies from 10^{-13} m^2 to 10^{-11} m^2. Applying these attenuation coefficients to the source strengths gives the ranges of potential indoor air concentrations shown in the Table. Comparing the resulting indoor concentrations of PCE and benzene with typical baseline values (about 10 mg/m^3) shows that subsurface contamination of VOCs may result in indoor concentrations many orders of magnitude higher than typical indoor levels. Liquid solvents or gasoline leaking or spilled near buildings are hazards of greatest concern, whereas contaminated groundwaters appear to pose a relatively small risk.

Table. *Estimate of potential elevation in indoor air concentration resulting from contaminated soil gas.*

Source of VOC	C_{source} (mg/m^3)	$C_{indoor}/C_{baseline}$
Liquid solvent (PCE)	74,500	2,200 - 220,000
Gasoline (Benzene)	6,500	200 - 20,000
Landfill (PCE)	750	60 - 6,000
Groundwater (PCE)	90	3 - 300

$C_{baseline}$ = average indoor concentration in the absence of a soil-gas source.

Macromodel for Assessing Residential Concentrations of Combustion-Generated Pollutants

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

A simulation model (macromodel) has been developed to predict distributions of indoor air pollutants in specified homogeneous residential housing stocks. Initial research has focused on predicting indoor concentrations of combustion pollutants (CO, NO$_2$, and respirable suspended particles). This effort is part of an ongoing 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).

Past research has concentrated on model development, model implementation, assumption testing, and sensitivity analyses. The model utilizes the Monte Carlo simulation technique and deterministic equations based on the physical laws that govern pollutant generation, transport, dilution, and removal processes. The model was implemented for four distinct regions of the United States, and seasonal simulations for distributions of indoor combustion pollutant concentrations were performed. Model assumptions were empirically evaluated, and general nonparametric sensitivity analyses were performed.

In general, the results show that residential combustion sources (e.g., indoor smoking, unvented gas or kerosene space heaters, malfunctioning "vented" space or water heaters) can cause some indoor pollutant concentrations to greatly exceed outdoor levels and outdoor air pollution guidelines or standards. Results of the sensitivity analysis demonstrated the importance of indoor pollutant source emission rates and usage rates in identifying houses having high levels of indoor air pollution and thus also the population groups at greatest risk. In addition, the reactivity rate of NO$_2$ was identified as an important factor in determining indoor levels of NO$_2$, and the "degree of venting" was an important factor in houses with a malfunctioning space heater. Many important causal parameters that had not been measured in past indoor air quality field studies now have been identified by our modeling efforts.

Residential Energy Use and Air Quality in Developing Asian Countries

M.G. Apte, K.R. Smith, A. Kulkarni,† Y. Ma,‡ F.G. Manegdeg,§ and W. Wathana ||*

Indoor and outdoor exposures to air pollutants are generally much higher in developing countries than in industrialized countries. LBL's Indoor Environment Program is involved in an international project measuring indoor air pollutants, outdoor air pollutants, and greenhouse gases 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, the 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 and greenhouse gas emissions that accompany increased urban development.

In FY90, a one-week survey training workshop on indoor air pollution 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 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, Manila, Bangkok, and Pune) was developed. Pollutants measured included respirable suspended particles, carbon monoxide, carbon dioxide, nitrogen dioxide, nitrous oxide, sulfur dioxide, and a wide variety of hydrocarbons and hydrocarbon groups. Miniaturized instrumentation packages for measuring these pollutants were assembled and were provided to the Asian research groups. We provided one week of onsite training in each of the Asian countries at the commencement of the monitoring project. Monitoring in all of the countries has been successfully completed. Sample and data analyses were begun in FY91, and a report on the impact of small-scale combustion in developing countries on global greenhouse gases was completed.

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Biologically-Based Models for Risk Assessment

F. Bois

In the course of 1991 the risk assessment group focused its efforts on the application of its physiologically-based toxicokinetic model for benzene, and on the development of a cancer model able to serve as a strong foundation for future research.

We have published three methodological papers describing our innovative parametrization methods and the structure of our benzene model. Describing the distribution of benzene in the mammalian body and its metabolism into 11 different chemical species with their own distribution, the model has been well received by the toxicology community as a landmark effort leading more realistic risk assessment. In the latest extension of this work, we investigated the effect of peak versus constant exposure levels, at realistic concentrations. On average, total amounts of hydroquinone, catechol, muconaldehyde and phenylmercapturic acid formed are increased by 20% during the peak exposure. The first three of these compounds are suspected to be directly involved in the carcinogenicity of benzene. This finding supports the use of regulatory Short Term Exposure Limits (STELs), so far empirically defined. Our work in the area provides a scientific base for monitoring exposure levels of toxicants in the workplace or in the community.

