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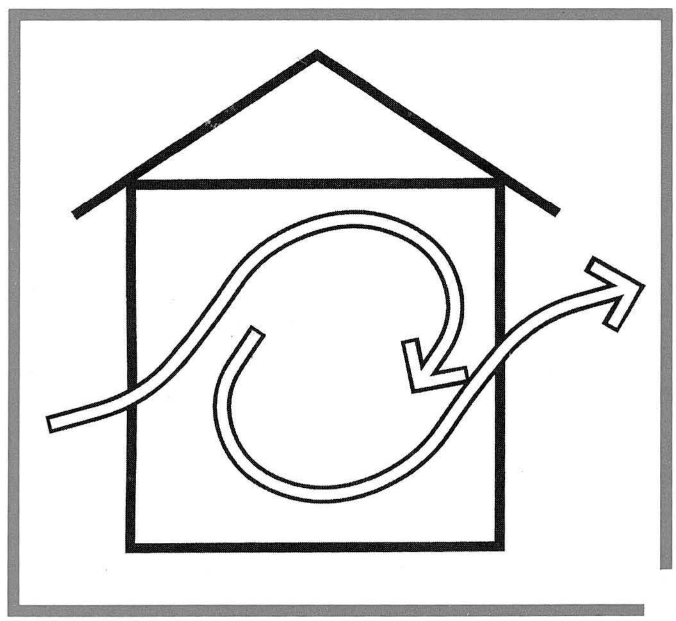

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Indoor Environment Program 1993 Annual Report

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Contents

Introduction

Approximately 38% of the energy consumed in the United States is used in buildings. Reduction of infiltration and ventilation in buildings holds great potential for saving energy since the energy use associated with conditioning and distributing ventilation air is about 5.5 EJ per year. However, since ventilation is the dominant mechanism for removing pollutants from indoor sources, reduction of ventilation can have adverse effects on indoor air quality, and on the health, comfort and productivity of building occupants.

The Indoor Environment Program in LBL's Energy and Environment Division was established in 1977 to conduct integrated research on ventilation, indoor air quality and energy use and efficiency in buildings for the purpose of increasing energy efficiency in buildings while maintaining or improving occupant health and comfort. The Program is part of LBL's Center for Building Science. Research is conducted on buildings energy use and efficiency, ventilation and infiltration, and thermal distribution systems; on the nature, sources, transport, transformation and deposition of indoor air pollutants; and on exposure and health risk associated with indoor air pollutants. Pollutants of particular interest include radon; volatile, semivolatile and particulate organic compounds; and combustion emissions, including environmental tobacco smoke, CO, and NO_x.

Research on exposure and risk analysis for indoor air pollutants provides a broad perspective on indoor air quality and associated health and comfort risks. It also helps to establish the relative significance of various categories of pollutants and to focus research efforts. New exposure metrics and risk assessment methods, based on understanding of fundamental biological processes, are developed as part of this effort.

Studies of whole buildings are undertaken in field experiments. Relationships between human health, comfort, and productivity and environmental and building factors are investigated in such studies. Whole-building field studies are also undertaken to understand building and subsystem dynamics with respect to energy and air movement and to develop representative databases of building characteristics for modeling energy use in U.S. buildings as well as population exposures to indoor pollutants.

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 developed 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.

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

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

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Energy Performance and Ventilation in Buildings

Existing Buildings Efficiency Research

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

With only a modest growth rate for residential and commercial buildings, most of the short-term energy savings potential is in existing buildings. Besides the energy consumption, comfort is an important issue when retrofitting or rehabilitating buildings. This is particularly important for the residential housing stock. Small commercial buildings offer significant energy savings potential by improving their systems' performance. Part of our effort was to characterize HVAC performance for these buildings and to understand the interactions between the buildings and systems. Work in residential buildings covered duct retrofits in single-family houses, leakage studies in low-rise multifamily buildings, and ventilation studies in high-rise multifamily buildings. In single-family houses, thermal conditioning is usually provided by forced air systems. Besides their poor performance for transporting conditioning energy, duct and system losses due to air leakage and insuffcent insulation increase their energy use and decrease their performance. In low-rise multifamily residences we studied the leakage characteristics before and after rehabilitation and retrofitting. Air flow distribution simulations were performed for a high-rise multifamily building to determine changes in air flow pattern and energy use before and after the building facade was retrofitted.

Packaged Air Conditioners in Small Commercial Buildings

Relatively new 5-ton packaged rooftop air-conditioner/furnaces with some exterior and drop-ceiling ductwork were examined in two strip-mall retail stores in California. The experiments included measurements of distribution-system leakage, distribution-system leakage to outside, the relative leakage on the return and supply sides of the fan, flows through all diffusers/registers, building-envelope leakage, fan power and compressor power, duct and plenum pressures during normal operation, and distribution-system temperatures (all diffusers and plenums) during normal cyclic operation.

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

Because 35%-65% of the ducts were located outside the conditioned space for the three systems, we measured conduction losses from these ducts and examined two means of reducing these losses. A key observation was that surface temperatures were as high as 65°C on the sunlit surfaces of the ducts, whereas the roof-side surfaces were 35°C and the outdoor temperature, 33°C. Increasing the insulation levels to 2" would save 54 watts on the surface of the box and 200 watts on the surfaces of the ducts, whereas painting the surfaces of the box and ducts white would provide thermal energy savings of 70 and 250 watts for the box and ducts, respectively. A 320-watt load reduction would reduce the on-time of a 5-ton system by 2%.

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

Duct Retrofits in Single-Family Residences

A retrofit protocol for residential duct systems was finalized and applied to several houses this year. The protocol includes: 1) a pressure safety test to avoid back-drafting of combustion appliances, 2) a blower-door test to assure that the house will meet ASHRAE Standard 62 ventilation requirements, 3) a step-by-step process to track duct air-tightness during the sealing process, 4) a log to track time requirements for sealing the different parts of the duct system, 5) a detailed, step-by-step procedure for insulating different configurations of duct systems, 6) a procedure for installing return-plenum whistles, and 7) a system for on-site materials and labor accounting.

A major accomplishment was the development and debugging of an automated data-acquisition/transfer/plotting package based upon cellular telephones. The rationale for its development was to improve data quality, minimize loss of data, and simplify analysis procedures. The data acquisition system incorporates the use of thermistors to improve accuracy (±0.2 °C) and provide interchangeability. The cellular phone speeds up data acquisition efficiency by providing immediate feedback of field data. Researchers can view the previous day's data collection with no impact on the occupants.

Monitoring results from the first five houses tested have indicated 40-60% reductions in duct leakage, and 25-45% reductions in conduction losses. The leakage reductions were found to increase register flows by 8% on average. One of the reasons for the lower-than-expected reductions in conduction losses was the fact that a number of ducts were found to be inaccessible for sealing or insulating. The retrofit protocol being tested was specifically designed to be flexible, allowing for substitution of alternative means for locating leaks (e.g., the pressure-pan technique), sealing leaks (e.g., the internal access sealing technology), and insulating ducts (e.g., blown-in duct insulation retained by a cardboard baffle system), all of which should be tested next year.

Ventilation in High-Rise Multifamily Buildings

The DOE-HUD Initiative is a response to the National Energy Strategy's directive to improve the energy efficiency in public housing. Under the Initiative's guidance, a collaborative project has been established to demonstrate energy efficiency in public housing as part of a utility's Demand-Side Management (DSM) Program. The partners in this project include the US DOE Boston Support Office, the Boston Edison Company, the Chelsea Housing Authority, with technical support from the Citizens Conservation Company and two national laboratories—Oak Ridge National Laboratory (ORNL) and LBL.The demonstration site is the Margolis Apartments, a 150-unit high-rise apartment building for the elderly and handicapped, located in Chelsea, Massachusetts, in the greater Boston metropolitan area.

In order to better understand the air flow patterns within the high-rise building, simulations have been performed using the multizone air flow model of COMIS (Conjunction of Multizone Infiltration Specialists). A parametric study was performed taking into consideration infiltration-only, mechanical ventilation, wind speed, wind direction and temperature difference between inside and outside, as well as leakage distribution.

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

The results show that the mechanical ventilation systems cannot avoid cross ventilation or reduce the stack effect significantly. Local exhaust, however, keeps units at a lower pressure than ambient, thus increasing the overall infiltration for the building. Ventilation air supplied to the corridors cannot reduce the cross flow; however, it mixes with the air coming from the windward-side apartments and therefore reduces pollutant concentrations in the air flowing into the leeward-side apartments on the same story.

Leakage Measurements in Low-Rise Multifamily Buildings

Monitoring of two multifamily apartment buildings in Chicago, Illinois, is a collaborative venture between the US DOE and U.S. Department of Housing and Urban Development (HUD) to demonstrate energy-efficient retrofits in federally assisted housing. In Spring 1993 a team of energy researchers from Argonne National Laboratory, the University of Illinois, and Lawrence Berkeley Laboratory performed ventilation and infiltration measurements in two multifamily apartment buildings to determine the leakage characteristics for two types of retrofits and adequate levels of ventilation for air quality throughout the building.

In one of the two buildings, blower-door measurements showed relatively high air-exchange rates. Pressure measurements in wall cavities indicated that internal and exterior walls experienced pressures close to those outside. Construction details of the walls showed that the use of metal studs (Figure), with breakouts for electrical wires, provided holes that connected all wall cavities of a dwelling. Depressurization of one zone caused air flows from the outside through all direct flow paths and through all wall cavities to openings in the walls (e.g., electrical outlets), including interior walls.

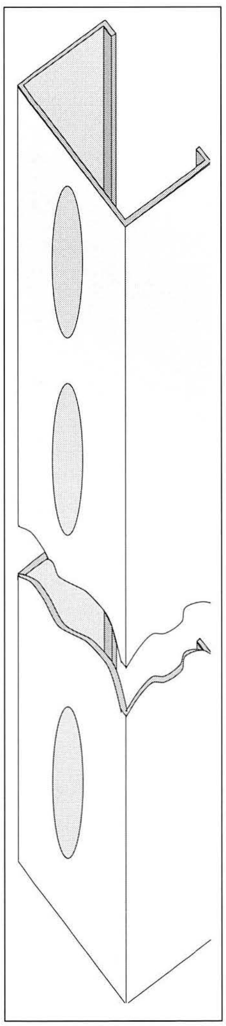

Figure. *Metal stud with breakouts for electrical wires.*

The building constructed with wooden studs had lower leakage levels. The pressure level for interstitial spaces was much closer to the level of the depressurized zone than to the ambient pressure.

In addition, a single-blower-door technique for measuring leakage in multifamily buildings was tested this year in two New York apartment buildings. One apartment was pressurized and depressurized to ±50 Pa, and the resulting pressures were measured in adjacent apartments. By incorporating the pressures measured in the adjacent apartments (1-15 Pa) into a mass balance equation, we were able to calculate that approximately 50% of each apartment's leakage was to outside in one building, and that a significantly larger fraction was to outside in the other.

Thermal Building Simulation Studies

A thermal building simulation program is a numerical model that calculates the response of the building envelope to weather and human activities, simulates dynamic heating and cooling loads, thermal distribution systems, and models building equipment operation. In order to determine the benefits and dangers of simplifying the building description for such a program, we progressively simplified the input files. First, an office building was simulated using the detailed floor plan description, then a simplified version of this floor plan, a very simple floor plan structure, and last, a single room of the building were used.

The simulation exercise showed that the magnitude of differences depends on the thermal regime of the building. The more the interior conditions of the building are controlled by air-conditioning, the smaller the differences introduced by simplification of the floorplans. Depending on the application, situations might occur in which the differences are negligible, and the building simulation can be safely performed using a simpler floor plan geometry. The character of the differences introduced does not depend on the building location in a given climate, or on the building's thermal mass. A study of how simplifying the building floorplan affects the simulation results is recommended whenever simplifications are being considered.

Residential Duct Research

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

Residential thermal distribution systems, which in the U.S. are predominantly duct systems, are a key determinant of space-conditioning energy use. In a recent report we estimated a current savings potential (i.e., application of existing technologies and knowledge) of almost 1 quad/year in 2020, and a full savings potential (with an integrated research/development/dissemination effort) of somewhat more than 2 quads/year in 2020. In 1990, we initiated a multi-year research program focused on understanding and improving the efficiency of residential duct systems. Co-sponsored by the California Institute for Energy Efficiency and the Department of Energy, this research program includes performance modeling, field experiments, technology development, and codes and standards development.

Performance Modeling

An important part of our work this year was to compare basement duct system with attic duct systems, using a new basement duct system prototype. The key findings were that approximately half of the losses to the basement were returned to the house and that the cooling savings potential was particularly small for basement duct systems. As most of the research to date has been focused on houses in the sunbelt with attic and crawlspace ductwork, this type of analysis is needed by numerous groups considering more widespread application of duct improvements, including application to basement houses.

We also performed a sensitivity analysis for an attic only duct system in California. The system included supply-leak sealing, return leak sealing, insulation of supply and return plenums, and added insulation of ducts. We found that: 1) the average duct efficiencies and percentage energy savings did not vary dramatically over the state, 2) the impact of most duct improvements was 2-4 times larger on minimum duct system performance compared to with average performance, 3) the dollar savings to the consumer was close to equally split between gas and electricity savings for gas-furnace/A/C systems, 4) approximately 15% of the savings theoretically provided by a retrofit was "taken-back" because of the lower equipment efficiencies associated with duct improvements, 5) cost-effectiveness calculations are hampered by uncertain cost estimates, and 6) although complete improvement packages were often cost-effective considering consumer savings only, variations in retrofit labor costs could easily push this result in either direction.

Field Experiments

We initiated a study of duct retrofit protocols including duct sealing and insulation retrofits. The energy impacts of residential duct retrofits are discussed in the Existing Buildings Efficiency Research section of this report. That study has also provided detailed data on the interactions between duct systems and houses. Modeling work in FY92 indicated that thermal siphon heat exchange could be significant, at least in a duct system that incorporated an attic return and crawlspace supplies. The thermosiphon effect is a natural convection air flow that can be set up between cycles in a residential duct system. Field measurements of air temperatures in all of the supply grilles in the first two test houses indicated that there was indeed a thermal siphon set up in even an attic-only system. Several of the supply grilles remained at room temperature between cycles, whereas several others decayed to a temperature very close to the attic temperature. Our explanation is that a continuous circulation loop was set up in the duct system as a result of asymmetric cooling of the ducts between cycles. If one duct cools more quickly than another, warmer house air is drawn up the warmer duct, which, combined with the cooling by conduction in the second duct, creates a stable stack effect, and thus a stable circulation loop. In the second house a thermosiphon flow was set up by a 1-ft. differential between the heights of ceiling/wall supply registers, even in cooling mode. These thermal-siphon findings provide evidence of an additional energy impact of duct systems which has not been incorporated into duct-system energy analyses.

Another field experiment performed over the past year was a case study of the performance of a residential zone conditioning system. The principal findings of this case study were confirmation of the dominance of thermal stratification over zoning efforts (at least in an open floorplan), confirmation of the importance of commissioning to assure airtight ducts, and an indication that conditioned-space ductwork can significantly reduce losses to outdoors.

Technology Development

The most significant results from our technology development work involved aerosol-based sealing technology. By accessing leaks from inside the duct, this technology should be able to remotely seal inaccessible ducts and simplify the sealing process in moderately accessible systems. Laboratory experimentation and theoretical modeling confirmed that slot-type leaks 3-5 mm across, as well as 1-3 mm joint-type leaks, could be sealed within 30 minutes even when located 3-5 meters and several bends or wyes from the aerosol injection point. We verified our predictive models of the sealing process by videotaping it (Figure). We can now predict the sealing behavior of the aerosol as a function of various parameters affecting the process.