Toxicokinetic analyses alone fall short of providing a complete framework for risk assessment. The quantitative description of the toxicity at the cellular level must also be investigated. Cancer in particular is a crucial endpoint by its long-term effect, its lethal nature, and its high prevalence in the population. Cancer has been causally linked to exposure to benzene and to other pollutants. We decided to bridge the obvious gap between current cancer models and the sum of biological knowledge accumulated so far on the natural history of this disease. Taking full advantage of computing facilities available to our group, we implemented a discrete event model of Carcinogenesis of unprecedented complexity. We analyzed sensitivity of the model to its parameters, contrasting particularly the growth and mutation rates. We found that the most important parameters are those describing the repair of DNA lesions and the division of cells. Further development is under way to refine the model implementation of those crucial processes.

Biomarkers of Somatic Mutation in Humans: Application to Risk Assessment

P.J.E. Compton-Quintana

Somatic mutation (stable genetic changes in cells of the body) is linked to several human diseases: cancer, birth defects, aging, heart disease, and even cataracts. Methods to assess the amount or "burden" of somatic mutation in a person could therefore link human exposure to environmental agents with a preclinical marker.

Only a few available assays can measure somatic mutation in humans due to the need for a marker to identify and select mutant cells against a background of normal cells. The four assays developed use the loss of a protein product normally produced by the gene in order to count cells with mutation at that gene. The assays are named after the gene measured. In order of development, they are the HPRT assay (hypoxanthine guanine phosphoribosyl transferase, a DNA recycling enzyme), the GPA assay (Glycophorin A, a red blood cell surface protein), the HLA-A assay (HLA-A is a cell surface protein involved in the immune response), and the Hb-S assay (the sickle-cell form of hemoglobin).

The LBL Indoor Environment Program is focusing on applying the GPA and HLA-A assays, because these assays detect the spectrum of mutational events important in cancer. These mechanisms include mitotic recombination, which has recently shown to be a major mechanism of functional tumor suppressor gene loss in a variety of human cancers. The GPA assay is performed on red blood cells (Figure 1). It requires a minimal (1 ml) blood sample that is fixed, reacted with anti-GPA antibodies, and run on a flow cytometer to count the frequency of mutant cells per million cells. Normal frequencies are about 10 per million in young adults. The HLA-A assay is performed on white blood cells (Figure 2). This assay requires a larger blood sample (~15 ml) and requires incubation of white cells with anti HLA-A antibodies, followed by complement treatment to kill normal white cells. The mutants remaining are cloned and the colonies counted. Normal frequencies are about 30 per million in young adults. Detailed molecular analysis of mutations is possible with this assay because it provides many individual mutant clones from one person. Therefore, a spectrum of the types of mutations found in one person versus another is possible. The HLA-A assay can also be used to detect the *in vitro* effects of specific exposures, allowing direct comparison of *in vitro* and *in vivo* effects in humans.

Ongoing studies include determining the mutagenic pattern of tobacco smoke in mutant cells isolated from smokers. Such a pattern could be used to determine whether mutant cells in persons exposed to environmental tobacco smoke are associated with tobacco-smoke exposure. We are also studying the mutagenic effects of benzene, a ubiquitous pollutant that causes human leukemia. We are studying benzene-exposed workers with the GPA assay, as this assay is rapid and measures bone marrow mutations. The HLA-A assay is being used to study the *in vitro* mutagenic pattern of benzene. This is of special interest because benzene is thought to be a "non-genotoxic" carcinogen but has never been tested for genetic effects such as mitotic recombination.

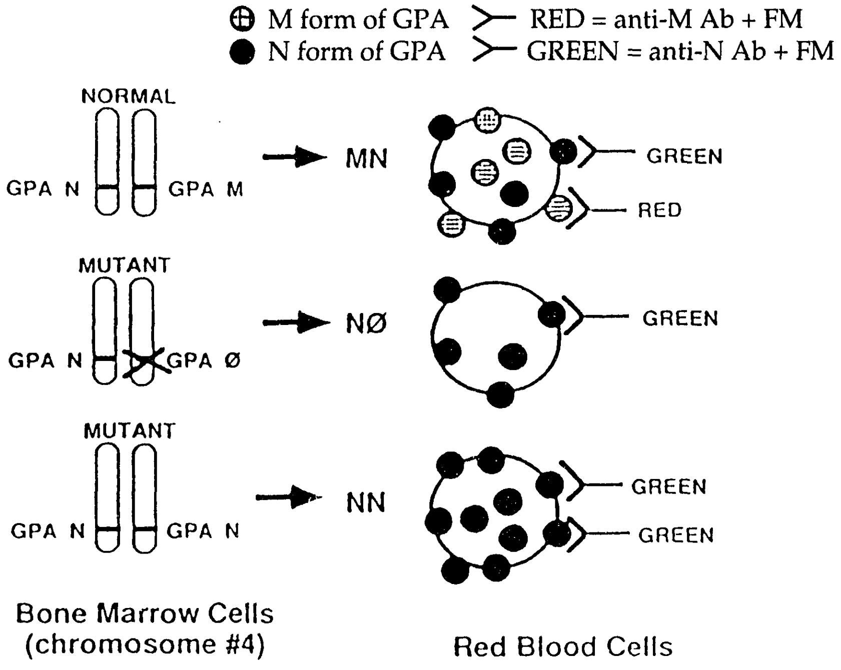
⊕ M form of GPA
● N form of GPA
RED = anti-M Ab + FM
GREEN = anti-N Ab + FM
NORMAL
GPA N
GPA M
MN
GREEN
RED
MUTANT
GPA N
GPA Ø
NØ
GREEN
MUTANT
GPA N
GPA N
NN
GREEN
GREEN
Bone Marrow Cells
(chromosome #4)
Red Blood Cells