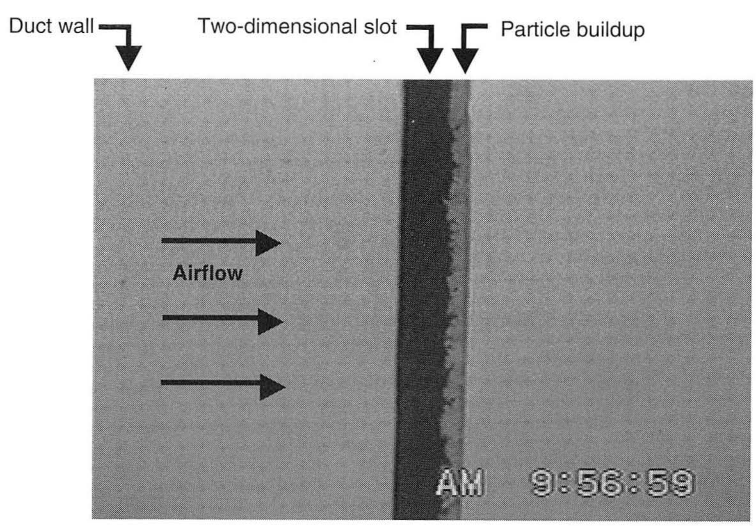

Figure. *Top view of a 3-mm × 40-mm leak after 20 minutes of aerosol injection.*

In addition, we completed the conceptual design of a field apparatus. We found that sealing could be achieved even with the end of the duct completely sealed (i.e., with the only airflow through the duct being that passing through the leaks). Less aerosol will be wasted, and fewer problems with injection into occupied spaces will be encountered in the field. Preliminary specifications for a field device indicate that an apparatus to simultaneously seal 12 supply branches can be assembled from standard parts.

Codes and Standards

A significant barrier to improving the energy efficiency of residential duct systems is the present lack of appropriate incentives for improvement. Our codes and standards efforts are directed towards addressing this barrier. We had two major standards accomplishments this year. ASTM approved our proposed test method for measuring duct leakage in the field (E1554), and under our direction, ASHRAE initiated a Standards Project Committee (SPC152P) to develop a method for determining the efficiency of residential thermal distribution systems. The result should be a yardstick to compare the efficiencies of ducts in attics with those located crawlspaces or basements, as well as with hydronic distribution systems. The ASHRAE committee can specify the ASTM test method as a means of obtaining data needed for characterization. These two standards represent important strides toward appropriate rewards and penalties for distribution-system efficiencies.

Reduction of Electricity Demand for Residential Cooling

M. Modera, H. Feustel, B. Treidler, J. Warner

From the point of view of electric utility companies and of society in general, residential air conditioners can result in a rather poor use of resources. More specifically, because residential air conditioners often represent the largest power draw in a house, and most houses require air conditioning at approximately the same time, residential air conditioning represents a large fraction of many utilities peak power demand. Moreover, they also often represent the largest single load on local electricity distribution systems and transformers. This problem is particularly severe in an arid climate such as is found in California, where the shape of the residential cooling load is particularly peaked due to low latent loads and relatively cool nighttime temperatures. In such a region, large investments in wires, transformers, and generation facilities must be made to serve a load that is not only large but also infrequent. The load factor (the ratio of average air-conditioner draw to maximum air conditioner draw) is typically less than 10% for residential air conditioning in California, whereas the load factor for cooling large commercial buildings is more like 30%. To address this issue, we recently initiated two research programs, one of which is part of an effort to eliminate completely the need for residential air conditioners in transition climates. The other involves improvement of overall air-conditioning-system per-formance during peak demand periods.

Improved Systems for Residential Space Cooling

The key focus of this research effort is to obtain a better understanding of the performance and operation of residential cooling equipment during peak electricity demand periods. The chosen approach involves improving our simulation capabilities, and using detailed field measurements to analyze the factors impacting peak demand. The simulation effort involves not only improving our ability to model the interactions among building envelopes, cooling equipment and duct systems, but also improving our understanding of the combinations of operating patterns and air conditioner size that are most frequently encountered. We ascertain the relative frequency of different operating patterns and air conditioning size combinations analyzing random samples of submetered air conditioner electricity demand usually used for utility load research purposes. The operating patterns include people who utilize a thermostat to control the air conditioner (perhaps including night setup), and people who use the thermostat as a switch, including those who leave the AC off all day and turn it on when returning from work, or those who only turn on the air conditioner when the temperature rises to an unbearable level.

Our sensitivity analysis work on California duct systems also included a preliminary examination of the performance of duct systems under peak demand conditions. In that effort it was found that a sealing and insulation retrofit (sealing 90% of the leaks and insulating up to R-8) that provided a 17% energy savings yielded a 45% improvement in the minimum performance of the duct system. Because the sizing of an air conditioner should depend on the product of its capacity and the duct system efficiency, both evaluated under peak weather conditions, this retrofit would theoretically allow the air-conditioner to be down-sized by 45% without adversely impacting the comfort of the occupants. This assumes that the minimum duct efficiency is coincident with the maximum demand on the air conditioner. Because there can be significant first-cost savings associated with purchasing smaller equipment, this result suggests that duct-repair pro grams targeted to new construction or equipment burn-out in existing construction could possible be paid for by reductions in cooling equipment size.

Development of Smart Ventilative Cooling Systems

Ventilation has been identified as a prime candidate to replace compressor cooling in transition climates. Ventilative cooling refers to any cooling strategy that utilizes outdoor air in the cooling process. There are two basic ventilative cooling approaches: direct cooling ventilation, in which ventilation air is supplied as cooling is desired, and thermal storage ventilation, in which ventilation air is supplied primarily during off-peak hours to reduce the temperature of the thermal mass in a building.

Direct cooling ventilation works by removing internal heat gains. The cooling effect of direct ventilation is enhanced because people feel cooler when air is moving over them. This method is used typically in climates that are not extreme (outdoor temperatures below 32°C) and that have small (less than 10 K) diurnal temperature swings. For example, it appears to work well in Hawaii.

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

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

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

Ventilation: Energy Liabilities in U.S. Dwellings

M. Sherman, N. Matson, D. Dickerhoff, B. Smith

Infiltration and ventilation are conventionally believed to account for one third to half of the space-conditioning energy used in dwellings. However, little measurement data or analysis substantiates this assumption. The purpose of this project is to use existing data to estimate the energy and ventilation liabilities in the current U.S. housing stock as well as in scenarios based on energy conservation and ventilation strategies (Figure). The LBL infiltration model and its derivatives will be used as the basis for the calculation.

Modeling each of the almost 75 million single-family households in the U.S. would require more data and human resources than currently exist. Our approach is to use data from available sources and combine them at an appropriate level of detail using database management tools.

We employed 32 different housing classification categories: old vs. new (using 1970 as a dividing point); single-story vs. multistory; poor condition vs. good condition; duct systems vs. none; and floor leakage vs. no floor leakage. The Residential Energy Consumption Survey (RECS) data is used to determine, for each of the nine census divisions, the average floor area, percentage of air conditioning use and number of houses for each of the 32 house types. The available (but limited) leakage data from the Air Infiltration and Ventilation Centre (AIVC) is used to determine representative leakage data for each house type. Every county within a given division is assumed to have the same relative distribution of house- types, where the number of houses in each county is determined from the census data and is the total of the number of single-family detached, single-family attached and mobile home dwellings. For each county, the most representative U.S. weather site is used, based primarily on geography.

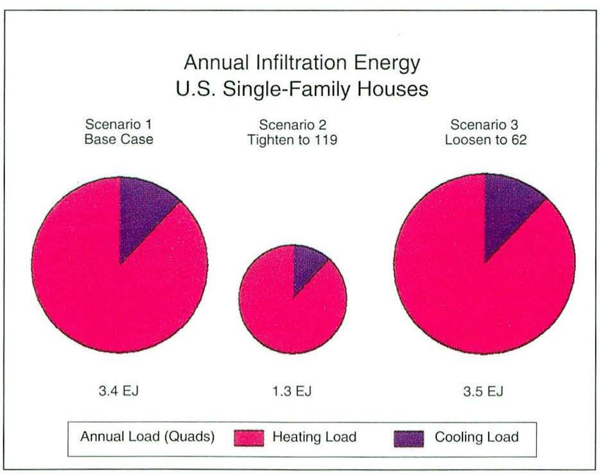

Figure. *Estimated residential energy load for U.S. housing stock and for two alternative scenarios.*

The fundamental relationship between the infiltration and the house and climate properties is expressed by the LBL infiltration model, which has been incorporated into the ASHRAE Handbook of Fundamentals. The LBL infiltration model is used to generate, on an hourly basis, specific infiltration and air flow rates. From these hourly results, seasonal average air change rates and corresponding energy consumption, as well as overall measures of tightness and rates for adequate ventilation, are determined.

The houses used in this analysis are selected to reflect the current U.S. single-family-housing stock, including almost 75 million households (86% of the total U.S. residential housing floor area). This scenario can be considered as the base case because it represents our best estimate of the housing stock. The same approach is used to consider two alterrnative scenarios: the "119 Case" and the "62 Case." These names reflect the ASHRAE Tightness and Ventilation standards that they respectively follow. For the "119 Case," any houses that do not meet the tightness standard are tightened to meet the standard. Conversely, for the "62 Case," any houses that do not meet the ventilation standard are loosened until they meet the standard.

Our results would indicate that the

national average effective annual air change rate is 0.83 ACH with a 19% standard deviation, based on county-averaged air change rates. Of real importance, however, is the compliance with the tightness and ventilation standards, Standards 119 and 62 respectively. Due to the looseness of the U.S. housing stock, 88% of the base case houses meet Standard 62, the standard for adequate ventilation. Conversely, 50% of the houses meet Standard 119, the tightness standard. Of interest is the fact that 38% of houses which meet both standards, implying that some balance between lower energy consumption and increased indoor air quality has been achieved for certain climates. Only a small portion of houses meet neither standard, and are too loose to meet the tightness standard but not loose enough to meet the ventilation standard.

If the houses in the base case are tightened to meet Standard 119, the tightness standard, the national average effective annual air change rate is smaller than that of the base case, at 0.34 ACH with a 20% standard deviation. As most of the houses are quite loose and have to be tightened to meet Standard 119, the percentage of houses which meet Standard 62 drops from 88% to 49%.

If the houses in the base case are loosened to meet Standard 62, the ventilation standard, the national average effective annual air change rates is slightly higher than that of the base case, at 0.87 ACH with a standard deviation of 16%. As most of the houses in the base case already meet Standard 62, the corresponding percentage of houses that meet Standard 119 drops slightly from 50% to 47%.

We summarized, on a national basis, annual heating, cooling and total infiltration energy consumption for the base case and each of the two scenarios (Figure). By modifying the housing stock to meet Standard 119, the potential national energy savings are projected to be up to 2.1 EJ/year (28 GJ/house/year). However, at the same time, the number of houses which meet the ventilation standard drops from 88% to 49%. The converse case, loosening the housing stock to meet Standard 62, results in a potential national increase in energy consumption of 0.1 EJ/year (1.3 GJ/house/year).

From an indoor-air-quality perspective, it is tempting to propose that existing houses be loosened to meet Standard 62. From an energy perspective, however, knowing that it is possible to save up to 28 GJ/house/year by tightening the houses, another tack should be taken. For much of the country, strategies such as mechanical ventilation and heat recovery could be utilized to create a middle ground and insure maximizing energy savings as well as provide adequate ventilation.

The 2 EJ potential infiltration savings cannot be tapped without accounting for the addition of mechanical ventilation systems in some climates. A true economic analysis requires fuel prices and heat recovery option efficiencies as well as the standard economic data. The huge potential savings, however, justifies an increased emphasis on residential ventilation.

Although the efforts reported here have begun to address the problem, they are only a beginning. The level of detail in key databases and the range of options considered are somewhat limited. Future work will focus on three main issues: the leakage database, evaluation of mechanical ventilation options and expansion to include analysis of the multifamily building sector. A request for U.S. single-family-home leakage data is being circulated to practitioners and researchers, and responses are currently returning to LBL. Work is underway to evaluate mechanical ventilation options, first for the states of New York and California, and eventually for the country as a whole.

Thermal Energy Distribution in Commercial Buildings

H. Feustel, M. Modera, B. Smith, C. Stetiu, B. Treidler, F. Winkelmann

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 passes through generally inefficient thermal distribution systems in buildings. Because the load shape due to inefficient distribution systems is often more peaked than general space cooling demand, distribution efficiency improvements can provide even larger savings in peak electricity demand.

Characterization of Thermal Distribution Stock

Our effort to assess the opportunity for savings involves several issues: fan power reduction as a large-building retrofit, thermal loss reduction for packaged units, development of improved design tools, increased application of hydronic-systems, reduction of uncontrolled airflows, and Indoor Air Quality (IAQ) implications of thermal distribution alternatives.

To arrive at savings opportunity assessments, we needed to characterize the thermal energy distribution stock in the United States. Our data suggest that the distribution of HVAC systems in California is quite different from the rest of the nation. Whereas there is a significant national trend toward variable air volume (VAV) systems in new construction (75% of all central systems in the last ten years), our stock characterization indicates only 19% VAV systems in large California office buildings (the predominant user of central systems).

In order to assess the savings potential, we determined the systems' penetration for each building type, because different HVAC systems have different fan power consumption. From the California Energy Commission (CEC) forecast data and a utility survey, we deduced the following division of HVAC systems into a small number of categories. As expected, small office buildings (>80%), restaurants (50%), food stores (95%), and warehouses (95%) are conditioned mostly by packaged equipment. Large office buildings (>90%), colleges (65%) and hospitals (60%) are more often equipped with central systems. Units without thermal distribution systems are most common in hotels/motels (>60%). Hydronic distribution systems are installed in much smaller numbers than air ducts. Only 6% of the offices, 12% of the hotels, and 8% of hospitals are equipped with fan coils. Only one percent of offices and hospitals are equipped with induction units.

Fan Power Reduction and Thermal Loss Implications

A prototype office building was used to investigate the characteristics of several thermal distribution systems for two California climates (Fresno, central valley, hot summers; and San Jose, coastal city, more moderate annual climate). When comparing the fan power consumption for different systems with no thermal losses (i.e., leakage or conduction), one sees that the smallest fan power is consumed by the hydronic system. The savings potential is about 80% when compared with constant volume systems and approximately 60% when compared with VAV systems.

Fan power consumption for VAV systems is approximately 47% of the fan power consumption for constant volume systems. Compared with the VAV system, the constant volume systems use between 70% and 90% more electricity to cool the building. This difference is due to different chiller COPs (coefficient of performance). While direct expansion systems (used for constant-volume simulations) typically have a COP of 2.5 to 3.0, chilled water systems (used for VAV simulations) reach COP values of 5.0. Fan power consumption is approximately 20% of fan and cooling power consumption for the hydronic system, 35% for the VAV system and about 40% for the constant volume systems. For the two climates, hydronic systems use 74% of the fan and cooling energy used by VAV systems and 40% of the energy used by constant volume systems. VAV systems save 48% in fan and cooling energy consumption when compared to constant-volume system.

A limited examination of the fan-power implications of thermal losses from supply ducts to ceiling return plenums was also undertaken. Thermal losses to the return stream represent short circuiting, and therefore increase the required fan power. For example, a 25% thermal loss would in theory produce a 137% increase in the required fan power. Although thermal losses cannot be eliminated completely, this analysis provides an impetus for more careful examination of thermal losses in ceiling return ductwork.

Hydronic Thermal Distribution

Energy consumption for cooling of nonresidential buildings can be reduced several ways: by reducing the cooling load of the building, reducing the requirements of mechanical cooling, and improving thermal distribution within the building.

A significant amount of the electrical energy used to cool buildings with all air systems is drawn by the fans used to transport cool air through the ducts. If ventilation and thermal conditioning of buildings are separated ("Air-and-Water Systems") the amount of air transported through buildings can be reduced significantly. In this case, the cooling would be provided either by convection (e.g., fan coils) or by radiation and convection (e.g., cooled ceilings). Water is used as the transport medium, and the ventilation is provided by outside air systems without recirculating the air. Due to the physical properties of water, hydronic thermal distribution systems can remove a given amount of thermal energy using less than 5% of the fan energy otherwise necessary.

Hydronic Radiant Cooling

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

Most hydronic radiant cooling systems can be categorized in three different design categories. The most often used system is the panel system, which uses suspended aluminum panels connected to metal tubes. The second system contains cooling grids made of small plastic tubes placed close to each other. The grids can be imbedded in plaster, gypsum board, or mounted on metal ceiling panels. The third system is based on the idea of a floor heating system. Metal or plastic tubes are imbedded in the core of a concrete ceiling. The thermal storage capacity of the ceiling allows for peak shifting.

When compared with conventional "All-Air-Systems," hydronic radiant cooling systems show several advantages. Owing to the large surfaces available for the heat exchange, the coolant temperature is only marginally lower than the room temperature. This allows the use of either heat pumps with high COP values or alternative cooling sources. The reduced air supply not only reduces the fan power requirement, but reduces noise and draft thus enhancing human comfort. In combination with a displacement

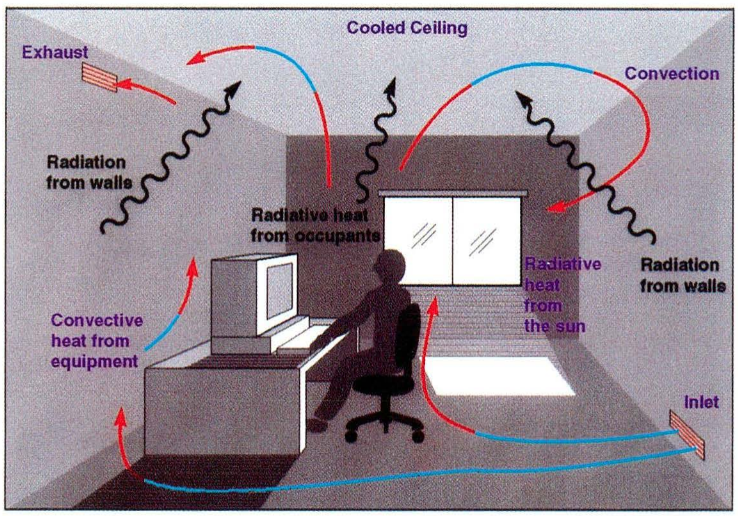

Figure 1. *Radiative and convective heat exchange in a room with a cooled ceiling.*

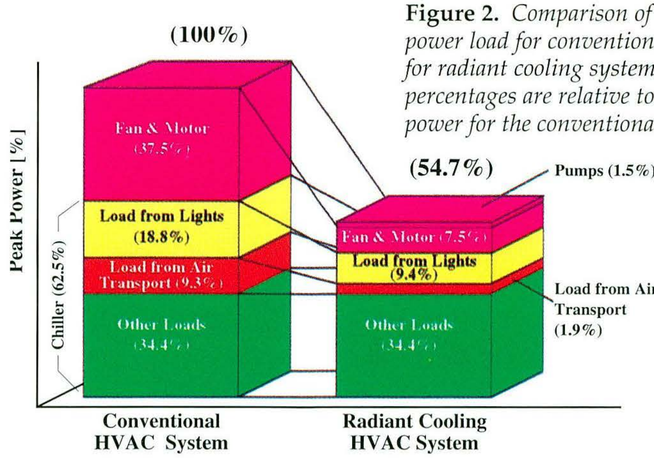

Figure 2. *Comparison of electrical peak power load for conventional systems and for radiant cooling system. For the latter, percentages are relative to overall peak power for the conventional system.*

ventilation system, an even temperature distribution can be achieved in the space. Reduced convective heat transfer improves the level of thermal comfort for the occupants (Figure).

The power reduction potential of hydronic radiant cooling systems is in the order of 40% when compared to conventional "All-Air-Systems" (see Figure 2). If alternative cooling sources are applied, the savings potential increases significantly. Energy analysis programs such as DOE-2 do not have the capability to simulate hydronic radiant systems. There have been attempts to adapt DOE-2 to the task. The consensus is that a separate module needs to be designed to model the hydronic radiant cooling, including the two-dimensional heat transfer in concrete slabs. Such a model is presently being developed together with LBL's Building Energy Simulation group in the SPARK (Simulation Problem Analysis Research Kernel) environment.

International Studies in Ventilation

H. Feustel, B. Smith, P. Suter, J. Warner

Awareness of infiltration as a major factor in the overall conditioning load of a building has led to tighter construction both of building components and the overall building shell. This has decreased the infiltration rate and its related ventilation heat loss and cooling requirement but sometimes creates another problem with regard to indoor air quality. The air mass flow distribution in a given building is caused by pressure differences evoked by wind, thermal buoyancy, mechanical ventilation systems or a combination of these. Airflow is also influenced by the distribution of openings in the building shell and by the inner pathways.

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

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

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

Annex 23

Within the framework of a technical committee, known as an annex, established by the Energy Conservation in Buildings and Community Systems program of the International Energy Agency (IEA), we are studying physical phenomena causing air flow and pollutant transport (e.g., moisture) in multizone buildings. An important part of this annex is the comparison between model results and results from *in situ* tests. Before these data sets could be used for model evaluation, however, internal model comparisons based on benchmark buildings had to be made.

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

Subtask 1: System Development
A multizone air flow and pollutant transport model is being developed on the basis of the COMIS model by developing flexible expert routines, incorporating additional modules, and developing user-friendly interfaces for input and output.

Subtask 2: Data Acquisition
Data sets are being obtained for evaluation and as input for the model.

Subtask 3: System Evaluation
The model is being evaluated using intermodal comparisons as well as data obtained from subtask 2.

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

In 1993 COMIS 1.2 was tested and was distributed to interested parties. It includes calculation of two-directional airflow through large vertical openings (e.g., door ways) due to air density differences (i.e., temperature differences or humidity differences in rooms connected by large openings). The User Guide has been updated to reflect the status of the program. Measurements have been performed to obtain data to be used in the evaluation exercise. Intermodal comparisons have been performed, and the results of a first user test have been analyzed.

Due to its international character, COMIS is expected to become a standard in multizone air flow modeling. So far we have more than twenty requests for the model. The latest requests for COMIS came from India and Israel. COMIS is currently being used in Belgium, Canada, China, France, Germany, Great Britain, Italy, Japan, The Netherlands, Sweden, Switzerland, and the United States. LBL's Energy Performance of Buildings Group is using the model for several of the studies currently being performed and is planning its use for future work. COMIS is currently used for the "Duct Leakage Study" performed for the California Institute of Energy Efficiency (CIEE), the "Modeling Radon Entry into Florida Crawlspace Homes" project co-sponsored by EPA and the State of Florida, and the "Alternatives to Compressor Cooling" project sponsored by CIEE.

We have received inquiries about COMIS from around the United States: Florida Solar Energy Center (FSEC), Penn State University, California State University Sacramento, the National Institute of Standards and Testing (NIST), Florida State University, the U.S. DOE-Bonneville Power Administration, and the Massachusetts Institute of Technology (MIT). Distribution of COMIS in the other member countries has not been documented.

Lawrence Berkeley Laboratory is managing the annex on behalf of the U.S. Department of Energy. By the end of FY 1993 Belgium, Canada, France, Greece, Italy, Japan, The Netherlands, Switzerland and the U.S.A. had officially committed to participate the annex.

Indoor Radon Research

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

A.V. Nero, M.G. Apte, D.A. Nolan, P.N. Price, K.L. Revzan, H.A. Wollenberg

Radon concentrations in homes vary substantially from one area to another, so that the homes with particularly high levels—e.g., exceeding 20 pCi/l (740 Bq/m^3)—tend to cluster geographically. We are developing a statistically based methodology to provide estimators of the indoor concentration distribution by area, and hence to focus monitoring and control efforts more effectively. The aim is to use existing data on indoor concentrations and on causative physical factors (such as soil, housing, and meteorological characteristics) to provide estimators on scales as small as individual census tracts (populations of about 4000 people).

Initial efforts in Minnesota and New York demonstrated the efficacy of our broad statistical approach, using a limited array of data analyzed at the county level. We also began to implement the statistical, database, and geographical information systems necessary to support a more comprehensive analytical approach, and to examine more thoroughly the availability and predictive power of various types of physical data.

A substantial effort has also been devoted to investigating statistical analytical approaches that could effectively make use of a wider range of data types and that could also more clearly determine the uncertainty in the concentration estimates that result from each approach. For our initial case of Minnesota, for example, the use of surficial radium data alone to predict county geometric-mean indoor radon concentrations can yield an R^2 of 0.6. This investigation is therefore providing a firmer foundation for using correlation analyses of this type for making estimates of geographically linked environmental parameters.

To incorporate meteorological information into such analyses, we have developed a national database that provides a range of direct and inferred meteorological parameters by county across the United States. This database is being used for performing an analysis of the results of a national survey of indoor radon concentrations and associated housing characteristics that was conducted by the Environmental Protection Agency. We are also beginning to use it in regional or statewide analyses. The database can also be used for other analytical problems besides identifying high-radon areas.

We have also added a third demonstration area to our efforts, Washington state, where state agencies have already been developing geological data for determining the local radon "potential." Our preliminary analyses, however, have relied primarily on surficial radium data as a predictor of indoor concentrations, using either short-term monitoring data from the EPA or long-term monitoring data from the Bonneville Power Administration. We are now focusing on ways to incorporate geological information into these analyses, relying particularly on our collaborators in this effort at the U.S. Geological Survey.

Ultimately, the aim is to yield a topographical map of indoor radon concentrations across the United States. The map will be used for the efficient and rapid identification of homes having very high levels.

Radon Sources And Emanation Rates in Soil at an Experimental Basement Site in Ben Lomond, California

S. Flexser, H.A. Wollenberg*, A.R. Smith†*

Radon in soil gas has its ultimate origins in the precursor elements radium and, originally, uranium, associated with minerals in the soil and parent rock. At the site of the Small Structures project in Ben Lomond, CA, where entry of soil-gas radon into experimental basements is being studied, structures were built in a relatively simple residual soil developed on granitic rock. The distribution of uranium and radium in soil and bedrock, as well as characteristics of radon emanation, were investigated at this site in order to better understand radon generation and its potential for transport through soil.

The concentrations of the radioelements Ra, Th, and K were determined for bulk soil taken from regular depth intervals, mainly from core and auger samples. Also determined for these samples was radon emanation, which is the fraction or percentage of Rn generated within solid phases that actually escapes into soil air or water. The pattern of variation of Rn emanation in the bulk soil samples approximately correlates with the gross zonation observed in the soil (Figure, next page at left), with highest emanation occurring in a transitional zone between shallow loamy soil and underlying granitic saprolite (highly weathered but intact parent bedrock). This suggests a relation between emanation and processes of soil formation. By contrast with emanation, the radioelement concentrations do not show a correlation with soil zonation. Instead, the main radioelement variations result from variability in composition of the

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parent rock, with rock fragments compositionally and texturally distinct from the main phase of the granitic parent abundant in soil samples most elevated in Ra, Th, and K (e.g., between 80 and 120 cm depth).

On the microscopic scale, uranium is associated both with primary minerals and with secondary (weathered) sites in the soil and parent rock. Secondary sites were of greater significance for this study, as uranium and radium were preferentially concentrated there near grain boundaries and pore walls, so that recoiling Rn atoms emanated much more readily than from primary minerals. Uranium-bearing secondary sites in the soil were mainly weathered mineral grains and iron-rich grain- and crack-coating materials. Significant uranium was also present in fractures in the saprolite, where it was associated with dense iron-rich fracture coatings, and with a secondary phosphate mineral. The preferential distribution of uranium and, by inference, radium on grain boundaries, cracks, and porous weathered minerals is reflected in relatively high radon emanation rates in the soil, between 28% and 48%. The highest emanation rates occurred in the depth interval between 1.3 and 2.3 m (Figure). It appears that mobilization of uranium and radium from secondary sites during soil-formation results in their redistribution, on a very local scale, by surface sorption onto colloidal particles in this depth interval, with a consequent increase in emanation rates.

In the underlying saprolite, the combination of increased depth and emanation values lower than those in the transitional zone might suggest that radon generated there would be a minor component of near-surface soil-gas radon. However, the localization of uranium along near-vertical fracture zones common in the saprolite, which may serve as permeable conduits for fluid flow, suggests that radon derived from deep in the saprolite could contribute significantly to shallow soil-gas radon.

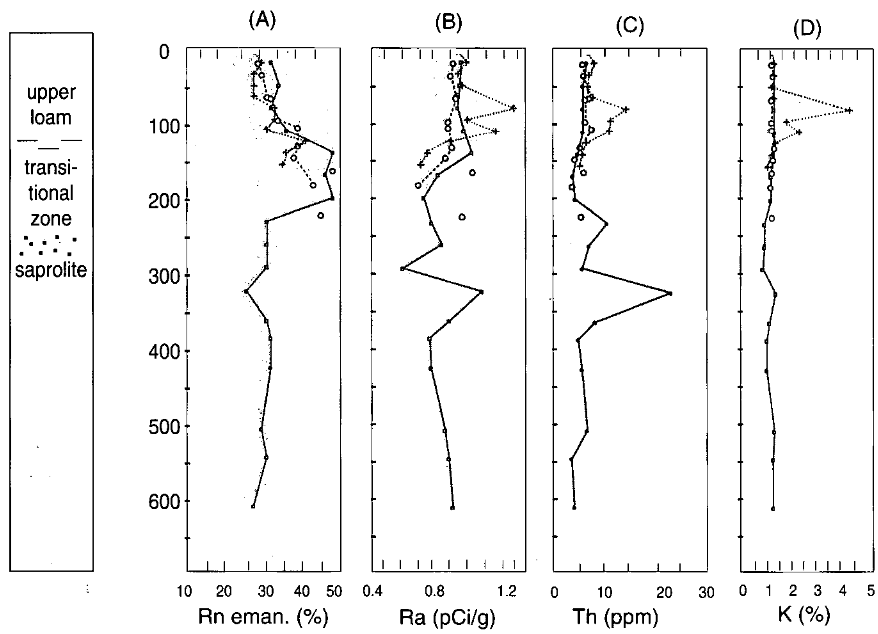

Figure. *Radioelement abundances and radon emanation rates of soil from core and auger samples (solid and dotted lines, respectively), and from walls and floor of the structure excavations (circles). Analyses by gamma-spectrometry. Soil zonation depicted schematically to left.*

Two-Filter Method for Measuring the Diffusivity of Unattached ^{218}Polonium

A.G.B.M. Sasse, A.J. Gadgil, W.W. Nazaroff

The radioactive decay product of radon-222 is polonium-218, which itself is radioactive. Once formed, a fraction of the isotope gets attached to ordinary indoor-air aerosols; this fraction is commonly called "attached." The remaining fraction is called "unattached." The unattached fraction has higher diffusivity, and as a result, per unit of inhaled dose, a significantly larger fraction of unattached isotopes get deposited in the respiratory tract compared to the attached isotopes. Diffusivity of unattached ^{218}Po is one of the important governing parameters in determining the fate of the newly formed ^{218}Po (i.e., the fraction of the ^{218}Po isotopes that get attached, the fraction that gets deposited on to the room surfaces, and the fraction that deposits in the lungs and other parts of the respiratory system).