Figure 1. *The GPA assay requires blood samples from persons heterozygous for glycophorin A, a cell surface protein on red blood cells. In a normal red blood precursor cell from a GPA heterozygote, one chromosome of the chromosome 4 pair carries the M form of GPA and one the N form (left). Mutant cells may arise from gene-loss/inactivating mutations (called NØ) and gene-duplicating mutations (NN). The right portion of the figure shows a normal heterozygous red blood cell with both M and N blood group proteins on the cell surface, and mutant cells with normal (NØ) or twice normal (NN) amounts of N GPA, but which lack normal M GPA. Normal and mutant cells are reacted with anti-GPA M and anti-GPA N antibodies labeled with fluorescent molecules, anti-M with red and anti-N with green. Fluorescence of each cell is measured by flow cytometry, and the number of green-only mutants, both NØ and NN, is determined for each sample.*

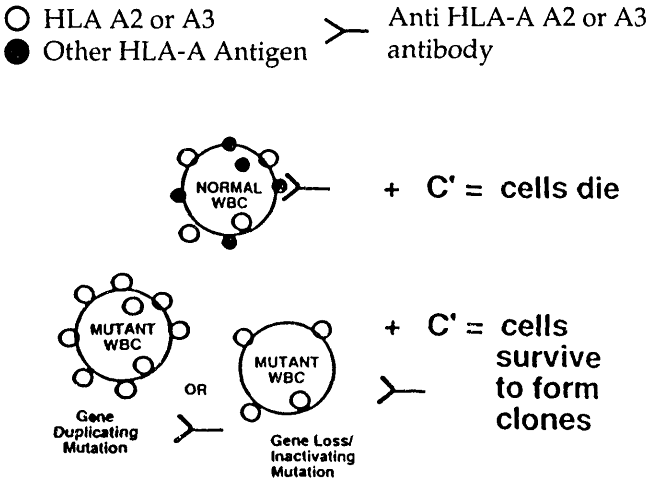
○ HLA A2 or A3
● Other HLA-A Antigen
Anti HLA-A A2 or A3 antibody
NORMAL WBC
+ C' = cells die
MUTANT WBC
MUTANT WBC
OR
Gene Duplicating Mutation
Gene Loss/ Inactivating Mutation
+ C' = cells survive to form clones

Figure 2. *The HLA-A assay requires blood samples from subjects heterozygous at the HLA-A gene, a gene with many alleles. In the current assay, subjects must be heterozygous for A2 or A3, i.e., A2Ax or A3Ax, where Ax = other HLA-A allele. The assay measures mutant T-lymphocytes that lack a normal A2 or A3 protein due to mutation at the HLA-A gene. To identify mutants, T-lymphocytes are reacted with anti-HLA-A-A2 or -A3 antibody. Normal cells bind antibody and are killed by the addition of complement (C'), which targets antibody-bound cells. Mutant cells do not bind antibody and survive. The assay detects gene-loss/inactivating mutants and gene-duplicating mutants, shown at the lower left.*

Concentrations of Indoor Pollutants (CIP) Database

M.G. Apte, 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 human exposure to air pollution is likely to occur indoors, especially when an indoor pollutant source exists and energy conservation measures have been taken to reduce building ventilation. A proliferation of research has been conducted on the subject of indoor air pollution, generating a large base of literature. In 1983, we started the *Concentrations of Indoor Pollutants Database* 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 in actual, unmodified indoor environments such as offices and residences.

Past activity on this project included 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. Current activities, funded by the Electric Power Research Institute, are directed at 1) modifying the database to include abstracts of papers and ranges of pollutant concentrations measured, and 2) continuing to update the database.

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