The two-filter method used to measure the diffusivity of unattached ^{218}Po uses a tube with filter at both ends. Aerosol-free air with a known concentration of ^{222}Rn is passed through the tube. The radon decays in the tube, and produces unattached ^{218}Po. Some of this polonium decays, some migrates by diffusion and deposits onto the tube walls, and the rest is collected on the downstream filter. In the usual application of this method, the ^{218}Po activity on the downstream filter in relation to the ^{222}Rn concentration in the air is interpreted to determine the diffusivity of ^{218}Po (see Figure, next page).

The interpretation scheme is based on a theoretical analysis of the ^{218}Po transport and production in a tube by earlier researchers. However, their analysis did not consider the radioactive decay of the airborne ^{218}Po inside the tube, and changes in the fluid flow in the tube caused by the downstream filter, and the resulting effects of these phenomena on the deposited activity on the downstream filter. The earlier analysis also assumed simplified flow profiles throughout the tube.

In this study, the two-filter method was reanalyzed numerically, from first principles. Continuity equations and Navier-Stokes equations for air, and equations for species concentration (including generation and decay of ^{218}Po) were solved to reinterpret experimental data more accurately. The results of this new analysis led to a 10-20% reduction in the reported diffusivities of ^{218}Po.

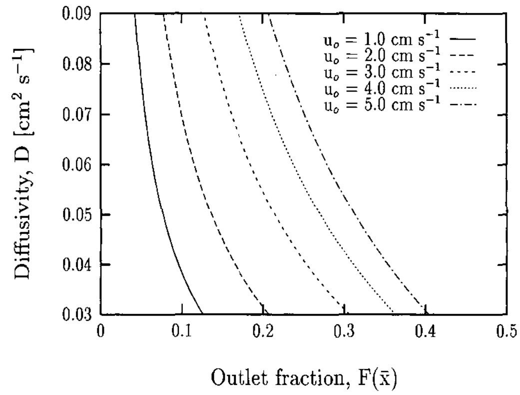

Figure. *Diffusivity of ^{218}Po (interpreted using the correct calculations) as a function of the calculated ^{218}Po fraction collected at the outlet filter. (The rest of the ^{218}Po deposits on the tube walls or decays.) This fraction is obtained by dividing the rate of deposition of ^{218}Po on the downstream filter by the rate of production of ^{218}Po in the tube by radioactive decay of ^{222}Rn. Comparison of experimental measurement of the fraction with theoretical predictions permits determination of ^{218}Po diffusivity. Results are shown for a range of mean air velocities (1.0 cm/s to 5.0 cm/s) in the tube. Calculations are for tube length of 100 cm and tube diameter of 1.585 cm.*

Use of Two Basement Structures to Study the Influence of a Gravel Layer and Open Area on Radon Entry Rate

A.L. Robinson, R.G. Sextro, W.J. Fisk

We have used our two basement structures located near Ben Lomond, CA, to study the effect of gravel and open area on radon entry. These two structures are identical except for the presence of a subslab gravel layer underneath the West structure. Both structures communicate with the surrounding soil environment through six precisely constructed slots, each 0.003 m wide and 0.86 m long extending through the floor, or through four 1.3-cm-diameter holes in the floor slab. The slots simulate the shrinkage gap that occurs in actual houses between footers and poured concrete floors. We have attempted to seal all other (unintentional) openings between the structure and the surrounding soil to close off any uncharacterized soil gas entry points.

We compared the steady-state advective radon entry rate through characterized openings into both structures as a function of open area (Figure). All of these measurements were made at a structure depressurization of -20 Pa. In the West structure the radon entry rate rapidly increases with increasing open area, quickly reaching a maximum entry rate of 16 Bq/s. In contrast, in the East structure the radon entry rate slowly and continually increases with increasing open area. When all six slots are open, the advective radon entry rate into the West structure is almost four times greater than the radon entry rate into the East structure.

The subslab gravel layer provides the explanation for the difference in radon entry rate response to open area in the structures. At the pressures used for these experiments, the flow resistance of either the slots or holes is negligible. In the West structure, the asymptotic limit of radon entry rate with respect to open area is effectively reached when the entire gravel layer is uniformly depressurized, which maximizes the flow of radon-bearing soil gas into this subfloor layer. Increasing the open area beyond this point does not increase the radon entry rate because the entire gravel layer is already at the same pressure as the structure. As can be seen in the figure, even one slot appears to be sufficient for depressurizing the gravel layer uniformly. Only when the open area consists of the holes in the floor is a pressure gradient detected in the gravel layer itself, and this pressure gradient leads to a somewhat lower radon entry rate. In contrast, in the East structure where there is no interconnecting high permeability region, the different slots or holes act almost independently of each other. Consequently, as the open area through the floor increases the size of the depressurized soil zone increases, drawing more radon-laden soil gas into the structure.

Our results also demonstrate that reducing the radon entry rate by sealing cracks or other openings in houses with an underlying gravel layer is likely to be very difficult because even a small open area can lead to significant soil-gas entry. This is consistent with the anecdotal observations by radon mitigators, who report difficulty in achieving substantial reductions in indoor radon concentrations by finding and fixing leaks.

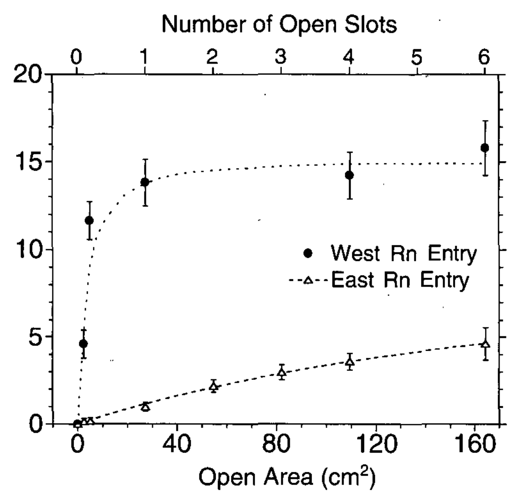

Figure. *Comparison of steady-state advective radon entry rate as a function of open area, measured at -20 Pa structure depressurization. West structure contains the subslab gravel layer; East structure sits directly on the natural soil. The first three data points for each structure represent, respectively, radon entry with 1) all slots and holes sealed, 2) two holes open, and 3) four holes open. The remaining points represent values obtained with various slots open and the four holes sealed. (Dashed lines serve only to guide the eye.)*

Impacts of a Subslab Aggregate Layer and a Sub-Aggregate Membrane on Radon Entry Rate: A Numerical Study

Y.C. Bonnefous, A.J. Gadgil, K. Revzan, W.J. Fisk, W.J. Riley

A layer of gravel is often laid down on the bare soil before the floor slab of a building is poured. This layer can increase the radon entry rate into the house by up to a factor of 5. We first used a previously tested numerical model to investigate and confirm this phenomenon and to assess the increase in radon entry rate as function of soil and gravel permeabilities. The model predictions (Figure) show how indoor radon concentration would depend on the soil permeability and subslab gravel permeability. Enhancement of indoor radon concentrations owing to the gravel layer was significant for almost all soil permeabilities investigated.

We then used the model to show that placement of a membrane under the gravel layer (i.e., placing the membrane on the bare soil before laying down the gravel layer) can substantially negate this increase in radon entry rate. The effect of the membrane would be seen even if the membrane did not perfectly cover the soil-bed—if, for example, it fell 10 cm short of reaching the foundation footer all along its perimeter.

With the help of the model, we analyzed why the membrane can be such an effective barrier to radon entry. If the right material is selected for the membrane, it is an effective barrier to diffusive entry of radon from the soil into the interstitial air in the gravel layer. The membrane is also impermeable to flow, limiting advective entry of radon bearing soil gas into the gravel bed, and thence into the house. This effect is akin to the lower entry rate of radon-bearing soil gas into basements of houses built without a subslab gravel layer.

Research using the model also predicts that such a subgravel membrane would greatly improve the performance of active subslab ventilation (SSV) systems for indoor radon mitigation and would also make passive systems more promising.

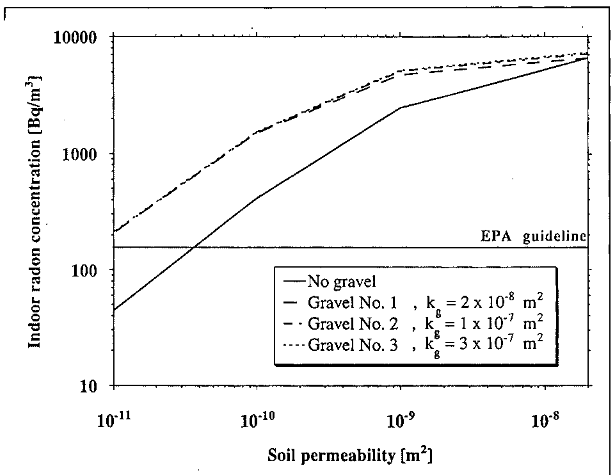

Figure. *Predicted radon concentration in a "typical" house (50-m² basement area, 245-m³ house volume, air exchange rate of 0.4 ACH) located in a hypothetical region where the radon concentration in deep soil is 59,000 Bq/m³. Basement is assumed to be depressurized to -10 Pa. Solid line represents values predicted for the case where subslab gravel layer is absent.*

Recent Results in Resolving the Model-Measurement Discrepancy of Radon Entry into Houses

K. Garbesi, R.G. Sextro, W.W. Nazaroff

Mathematical models have consistently and significantly underpredicted rates of advective entry of radon into houses and experimental structures. A critical input to the models is an empirical estimate of soil permeability to air. To explain the model-measurement discrepancy, We hypothesized that soil permeability depends upon length scale (an effect frequently observed in aquifer and fractured rock systems). Based on measurements of the static pressure field in the soil surrounding depressurized probes and houses, houses appear to interact with the soil over length scales of ~10 m, whereas probes interact over smaller scales (<0.5m). If soil permeability increases with length scale, then smaller-scale probe measurements of permeability would systematically underestimate bulk permeabilities 'experienced' by houses.

We conducted an intensive field investigation of soil permeability over different length scales using a new, dual-probe dynamic pressure (DDP) technique. Measurements were carried out at our Ben Lomond site, the location of two experimental basements used to study radon transport and entry. Figure 1 shows the arithmetic mean and full range (for n > 1) of horizontally oriented DDP measurements made at 5 different length scales (for n = 1, the single value and uncertainty are indicated). For comparison, the results of standard, single-probe static pressure (SSP) measurements are also indicated for two different types of probes that integrate over different length scales (0.1 and 0.5 m). Analysis of the 48 0.5-m-scale measurements suggests a lognormal permeability distribution. We therefore show the geometric mean and full range for the SSP measurements.

Figure 1 demonstrates that the mean permeability is strongly scale-dependent, with permeability increasing by a factor of about 10 as scale increases from 0.1 to 3.5 m. Note that at smaller scales the full range of observed values span the mean values found at all scales. This is to be expected if the scale-dependence effect is caused by networks of fast flow paths in the soil, as suggested by the presence of root structures observed in several 2- and 3-m-deep trenches cut at the site.

Figure 2 (see next page) shows the entry rates measured in the experimental basement with the structure depressurized as indicated. Also shown are predictions of the three-dimensional finite difference model based on permeabilities measured at the 0.5-m and 3-m scales. The prediction based on the larger length scale estimate is a significant improvement, reducing the discrepancy in the measured-to-modeled entry rate from a factor of 5.7 to about 1.3. It is likely that the structure actually interacts with the soil at a somewhat larger scale than 3 m in the horizontal direction, as indicated by observed pressure coupling between the soil and structure. Although Fig. 1 is ambiguous about whether permeability continues to increase with scale above ~3 m, measurements of soil-radon depletion with structure depressurization suggest that some significant fraction of the remaining discrepancy might be accounted for by soil permeability (as seen by the structure) exceeding the 3-m scale result.

In summary, scale-dependent permeability of soil to air substantially resolves the model-measurement discrepancy in radon entry rates for the controlled test structure at this site and is consistent with discrepancies measured at real houses. Future research will determine to what extent this effect is observed in other soils at other sites.

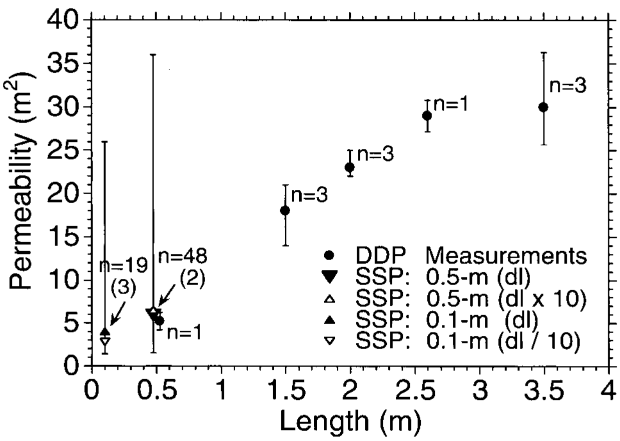

Figure 1. *Air permeability of soil as a function of length scale, combining both SSP and DDP measurements. SSP measurements were taken using an open-pipe probe for the 0.1-m-scale results, and a 15-cm-long well-screen probe for the 0.5-m-scale values. Parentheses indicate number of measurements below or above the detection limit (DL), e.g., 2 of 48. Solid triangles indicate that the GM is calculated by setting those values equal to the DL. Open triangles use DL*10 or DL/10, depending on whether an upper or lower detection limit was found.*

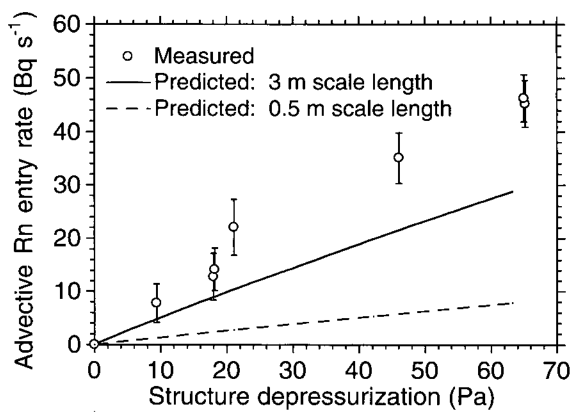

Figure 2. *Radon entry rate in the West structure at Ben Lomond as a function of structure depressurization, comparing the experimental results with those modeled using permeabilities measured at 0.5-m and 3.0-m length scales.*

A New Technique for Energy-Efficient Radon Mitigation

W. Fisk, J. Wooley, R. Prill, Y. Bonnefous, A. Gadgil, W. Riley

We have used numerical modeling and field experiments in a preliminary evaluation of a new energy-efficient radon mitigation technology—"E-SMART" (Energy-efficient Short-circuit plus Membrane for Abatement of Radon Transport). The E-SMART technology relies on a plastic membrane placed beneath a layer of coarse subslab gravel plus one or more pipes (without fans) external to the house connecting the subslab gravel to the outdoor atmosphere. The membrane, which can have small gaps and holes, greatly inhibits radon diffusion into the gravel from the soil and prevents advective flow between the gravel and soil except through the gaps and holes. The pipes provide low-resistance pathways for flow of outdoor air into the gravel layer. In theory, the pressure within the gravel is maintained close to the undisturbed soil gas pressure, despite the depressurization of the house. Consequently, soil-gas entry into the gravel and, therefore, into the house is reduced.

Initial numerical modeling indicated that properly-designed E-SMART systems should reduce indoor radon concentrations by a large factor (e.g., 10 or more). A retrofit E-SMART system was installed in a house with an existing subgravel membrane. System performance was monitored for several months using real-time instrumentation while the pipes were periodically capped and uncapped at their outdoor ends. The reductions in indoor radon concentrations with open pipes (Figure) have been highly variable, and averaged approximately 50%. Although 50% reductions in radon using a low-cost and essentially zero-energy technology are significant, the system's performance fell well short of initial pre-

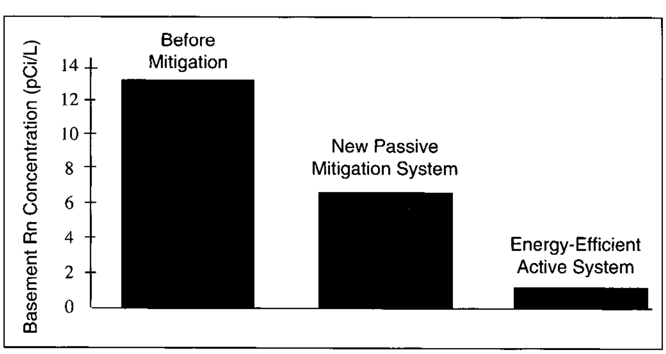

Figure. *Impact of passive and active versions of E-SMART mitigation technology on time-average indoor radon concentrations.*

dictions. The compromises required for a retrofit installation and extremely permeable soil may partially explain the reduced system performance; however, temporally varying wind pressures appear to also have contributed significantly to the degradation of performance. An active version of E-SMART with two 10-watt fans forcing outdoor air into the gravel has also been evalu-ated. Conventional systems without a subgravel membrane typically use one or two 75-watt fans. The active E-SMART system has maintained low radon concentrations in the house and in the subslab gravel (Figure, previous page). Because the fans 10-watt fans generate only small pressure differences between the basement and the gravel, this system should have only a small impact on the house ventilation rate. Consequently, the active version of E-SMART appears to be effective in controlling radon and much more energy efficient than conventional subslab ventilation without a subgravel membrane. Further evaluations of both the passive and active versions are planned.

Characterization of Indoor Air Pollutants

Volatile Organic Compounds in Twelve California Office Buildings: Classes, Concentrations, and Sources

J.M. Daisey, A.T. Hodgson, W.J. Fisk, M.J. Mendell, J. Ten Brinke

Volatile organic compounds (VOCs) are suspected to play a role in "sick building syndrome" (SBS), although the exact relationship between exposure and symptoms has not yet been determined. SBS symptoms include eye, nose and throat irritation, headache, fatigue, dry or itchy skin, and difficulty breathing. Although VOCs are often measured in "sick buildings," data are rarely reported. Furthermore, we lack data on typical indoor concentrations of VOCs in U.S. office buildings for comparison to "sick buildings." As part of the California Healthy Building Study, concentrations of total volatile organic compounds (TVOC) and of 39 individual volatile organic compounds (VOCs) were measured in 12 office buildings in the San Francisco Bay Area in Northern California to characterize indoor air exposures, to investigate interoffice variations in chemical classes and concentrations, and to identify major sources of VOCs.

Buildings were selected from lists of city- or county-owned buildings in the San Francisco Bay area: three naturally ventilated (NV), three mechanically ventilated (MV) with operable windows and no air conditioning, and six mechanically ventilated with sealed windows and air conditioning (AC). All were nonsmoking buildings; one of the AC buildings was a classic "sick building" with a long history of occupant complaints and unsuccessful investigations. The VOCs were collected on multisorbent samplers for eight-hour workday periods and were analyzed for TVOC using a flame-ionization detector and for individual VOC using a capillary gas chromatograph-mass spectrometer. Outdoor samples were also collected and analyzed for comparison.

The indoor concentrations of TVOC and VOCs measured in these northern California office buildings were generally fairly low (Table), with the exceptions of those buildings which had liquid process photocopiers. For these buildings, TVOC levels were 2,662 and 6,972 $\mu g/m^3$, respectively (5 and 13 times greater than the average for the other buildings). The average concentrations of TVOC (excluding the liquid-process photocopier buildings) did not differ significantly among the three types of building ventilation: 462 ± 272 $\mu g/m^3$ (NV); 400 ± 116 $\upsilon g/m^3$ (MV); 452 ± 129 $\mu g/m^3$ (AC), nor did TVOC levels in the "sick building" differ from levels in other buildings. The sums of the 39 individual VOCs which were quantified accounted for 34.6% to 89.9% of the TVOC values, excluding the buildings impacted by the liquid-process photocopiers. Concentrations of both TVOC and individual VOCs were generally consistent with indoor concentrations that have been reported for these species in office buildings by others.

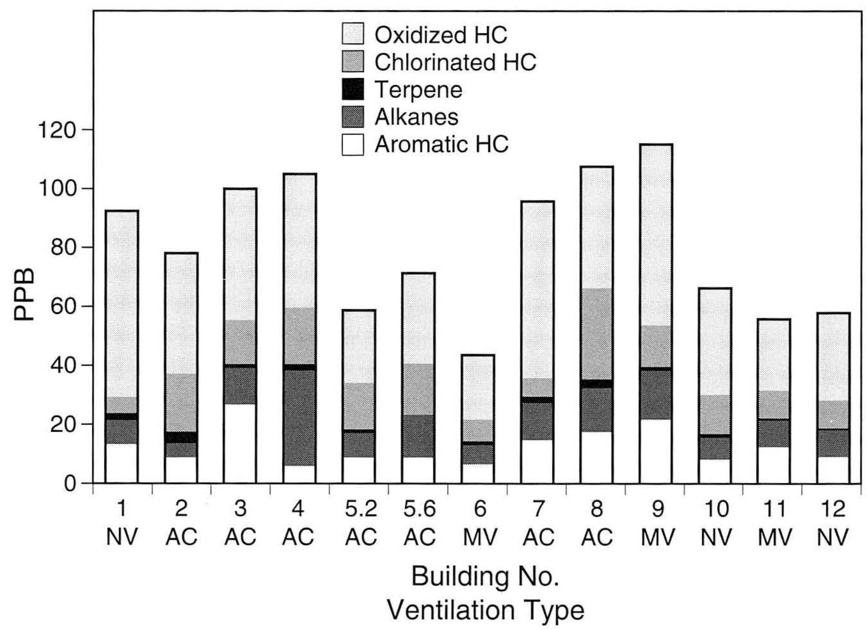

Figure. *Average concentrations of five chemical classes of VOCs in 13 Northern California buildings. Two sampling areas within one building were treated as for separate buildings because the two areas (floors) had separate ventilation systems and one was affected by the presence of liquid-process photocopiers. This gave an effective total of 13 buildings.*

Although there was relatively little variation in the overall levels of TVOC and VOCs among these buildings (excepting the buildings with the wet process photocopiers), there was considerable variation in the chemical composition of the VOC mixtures (Figure). The oxidized hydrocarbons accounted for the greatest proportion of the VOCs for almost all of the buildings. Ethanol contributed substantially to the oxidized hydrocarbon class in many buildings; concentrations ranged from 12 to 239 µg/m³. Concentrations of chlorinated hydrocarbons were highly variable among buildings and even within buildings, ranging from a few percent of the sum of the VOCs to as much as one third. In several buildings, the chlorinated hydrocarbons were the second most abundant class of VOCs; for five of the buildings, the alkanes or aromatic hydrocarbons were the second most abundant class of VOCs.

In order to identify major VOC sources common to the buildings, both factor analysis and indoor/outdoor concentration ratios were used. VOCs identified as coming predominantly from indoor sources were dichloromethane, trichloroethene, 1,1,1-trichloroethane, ethanol, 2-propanol, 2-propanone (acetone), n-dodecane, n-pentanal, n-hexanal, and limonene. The VOCs identified as coming predominantly from outdoor air were benzene, ethylbenzene, 2-ethyltoluene, 3-/4-ethyltoluene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, o-xylene, m/p-xylene, n-pentane, n-hexane, methylcyclopentane, 3-methylhexane, n-decane, benzaldehyde, 1-phenylethanone, and tetrachloroethylene (dry cleaning). The emainder appeared to originate from both indoor and outdoor sources.

Factor analyses (across buildings to identify sources common to the buildings) consistently gave as the first factor one which had high loadings on the aromatic hydrocarbons and a few other VOCs associated with motor vehicle exhaust, specifically, the aromatic hydrocarbons listed above as originating from outdoor air plus n-pentane, methylcyclopentane, and n-hexane. The relative proportions of these aromatic and aliphatic hydrocarbons in both the office buildings and the outdoor air near the buildings were very similar to those reported for motor vehicle emissions. Using benzene as a reference compound (100% assumed to come from motor vehicle emissions since its I/O ratio was less than one for 9/12 buildings), the motor vehicle emissions from outdoor air were estimated to account for about 75 to 100% of the indoor air concentrations of seven aromatic and five alkane compounds in most of the buildings.

Factor analysis also consistently yielded a freon factor with a high (>0.9) loading for trichlorofluoromethane (freon). For four of the seven AC buildings, two of the MV buildings, and one NV building, there was an excess of this compound in indoor air. This compound is commonly used as a refrigerant and is probably leaking from the HVAC systems or from some refrigeration system in these buildings. The MV and NV buildings which had excess freon are all physically connected to AC buildings. The source strength appeared to be of the order of grams per day. (Because efforts to use a new technique to measure the building ventilation rates was not completely successful the source strength could not be calculated exactly.)

Table. *Geometric mean indoor concentrations of total volatile organic compounds (TVOC) and individual volatile organic compounds in San Francisco Bay Area office buildings*

Compound	Concentration Range	Geometric mean ± GSD
TVOC (µg/m³)	227 - 6,972	592 ± 3.1
Alkanes (ppb)		
n-decane	0.05 - 3.88	0.49 ± 3.06
n-dodecane	0.44 - 23.8	1.46 ± 2.77
n-heptane	0.16 - 0.72	0.40 ± 1.41
n-hexane	0.05 - 1.61	0.55 ± 2.45
methylclopentane	0.18 - 1.17	0.45 ± 1.69
methylcyclohexane	0.13 - 0.76	0.38 ± 1.50
3-methylhexane	0.18 - 0.71	0.34 ± 1.51
n-nonane	0.05 - 3.58	0.36 ± 2.57
n-octane	<0.01 - 2.74	0.28 ±4.40
n-pentane	0.46 - 8.88	2.52 ± 2.12
2,2,5-trimethylhexane	<0.01 - 0.31	0.15 ± 1.43
n-undecane	0.05 - 11.1	1.08 ± 2.74
Aromatics (ppb)		
benzene	0.01 - 2.72	0.91 ± 3.54
ethylbenzene	0.27 - 0.98	0.50 ± 1.44
2-ethyltoluene	0.21 - 0.98	0.48 ± 1.68
3- & 4-ethyltoluene	0.35 - 1.68	0.75 ± 1.61
styrene	0.06 - 0.95	0.42 ± 1.95
toluene	0.58 - 16.6	2.63 ± 1.87
1,2,3-trimethylbenzene	0.05 - 1.13	0.29 ± 3.09
1,2,4-trimethylbenzene	0.28 - 1.74	0.76 ± 1.69
1,3,5-trimethylbenzene	0.05 - 0.69	0.38 ± 1.78
m,p-xylene	0.93 - 4.61	2.12 ± 1.57
o-xylene	0.30 - 1.36	0.66 ± 1.53
Oxidized Hydrocarbons (ppb)		
benzaldehyde	0.03 - 1.48	0.46 ± 2.1
butyl acetate	0.05 - 1.37	0.21 ± 2.84
2-butoxyethanol	0.20 - 27.40	1.57 ± 3.72
ethanol	6.37 - 126.7	19.15 ± 1.83
ethyl acetate	<0.01 - 3.02	0.37 ± 2.91
hexanal	0.10 - 1.92	0.46 ± 1.94
n-pentanal	0.05 - 1.68	0.17 ± 3.65
1-phenylethanone	0.67 - 2.82	1.01 ± 1.33
2-propanol	0.10 - 61.5	2.35 ± 3.86
2-propanone	2.70 - 11.6	4.36 ± 1.52
Chlorinated Hydrocarbons (ppb)		
dichloromethane	0.05 - 41.2	0.40 ± 6.72
tetrachloroethene	0.01 - 1.98	0.40 ± 3.21
trichlorofluoromethane	0.21 - 6.28	0.75 ± 2.16
trichloroethene	0.23 - 6.93	1.82 ± 2.20
1,1,1-trichloroethane	0.08 - 72.4	4.45 ± 3.54
Terpenes (ppb)		
limonene	0.10 - 5.57	1.17± 2.34

Data for one building not included in table.

Volatile Organic Chemical Emissions from New Carpet Cushions

A.T. Hodgson, T.A. Phan

Emissions of volatile organic compounds (VOCs) from new carpet systems are often a cause of complaints of discomfort and may be a cause of adverse health effects among building occupants. Previous studies, including one performed by LBL, have shown that carpets emit a variety of VOCs. This study was undertaken to qualitatively and quantitatively investigate the emissions of VOCs from samples of new carpet cushions, the other major component of carpet systems.

There are five types of carpet cushions. The types and their approximate market shares are as follows: bonded polyurethane, 56%; prime polyurethane, 33%; rubber, 6%; synthetic fiber, 3%; and rubberized jute, 2%. Samples of 17 cushions, representative of the five types, were collected directly from manufacturers' production facilities and from dealers. Using small-volume chambers, these samples were quantitatively screened for emissions of total VOCs and individual VOCs, including formaldehyde and, for the polyurethane cushions, isomers of toluene diisocyanate. Toluene diisocyanates are highly irritating chemical monomers used in the manufacture of flexible polyurethane foams. The chambers were constantly ventilated and held at 23 °C. Air samples were periodically collected from the chamber exhausts over a period of six hours. Analyses were performed by gas chromatography-mass spectrometry and high-performance liquid chromatography.

Because of the different manufacturing processes, the identities and amounts of emitted VOCs varied significantly among the different types of cushions. For each type, the dealer-obtained sample had the lowest emission rates of total VOCs, reflecting a decay in emissions with age since production. Among the manufacturer-obtained samples, the synthetic fiber cushions generally had the lowest emission rates of total VOCs. The rubber cushions emitted the most complex mixtures of VOCs, including chemical intermediates. None of the polyurethane cushions tested emitted toluene diisocyanates.

A Method for Measuring Trace Concentrations of Toluene Diisocyanates in Air

A.T. Hodgson, R.K.K. Mahanama

Toluene diisocyanates (TDI) are strong irritants, chemical sensitizers, and suspected carcinogens. The two isomers of TDI are used in the manufacture of architectural finishes and flexible foams, such as carpet cushions. At present, there are no data on indoor concentrations of TDI or on emissions of TDI from materials due, in part, to the lack of a suitable analytical method.

This method was developed and validated to measure trace concentrations of TDI in air for investigations of indoor air quality and for chamber experiments. The method is based on an OSHA Method for industrial hygiene applications, which utilizes a derivatizing reagent coated onto glass-fiber filters. The derivatives are solvent extracted from the filters and analyzed by high-performance liquid chromatography with a fluorescence detector. Significant modifications to the OSHA method resulted in a lower limit of quantitation of 0.03 ppb for a 15-L sample, a tenfold improvement in sensitivity.

Sample blank values were substantially reduced compared to the OSHA method. There was no observed breakthrough of TDI on the coated filters. The overall recovery efficiencies determined by spiking using a vapor generation system were about 70%. The precision of the analysis was typically 10% or better. Samples collected on the filters were stable at room temperature for storage periods of at least two weeks.

The recoveries of TDI from small-scale environmental chambers were incomplete. Significant losses probably occurred onto the chamber surfaces due to the compounds' low vapor pressures. The reactivity of the isocyanate functional group with water may have also contributed to the low recoveries. Additional work is needed to improve the design of the chamber experiments to achieve more accurate estimates of the emission rates of TDI from materials.

Concentrations of Indoor Pollutants (CIP) Database

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

In the last decade and a half, air pollution in the indoor environment has emerged as an important environ–mental issue. Research has shown that people spend 60-90% of their time indoors. In many cases, a significant if not dominant portion of people's exposure to air pollution occurs indoors, especially when an indoor pollutant source exists and energy conservation measures have been taken to reduce building ventilation. To assist researchers and others in the indoor air quality field, the Concentrations of Indoor Pollutants (CIP) Database was initiated in 1983. The CIP Database is a bibliographic management tool for tracking the rapidly expanding amount of literature being generated in this field. The CIP Database contains references to articles that explicitly report concentrations of pollutants measured in actual,unmodified indoor environments such as office buildings and residences.

The database has been provided at no cost to 433 users. Current activities, funded by the Electric Power Research Institute, include modifying the database to include abstracts of papers and ranges of pollutant concentrations measured, improving the software to make the Database more user-friendly, and continuing the Database updating process of entering new articles. LBL is working closely with Fourth Floor Databases, Inc. (Palo Alto, CA) to develop improved software for the Database, whose next version (including updated code and literature entries) is scheduled for release in 1994.

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

G.W. Traynor, G. Chang

One goal of many local, state, and federal agencies is to reduce outdoor air-pollution levels in California's South Coast Air Basin (SCAB) and other urban airsheds. The development of gas-fired burners that produce low levels of NO_x and CO would help reduce outdoor air pollution emissions from gas-fired appliances. Measures that reduce the need for gas combustion (such as increased space- and water-heater efficiencies and increased house insulation) would also help decrease pollutant emissions. The goal of this project is to collect information on pollutant emission factors for the existing stock of residential natural gas appliances so that this information can then be included in a quantitative model to predict outdoor pollution emissions from residential natural-gas appliances and evaluate various pollutant-reducing strategies on a cost-benefit basis. The model will use detailed information on residential natural gas appliance emission factors, usage rates, and market penetrations. The model will then be able to evaluate the benefits of various pollutant-reducing strategies, rank the strategies, and compare them to similar measures proposed in other pollutant-producing sectors such as large industrial and mobile sources.

Pollutant emission rate data have been collected from published journal articles and reports. To date, we have found more than 80 papers that report pollutant emission rates from over 700 residential gas appliances. The data have undergone a quality assurance review, and, based on the review, some data were omitted from the final summary.

This literature survey of pollutant emission rates from residential natural gas appliances reveals mixed results when values are compared with those published by the U.S. Environmental Protection Agency (EPA) in its *Compilation of Air Pollutant Emission Factors (AP-42)*. NO_x and fine particulate emission factors collected in our literature search are consistent with the emission factors in EPA's AP-42. However, CO and methane/hydrocarbon emissions collected in our literature search are an order of magnitude greater than the AP-42 values. These results may indicate that the impact of residential natural gas combustion on outdoor CO and hydrocarbon levels has been underestimated. A well-designed field study is needed to test this hypothesis.

Environmental Tobacco Smoke

Emission Factors for Volatile Organic Compounds in Environmental Tobacco Smoke

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

Environmental tobacco smoke (ETS) is a complex mixture of gases and particles to which nonsmokers are exposed when located in an indoor environment with smokers. ETS is composed largely of sidestream tobacco smoke (SS), the smoke emitted by the smoldering end of a cigarette between puffs. It also has minor contributions from exhaled mainstream smoke (the cigarette smoke directly inhaled by the smoker), smoke that escapes from the burning part of the tobacco during puff-drawing by the smoker, and vapor-phase compounds that diffuse through the cigarette paper. In contrast to sidestream smoke, ETS is diluted and dispersed within a room and undergoes aging.

A growing body of scientific evidence shows that exposure to ETS increases the risks of lung cancer, respiratory infections in young children, reduced lung growth in children, and exacerbation of asthma in children. Although recent studies have provided evidence of adverse health risks from ETS exposures, exposure assessments in these studies were qualitative; that is, individuals were classified only as *exposed* or *not exposed*. Thus, adverse *health risks* from ETS exposures and *exposures* have not been quantitatively linked. Furthermore, the distributions of exposures of the population and various subgroups (e.g., children) have not been determined.

Population exposures to ETS can be estimated indirectly using unique tracers or emission factors. Vapor-phase nicotine has often been used as a unique tracer of exposure to ETS particulate matter because the ratio of ETS particulate matter to nicotine is fairly constant among different brands of cigarettes. Greater variability is seen in this ratio indoors than in chamber studies because of differences in the surface deposition of vapor-phase nicotine and particulate matter. Nonetheless, nicotine has been shown to be a useful, if only semiquantitative, indicator of exposures to ETS particles. If ratios of toxic VOCs in ETS to nicotine were available, they could be used with measurements of vapor phase nicotine to estimate exposures, assuming that the ratios are relatively constant over time. Alternatively, emission factors for ETS could be used in combination with information about smoking habits and building characteristics (e.g., volumes, air-exchange rates, deposition rates) to estimate exposures to air toxics from ETS.

Emission factors for some VOC toxics have been reported for sidestream smoke that had been freshly collected from smoldering cigarettes, but they have not generally been measured for ETS. Furthermore, there have been no comparisons between emission factors measured for SS and ETS. Although there have been some measurements of the concentrations of some VOCs in ETS in rooms with smokers, neither the air exchange rates for the room nor the background (non-ETS) concentrations of the VOCs were reported. Consequently, emission factors cannot be inferred from these uncontrolled experiments.

Clearly, there is a need for emission factors for ETS that can be used with confidence in appropriate models to estimate exposures of the population to toxic VOCs. In late 1992 we initiated experimental work to meet this need. Our specific objectives:

- Determine the emission factors (µg/cigarette) for selected N-nitrosamines, aldehydes, and other VOCs for ETS in a room-sized environmental chamber under conditions that simulate typical indoor settings;
- Determine emission factors for the same VOCs in sidestream smoke for comparison with the ETS measurements;
- Estimate range and variability of the emission factors among a subset of popular cigarette brands that have large market shares in California;
- Investigate the effect of aging on the apparent emission factors of 1,3-butadiene and other VOCs in ETS;
- Investigate and identify new tracers of ETS.

Emission factors are being determined for several volatile N-nitrosamines, aldehydes (formaldehyde, acetaldehyde, and acrolein); and for 19 VOCs that can be collected on a multisorbent sampler and analyzed by capillary gas chromatography-mass spectrometry. Vapor-phase nicotine, suspended particulate matter (PM-2.5), CO and NO_x are being measured. Losses of 1,3-butadiene, a chemically reactive candidate VOC, due to aging of the ETS, will also be investigated.

Experiments are being conducted in the LBL room-sized environmental chamber, under conditions of controlled temperature and humidity, with simulated ETS from six commercial brands of cigarettes and one reference cigarette, Kentucky Reference cigarette 1R4F. The six commercial brands of cigarettes account for 62.5% of market share in California. Five of the commercial brands have filters (which influence mainstream exposures) and two are men-tholated. Two or three cigarettes are smoked with a smoking machine using a standard smoking cycle. The SS is emitted into the 20-m^3 chamber and is mixed to simulate ETS.

Emission factors for the same compounds in sidestream smoke are being measured for each brand using the sidestream smoke apparatus (Figure). Under the conditions of high concentration encountered in the sidestream apparatus, some of the VOCs (e.g., formaldehyde, and 1,3-butadiene) reacted chemically and could not be detected above the lower limits of detection for sampling and analysis. The reproducibility of the sampling and analysis was found to be about ± 10% based on duplicate experiments. For the N-nitrosamine measurements, we adapted and validated a commercial solid-phase sampler, Thermosorb/N, for ETS and SS measurements and demonstratedthat emission factors measured with this sampler were in good agreement with the older method which uses wet bubblers to trap the N-nitrosamines. Only N,N-dimethylnitrosamine and N-nitrosopyrrolidine were found in SS or ETS at concentrations above the lower limits of detection.

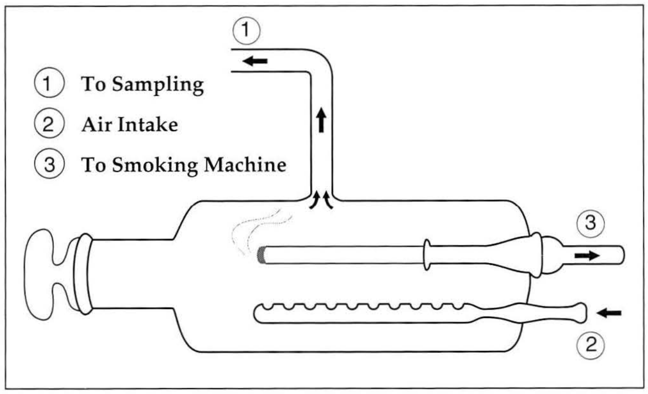

Figure. *Schematic diagram of apparatus used to generate and sample sidestream smoke (apparatus as modified by K.D. Brunnemann and D. Hoffmann in 1978).*

Measurements of SS emission factors were completed and were compared (Table) to SS emission factors reported in the literature. The emission factors measured in our laboratory for comercial cigarettes currently sold in California were generally lower than older data reported in the literature. The emission factors determined for the sidestream smoke varied little among the different brands of cigarettes. The variability was even smaller when emission factors were expressed as micrograms of VOC per gram of tobacco smoked.

Table. *Emission Factors for Some Volatile Organic Compounds in Sidestream (SS) Tobacco Smoke*

Compound	SS Emission Factor ± S.D.* (µg/cigarette)	SS Emission Factors reported in Literature† (µg/cigarette)
2-butanone	197 ± 48	722 ± 20
benzene	241 ± 27	431 ± 23
toluene	509 ± 79	848 ± 27
styrene	101 ± 20	105 ± 9
m,p-xylene	224 ± 51	200 ± 30
o-xylene	44 ± 9	478 ± 0
acrylonitrile	69 ± 24	
pyridine	394 ± 18	
pyrrole	409 ± 19	
4-vinylpyridine	298 ± 23	
N,N-dimethylnitrosamine	0.27 ± 0.05	
N-nitrosopyrrolidene	0.14 ± 0.02	
acetaldehyde	828 ± 140	
acrolein	20 ± 6	
nicotine	5,070 ± 660	

*Average and standard deviation (S.D.) for six commercial brands and reference cigarette. Physical dimensions and tobacco masses are slightly different for each.

†Jermini C, Weber A, Grandjean E. Quantitative determination of various gas-phase components of sidestream smoke of cigarettes in the room air as a contribution to the problem of passive smoking. *International Archives of Occupational Environmental Health* 1976; 36: 169-181.

Effects of Indoor Environmental Conditions on the Size Distribution of Environmental Tobacco-Smoke Particles

R.G. Sextro, M. Xu, A. Nematollahi, W.W. Nazaroff, A.J. Gadgil, J. Daisey

Aerosol size affects the behavior of particles indoors in a number of ways, including coagulation and deposition on surfaces. This dynamic behavior results in changes in the aerosol concentration and size distribution with time, and it is an important determinant of the deposition and retention pattern of particles in the lung, which in turn affects the lung dose of the constituent chemicals. Indoor particles, of which environmental tobacco smoke (ETS) is an important category, constitute a significant fraction of the total human exposure to aerosols.

We examined the size distribution and concentration of ETS under differing environmental and source conditions as a function of time under controlled chamber conditions. The cigarettes used in this study were selected to represent a range of commercial brands and Kentucky reference cigarettes. Particle concentrations and size distributions were measured continuously throughout the course of the ~20 h experiments. Size distributions were fit with a lognormal distribution, yielding the geometric mean (GM) and geometric standard deviation (GSD) for each distribution. We used these size distribution parameters to characterize the effects of various indoor environmental and source conditions on the behavior of ETS particles as a function of time.

The dynamic behavior of environmental tobacco smoke (ETS) particles indoors, even at more than 10 h after cigarette ignition, results in continuing changes in the GM and GSD of the aerosol distribution. At the low ventilation rates used in this study (about a factor of 20 lower than may be typically found in indoor environments), particle-size distribution generally increased in geometric mean size with time, mainly due to the effects of coagulation and deposition. The overall spread in the distribution decreased slightly, as reflected by the reduction in GSD with time.

Changes in the GM and GSD are also influenced by several indoor and source parameters. Some differences among the cigarettes were observed. However, the smoking pattern (smoldering vs. one or two puffs per minute by the smoking machine) had only a small effect on the size distribution. Indoor temperature appeared to have the most dramatic effect (Figure). At a room temperature of ~30°C, the ETS size distribution changed little with time, compared with the change seen at 21°C. The temperature difference could have led to differences in the gas-particle phase distribution in ETS; due to the liquid nature of ETS particles, dramatic changes in composition and coagulation properties could be expected. At 21°C greater particle deposition may have occurred within the chamber owing to increased natural convective flow conditions in the room at the lower temperature.

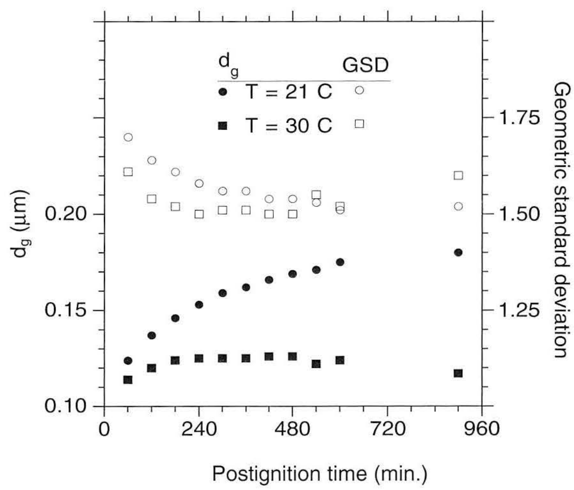

Figure. *Effect of room temperature on temporal change in ETS particle-size distribution. Solid points indicate geometric mean, d_g; open points show geometric standard deviation, GSD.*

Determination of ETS Particle Density as a Function of Particle Size and Aging

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

The density of environmental tobacco smoke (ETS) particles is required for interpretation of particle behavior in indoor environments and in predictions of lung deposition. Measurement of ETS particle density, especially under typical room conditions, has not been previously reported. Current estimates of ETS particle density rely on measurements of mainstream tobacco smoke particle density, for which reported values range from 0.9 to 1.4 g/cm^3.

In this study, ETS particle density has been determined by sequentially measuring electrical mobility and aerodynamic particle sizes of ETS generated in a room-size chamber. ETS particles were produced with a smoking machine and sampled with an electrostatic classifier (EC). A calibrated one-stage impactor then sampled the output of the EC. Two condensation nucleus counters (CNC) measured particle concentrations upstream and downstream of the impactor. Collection efficiency was calculated from the CNC measurements and used to determine particle aerodynamic diameter from the impactor calibration curve. These results were used, along with the mobility diameter measured with EC, to calculate particle density. Two different impactor stages were used. The first collected particles with diameters from 0.09 to 0.21 mm; and the second was used to measure particles with diameters from 0.4 to 0.6 mm. The experiments were conducted at different ventilation rates, ranging from 0.03 to 0.78 h^{-1} and for aging times up to 20 h.

For aged (20 hours) ETS particles with diameters of 0.09-0.21 µm, the density is strongly size dependent (Figure, next page) and ranges from a maximum value of 1.6 g/cm^3 for a diameter near 0.1 µm to a value of 1.1 g/cm^3 for diameter of 0.21 µm. In contrast, particles collected only 30 minutes after the cigarette was smoked do not show a size-dependent particle density. ETS particles with diameters 0.4-0.6 µm have a constant density of about 1.08 g/cm^3, which appears to be independent of aging time.

As volatile materials evaporate, ETS particles become smaller and more dense. This dynamic evolution of ETS particles could result in the change of particle density with size. This evaporation effect could be more pronounced in the smaller particles where the surface-to-volume ratio is greater.

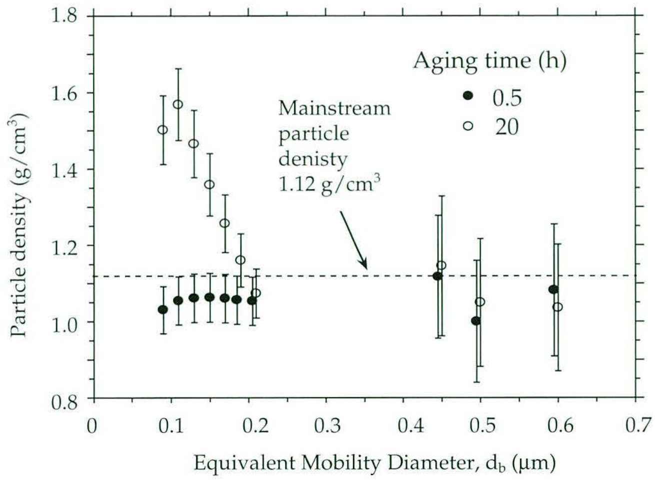

Figure. *ETS particle density as function of particle size and for two different aging times. Average density of mainstream particles is shown for reference. Note that density values for particles larger than 0.19 μm collected after 30 minutes are offset slightly from the 20-h data to separate the error bars. Ventilation rate of the room-size chamber for these experiments was ~0.05/h.*

Phase Distributions of Polycyclic Aromatic Hydrocarbons in Environmental Tobacco Smoke

L. Gundel, V.C. Lee, K.R.R. Mahanama, J.M. Daisey

Accurate measurements of gas and particle phase distributions of semi-volatile organic compounds such as polycyclic aromatic hydrocarbons (PAH) in indoor air and environmental tobacco smoke (ETS) are needed in order to assess their health effects since lung deposition patterns differ between the gas and particle phases. Most phase distribution measurements have been made by determining concentrations of particulate-phase semivolatile organic species from filters that are followed by adsorbents. Gas-phase concentrations have been determined from extracts of the adsorbents. Since such sorbent beds follow filters, desorption of semivolatile compounds from the particles on the filters (negative artifacts) or adsorption of gases by the filter materials (positive artifacts) can lead to incorrect measurements of gas- and particle-phase concentrations. Denuder technology provides a less artifact-encumbered approach to accurate determination of phase distributions of semivolatile species because the gas phase is collected before the particulate phase. Large particles are typically removed from the airstream by a size-selective inlet that is followed by a denuder surface which retains gas-phase species but does not influence particle transport to a downstream filter. A sorbent after the filter can collect any material desorbed from the filter.

The work reported here uses a new integrated organic vapor-particle sampler (IOVPS), based on an annular denuder that has been coated with the adsorbent resin XAD-4. The denuder strips the gas-phase species from the air stream before collection of the particles on a filter. A second filter and denuder or sorbent bed can be used downstream of the filter to assess "blowoff" or volatilization loss of semivolatile species from the particles. Concentrations of the species of interest are determined in extracts of the denuders and filters. The success of the IOVPS depends heavily on the fact that the ground XAD-4 resin adheres to sandblasted glass and is resistant to removal by handling, solvent washes and air sampling. This article reports concentrations and phase distributions of several semivolatile PAH in simulated environmental tobacco smoke measured with IOVPS.

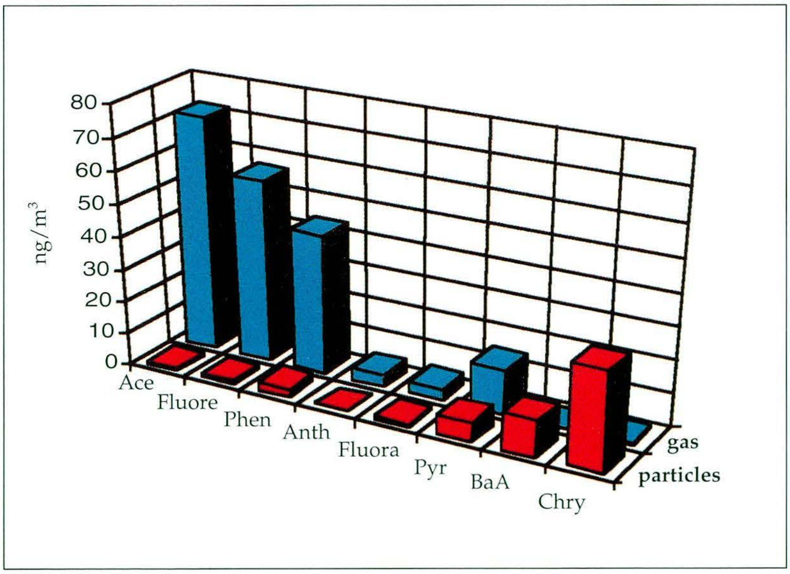

Figure. *Concentrations of acenaphthylene (Ace), fluorene (Fluore), phenanthrene (Phene), anthracene (Anth), fluoranthene (Fluora), pyrene (Pyr), benz(a)anthracene (BaA) and chrysene (Chry) in simulated environmental tobacco smoke are shown for gas- and particulate-phase polycyclic aromatic hydrocarbons. Not shown: concentrations of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene concentrations (822, 334, and 526 ng/m³, respectively) in gas phase.*

Gas- and particulate-phase PAH concentrations are shown (Figure) for ETS sampled after three cigarettes were machine-smoked in a room-sized environmental chamber (36 m^3) with low air exchange rate (0.03/hr). The IOVPS operated at 5 L/min for one hour. The fractions of the semi-volatile PAH (fluoranthene, pyrene, benz(a)anthracene and chrysene) found in the particle phase of ETS (0.4, 0.18, 0.99 and 0.97, respectively) were higher by about 30% than those found in ETS sampled simultaneously with a conventional filter-sorbent bed sampler. The conventional sampler has known artifacts that minimize particulate-phase concentrations of PAH. These results suggest that the IOVPS minimizes sampling artifacts, and its use can lead to more accurate assessment of ETS exposures and doses to the lung.

During the next year the phase distributions of both PAH and nicotine will be measured using the IOVPS in chamber studies of ETS under different conditions of dilution, aging, lighting and temperature. The IOVPS will also be evaluated for determining phase distributions of tobacco-specific nitrosamines.

Selective Fluorescence Detection of Polycyclic Aromatic Hydrocarbons in Environmental Tobacco Smoke and in Other Airborne Particles

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

Polycyclic aromatic hydrocarbons (PAH) have received considerable attention as an important class of atmospheric organic pollutants due to the carcinogenic and mutagenic properties of some of these compounds and their derivatives. Exposure to airborne PAH is considered an important environmental and occupational health problem, and increased incidence of lung cancer has been demonstrated in workers exposed to high levels of airborne PAH. PAH are generated as products of incomplete combustion of carbon-containing materials and are byproducts of all the combustion processes, e.g., industry, motor vehicles, smoking, and residential heating.

Determination of PAH in atmospheric particulate matter and other environmentally significant mixtures, such as environmental tobacco smoke (ETS), presents two problems. First, the PAH of interest must be adequately separated from related substances in the complex mixtures in which they are found. Second, high sensitivity is often needed to analyze small samples collected over a relatively short periodof time. We have developed a dual-detector selective fluorescescence method to overcome both problems. The method is sufficiently sensitive that samples as small as 2 mg of airborne particles can be analyzed.

Reversed-phase high performance liquid chromatography (RPLC) on chemically bonded octadecyl stationary phases is by far the most popular method for the separation of PAH. Since chromatograms of complex samplesare always complicated, overlapping peaks often lead to imprecise estimation of the airborne PAH levels to overcome this problem. We have developed a dual-detector method to overcome this problem that takes advantage of the sensitivity and selectivity of fluorescence spectroscopy.

Coupling of two programmable fluorescence detectors allows simultaneous detection of PAH under two sets of excitation and emission wavelengths. By careful selection of the excitation and emission wavelengths, a high degree of specificity and selectivity was achieved. Since optimum wavelengths were used for the quantitation, the detection limit was improved to sub-pg levels, or roughly thousand times more sensitive than conventional absorbance. Class-selective fluorescence wavelength combinations were used to tentatively identify the alkyl-PAH derivatives and estimate their concentrations in ETS even in the absence of the respective standard compounds.

We successfully used the method to determine PAH levels in ETS, in standard reference materials, in SRM 1649, in an urban dust sample, and in airborne particulate matter collected from Kuwait during the oil well fires. The table compares selected PAH concentrations in SRM 1649 measured using the selective fluorescence method with 5 mg of SRM compared with reference values determined using 1.0-g samples.

Table. *Comparison of selected PAH concentrations in SRM 1649* with reference values*

PAH	Reference (μg)	Measured (μg)	n	Coef. Var.%†
phenanthrene	4.5 ± 0.3	7.3 ± 0.6	5	8.59
fluoranthene	7.1 ±0.5	6.5 ± 0.7	6	11.15
pyrene	6.3 ± 0.4	5.6 ± 1.0	6	17.80
benz(a)anthacene	2.6 ± 0.3	2.8 ± 0.1	6	4.10
chrysene	3.5 ± 0.1	3.4 ± 0.1	6	3.66
benzo(b)fluoranthene	6.2 ± 0.3	5.7 ± 0.3	6	4.99
benzo(k)fluoranthene	2.0 ± 0.1	2.2 ± 0.1	6	4.27
benzo(a)pyrene,	2.9 ± 0.5	2.8 ± 0.2	6	7.76
benzo(ghi)perylene	4.5 ± 1.1	3.4 ± 0.2	6	4.92
indeno(cd)pyrene	3.3 ± 0.5	4.0 ± 0.1	6	3.40

*Certificate of analysis, SRM 1649, Urban Dust/Organics, National Bureau of Standards (Now NIST), Washington D.C.
†Coefficient of Variation % = 100 × standard deviation/mean

Indoor Air Quality Controls

Indoor Airflow and Pollutant Removal in a Room Equipped with Floor-Based Task Ventilation

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

In today's typical office buildings, occupants are usually not in control of ventilation and thermal conditions in their work environment. 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 the occupants. Task ventilation allows occupants to control some aspects of their local ventilation and thermal conditions.

A series of 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 contained three workstations, office furniture, and sources of heat and air motion—i.e., overhead lights, task lights, and a personal computer—typical of real offices. Two of the workstations were occupied by a heated, seated mannequin. The task ventilation system supplied air through floor-supply units with four grilles which permit manual adjustment of supply direction and flow rate. Air exited the CEC through a ceiling-mounted return grille.

To study indoor airflow patterns during periods with stable supply temperatures and flow rates, a tracer gas was injected into the supply air and multipoint measurements of tracer-gas concentrations versus time were made inside the chamber. Local ventilation rates were determined from these tracer concentration histories. To study the intraroom transport of tobacco smoke particles, cigarettes were smoked mechanically in one workstation and particle concentrations were measured at multiple indoor locations. Test variables included the furnishing of the chamber, the location(s) of air supply, supply flow rates, temperatures, supply directions, and internal heat loads. During this series of experiments, multiple floor-supply units were in operation at the same time, supplying air at flow rates lower than during our previous tests. An objective of these experiments was to determine if this task ventilation system resulted in an upward displacement air flow pattern when supply velocities were low. Upward displacement flow generally leads to improved air quality where occupants breathe, compared to traditional ventilation systems with well mixed indoor air.

With two floor-supply units operating at low flow rates, there was evidence of a general upward flow in the room. With three units operating, a two-zone flow pattern, with upward flow in the lower region of the room and mixing in the upper region, was evident at some operating conditions. A correlation (r^2 = 0.76) was found between the rate of change in the average local with height and two factors hypothesized to be determinants of the indoor airflow pattern: the Archimedes number of the supply jets and the ratio of internal heat load tototal supply flow rate (Figure). With this upward airflow pattern, the improvement in the local ventilation rate in the breathing zone, as compared to room air that was perfectly mixed, was 20%-40%. However, workstations with an operating task ventilation system were not significantly protected from tobacco smoke exposure when the smoke was generated in an adjacent workstation.

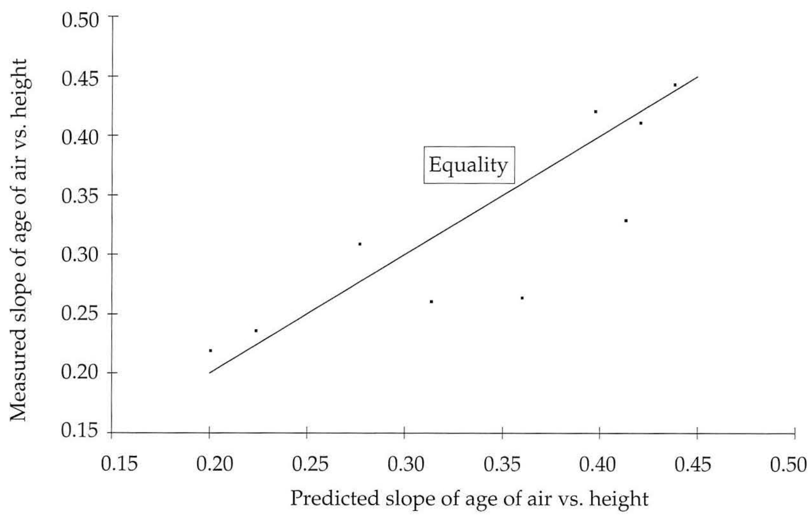

Figure. *Measured versus predicted slope of age of air (reciprocal of local ventilation rate) versus height. Prediction based on multiple linear regression with Archimedes number and ratio of supply flow rate to internal heat load.*

Experimental Procedures for Measuring the Pollutant Control Index

D. Faulkner, W.J. Fisk, D.P. Sullivan, A.T. Hodgson

At present, to indicate the effectiveness of ventilation systems in removing indoor-generated air pollutants, ventilation researchers and contractors exclusively use rates of outside air supply, often normalized by the indoor volume, floor area, or number of occupants. Existing methods of determining rates of outside air supply are very difficult to implement in many buildings, require stable airflow rates, and yield data that are only representative of short time periods, typically a few hours.

As described in the 1992 Annual Report, we have proposed a simple new index, the Pollutant Control Index (PCI), for characterizing the effectiveness of the ventilation process in controlling the indoor concentrations of a simulated pollutant during the period of occupancy. The PCI is effectively a time-average pollutant concentration during the period of occupancy at locations where occupants breathe. The pollutant source is simulated with numerous (50-100) tracer gas sources with known emission rates distributed uniformly throughout a building. The PCI is adjusted for any variation in emission rates between buildings. The PCI remains valid when airflow rates vary over time. In addition, the PCI can be representative of an extended time period such as a work-week or work-month.

During the past year, we have been developing experimental procedures for measuring the PCI. Two tracers, perfluoro(methylcyclohexane) (C_7F_{14}) and perfluoro-1,3-dimethylcyclohexane (C_8F_{16}), have been selected as the most promising. The tracer sources are small glass vials with silicone rubber-septa with a volume from 1.5 to 15 mL of liquid. The tracers diffuse through the silicone rubber. Tracer emission rates vary from approximately 0.003-0.050 g/day depending on the tracer type, septa size and temperature. The coefficients of variation of emission rates from identical sources are 5%-9%. At room temperature, the emission rates vary with temperature about 4% per °C. The tracer sources emit tracer continuously, similar to the emission of pollutants by building materials.

To measure the concentrations of tracer gases in the indoor air, samples are collected on solid sorbents. Air samples are drawn from locations near workstations and pumped through tubes packed with solid sorbent at a constant and known rate, but only during the period of occupancy, typically 9:00 A.M. to 5:00 P.M., Monday through Friday. Through laboratory experiments, we have defined the following acceptable sampling conditions: sample flow rates from 0.05 to 10 ml/min; total volume of air sampled should not exceed 10 L; and the mass of tracer collected on the sorbent should be between 5-500 ng. Sample periods as long as two work-months have yielded acceptable results. We have also determined that sorbent tubes can be stored for at least one month prior to analysis with no significant loss in tracer.

The PCI is thus based on the average tracer gas concentration during the period of sampling, which equals the mass of tracer collected on the sorbent divided by the volume of air sampled. To determine the tracer mass, the sorbent tube is heated to drive off the tracer, which is then passed through a gas chromatograph and a mass spectrometer (GC/MS). Use of a GC/MS, compared to a gas chromatograph with an electron capture detector, greatly reduces the potential for measurement errors due to interference by indoor air pollutants. Based on laboratory experiments with samples drawn from airstreams with a known tracer concentration, the accuracy of the sampling and sample analysis process should be approximately 10%.

Our FY 1994 plans include development of an improved calibration system, automation of the sample analysis process, and performance of field trials of the measurement technique.

Particle Filter Based on Thermophoretic Deposition from Natural Convection Flow

A.G.B.M. Sasse, A.J. Gadgil, W.W. Nazaroff

In the presence of a temperature gradient, aerosol particles experience a force in the direction opposite to the gradient (i.e. a force in the direction of the cooler side). This is called the thermophoretic force. We investigated the possibility of thermophoretic fil-tering of aerosol particles using natural convection induced between two asymmetrically heated parallel vertical surfaces.

The chimney effect owing to the heating would draw air into the channel formed by the two surfaces, and the asymmetric nature of the heating would produce a transverse thermophoretic force on the entrained aerosol particles. Under certain conditions, the magnitude of this force, the residence time of the particles in the channel, and the channel spacing may be right for complete removal of the particles by thermophoretic deposition onto the cooler of the two surfaces.

The analysis was undertaken for two kinds of flow: between parallel plates and between the sufaces of the annulus formed by concentric tubes. Particles move along with the airflow in the vertical direction and by thermophoresis in the horizontal direction. From scale analysis, we demonstrated that particles can be completely removed from the air stream if the length of the channel exceeds a critical length. This length depends on the channel width, the thermophoretic coefficient, the viscosity of air, and the force of gravity. We then obtained precise predictions of the particle removal efficiency for this system using numerical solutions of the governing equations.

Based on model results, it appears feasible to develop a practical filter for removing smoke particles from a smoldering cigarette in an ashtray, using natural convection in combination with thermophoresis.

Epilogue: In the summer of 1993 we designed and built a cigarette ashtray with a thermophoretic chimney to capture sidestream smoke. The "smokeless ashtray" worked but is not ready for commercialization.

Indoor Air Exposure and Risk

Occupant Health in Office Buildings: Phase 2 of the California Healthy Building Study

W. Fisk, D. Faulkner*, M. Boyle*, A. Hodgson*, D. Sullivan*, J. Daisey*, Janet Macher†, M. Mendell‡, P. Jensen‡, F. Offermann§, S. Loiselle§*

Phase 1 Summary

Data collection for the first phase of the California Healthy Building Study (CHBS) took place during the summer of 1990. Occupants of 29 study spaces located in twelve office buildings reported the prevalences of their acute building-related health symptoms on a written questionnaire. Information was collected on the prevalences of symptoms commonly associated with sick building syndrome such as eye, nose, or throat irritation; headache, and fatigue. Demographic, job, and work space information were also collected via the questionnaire. Building ventilation type and other building characteristics were determined by inspections. Indoor temperatures, humidities and concentrations of carbon dioxide, volatile organic compounds (VOCs), culturable fungi, and culturable bacteria were measured. Logistic regression models were used to determine associations between health symptom prevalences and the other parameters.

The following factors were associated significantly with increased prevalences of health symptoms:

- mechanical ventilation with or without air conditioning;
- use of carbonless copy paper or photo copy machines greater than one hour per day;
- high level of self-reported job stress;
- presence of carpet in the test space; and
- absence of a window within 15 feet of the workstation.

Phase 2: Activities and Preliminary Results

In a Phase-2 research effort, conducted between November of 1992 and March of 1993, we studied the same 12 buildings. One Phase-2 objective was to collect additional data on buildings or indoor environments that could be compared to the Phase-1 symptoms. Only building characteristics, certain building-related practices, and environmental parameters that were unchanged since the prior period of health symptom collection could satisfy this objective. In each test space with carpets, the surface area, age, and type of carpet were determined. Using interviews, information on housekeeping practices (e.g., frequency and types of cleaning) and HVAC maintenance practices was compiled. The accessibility of HVAC components for maintenance and cleaning was determined. Finally, we measured the extent of lighting flicker at multiple locations in each space. Flicker is determined primarily by the type of fluorescent ballast and lamp and was hypothesized to be correlated with the prevalence of headache.

A second Phase-2 objective was to develop and evaluate selected measurement or data collection procedures that could be used in a future study coincident with the collection of data on health symptoms. Consistent with this objective, the spatial and temporal variability of sound levels were determined in each test space—yielding information for defining measurement locations and times in a future study. We developed a protocol and form for inspecting HVAC systems, primarily to determine component accessibility and cleanliness, to check for microbiological contamination, and to check for potential sources of VOCs or fibers in HVAC systems. The protocol and inspection form were pilot-tested by application to 29 HVAC systems within nine buildings. A convenient and non-obtrusive technique of collecting dust samples from carpeted floors and upholstered chairs was also developed and pilot tested. In this technique, a small battery-powered pump drew dust through a short metal tube onto a polycarbnate filter. The carbonate tube was drawn across the surface of the carpet in a controlled manner, guided by the slot in a metal template placed on the floor. The template could not be used on the uneven surfaces of chairs. Material collected on the filter was then cultured to determine counts and types of bacteria and fungi. In a final activity related to this objective, we experimented with the collection of airborne bacteria and fungi on polycarbonate filters for periods of two to eight hours. The airborne concentrations of viable organisms based on culturing the material on the filters were compared to the concentrations from sequential short-term impaction samples collected directly on culture media. Sample collection directly on culture media is the conventional practice; however, the sample collection periods are only a few minutes which is inadequate for characterization of indoor exposures that can be related to symptoms.

A third objective was to investigate the VOC emissions from the internal duct liners used in HVAC systems, with and without exposure of the duct liners to ozone. During the HVAC inspection, samples of each unique type of duct liner were collected and stored in air-tight containers. Emissions tests have not yet been completed.

Because much of the data analysis is still underway, only a few very preliminary comments can be made on the results of the Phase-2 efforts. There was considerable spatial variability in lighting flicker within study spaces, indicating that many measurements are required to adequately determine the extent of flicker at each work space. Similarly, sound levels varied a great deal both spatially and temporally within test spaces. The HVAC inspection protocol and form were found to be generally acceptable, although the need for

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several minor improvements was noted. We did not find evidence of extensive microbiological contamination in any of the accessible HVAC systems. A few small systems were inaccessible and cleanliness varied substantially between HVAC systems. The new technique of collecting dust samples was found to be very convenient and adequate for floors. The repeatability of sample collection from chairs, with curved surfaces, was questioned. Finally, the dust from chairs generally had higher concentrations of microorganisms than did the dust from carpets.

Development of a Carbon Monoxide Passive Sampler

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

Fifteen thousand to 20,000 carbon monoxide (CO) poisonings occur every year in the U.S., with hundreds of these poisonings resulting in death and thousands resulting in some type of physical or mental damage. In addition, exposures to high concentrations of CO can cause damage to the fetus and the heart, including causing the onset of heart attacks. High concentrations of indoor 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; the indoor use of charcoal; and the indoor operation of an internal combustion engine (e.g., operating cars or generators in a garage). Some poisonings can be avoided by better education while others (e.g., those caused by malfunctioning vented appliances) can only be avoided by an active mitigation program or the widespread installation of CO alarms. Of special concern are the poor and the elderly who often do not have the resources for routine inspection and maintenance of their gas or other combustion appliances.

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

Our research program 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, reduce the batch-to-batch variations, and reduce the reversibility of the disks. To date, we have established the linearity of the sensors response to CO; developed and tested a critical non-reversible formulation of the sensor; tested new sensor substrates that are free from impurities; and developed our first laboratory prototype (Figure). The prototype was successfully tested in the laboratory under a wide variety of humidity levels. Further refinements of the CO-sensing disk and the passive sampler configuration are planned to optimize performance.

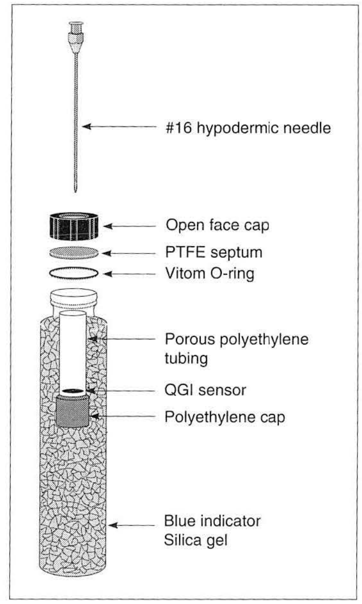

Figure. *Schematic of a laboratory prototype carbon monoxide passive sampler using a Quantum Group Inc. (QGI) sensor (XBL-937-4602).*

Biologically Based Risk-Assessment Models

F. Bois

Correct assessment of the risks of toxic injury from chemicals usually cannot be made without evaluating target tissue doses. Such doses can be estimated via biomarker measurements or derived from external exposure data with the help of pharmacokinetic principles and models.

Physiologically-based pharmacokinetic models, which describe the distribution of toxicants in the body, are currently believed to be more reliable for low-dose extrapolations than simpler empirical models. Most of the predictive power of these models stems from the constrained behavior that their mathematical structure provides. They also offer the possibility of including experimentally measured parameters that have direct biological meaning (e.g. blood flows and organ volumes). However, statistical methods that would allow us to take full advantage of these models are still lacking. We pioneered the use of global optimization through Monte Carlo simulations and uniform likelihood methods in this area. We are now working on formally incorporating data on inter-intraindividual variability into risk assessments, using population toxicokinetic techniques. We are already able to give far more reliable estimates of extrapolated doses, along with realistic confidence intervals, than usually available.

We have focused some of our recent research on the methodological aspects of physiologically-based pharmacokinetic modeling, with an application to benzene, a human carcinogen and widespread industrial pollutant. In the case of benzene, we found evidence of strong population effects. These call for a better understanding of the sources of interindividual variability in benzene metabolism. We also showed evidence for the absence of strong dose-rate effects at moderate-to-low benzene exposure levels. Yet the model shows that exposure of the bone marrow to benzene metabolites is a nonlinear s-shaped function of benzene air concentration, even at low levels. This nonlinearity should be taken into account when assessing exposure in epidemiologic studies or when forecasting low dose risks.

Regional Lung Deposition of Environmental Tobacco-Smoke Particles

W.W. Nazaroff, W.-Y. Hung, A.G.B.M. Sasse, A.J. Gadgil

Inhalation exposure to environmental tobacco smoke (ETS) particles may increase health risks, but only to the extent that the particles deposit in the respiratory tract. We have developed a technique to predict regional lung deposition of environmental tobacco smoke particles. The method combines experimental data on ETS particle emission profiles with two existing mathematical models: an indoor aerosol dynamics model and a lung deposition model. The method is capable of predicting where deposition occurs within the lung, an important feature since different regions have different properties that influence the potential health response, such as the clearance rate. The method is also capable of predicting the size of particles deposited in each region. This is important because the chemical composition of environmental tobacco smoke particles may vary according to size. The method accounts for the effects of other conditions that influence exposure such as building factors, smoking rates, and the presence of other airborne particles. Finally, the method incorporates important physiological characteristics associated with the exposed individual, including breathing cycle and lung size and structure.

The emission rate of ETS particles is based on the analysis of a series of experiments conducted in a full-scale room of LBL's Indoor Air Quality Research House. In each experimental run, a single cigarette was smoked by machine in an unoccupied room. After the cigarette was ignited, the machine drew two 35-ml puffs per minute for six minutes, then the cigarette was extinguished. Particle size distribution was measured using an optical particle counter (PMS model LAS-X) and a differential mobility analyzer (TSI model 3071) coupled to a condensation nucleus counter (TSI model 3020) during, and for several hours after, cigarette combustion. The air-exchange rate was determined by tracer-gas decay. Each experiment was interpreted using an indoor aerosol dynamics model to extract the effective emission rate of particles as a function of size.

The indoor aerosol dynamics model predicts the time-dependent evolution of particle size distributions in buildings. The particle size distribution is represented by a series of discrete contiguous size sections defined by particle diameter. The model employs a flexible multichamber description of a building with each chamber assumed to be well mixed. In simulating the evolution of particle size distribution, the model accounts for the influences of direct indoor emission, ventilation, filtration, mixing between chambers, coagulation, and deposition onto indoor surfaces. Evaporation, condensation, and homogeneous nucleation are not included. The model has been successfully validated against experimental data on the evolution of particles from cigarette smoke.

The lung deposition model represents the respiratory tract as a branching network of airways, with each generation of branches characterized by the number of airways, their length and diameter. Particle deposition in each generation is computed by deterministic formulae, accounting for gravitational settling, impaction, and diffusion.

To illustrate the nature of the results generated by this procedure, predictions have been generated for regional lung deposition of environmental tobacco smoke particles resulting from exposure in a residence. The simulation tracks a one-day period. During the first sixteen hours, the residents are awake, and cigarettes are smoked at a uniform rate. During the final eight-hour period, no cigarettes are consumed. The building volume, 360 m^3, corresponds to a typical single-family residence in the United States.

The figure shows the particle size distribution deposited in each of the three major lung regions for a 6-year-old boy under typical residential exposure conditions (two cigarettes smoked per hour, air-exchange rate of 0.68/h, respiratory volume of 0.66 m^3/h during the day time and 0.26 m^3/h at night). This figure shows that the median particle size depositing in the nasopharyngeal region (1.2 μm) is larger than that depositing in the tracheobronchial region (0.50 μm) which is, in turn, larger than that depositing in the alveolar region (0.42 μm). The total respiratory tract deposition for the 21-kg boy is 164 μg/day, partitioned as 31% in the nasopharyngeal region, 27% in the tracheobronchial region, and 42% in the alveolar region.

This technique should be useful for evaluating health risks and control techniques associated with exposure to ETS particles. The method is also suitable for predicting lung deposition for other classes of airborne particles. Examples include soot or photochemical smog particles which enter buildings from polluted urban air, or particles generated by indoor sources other than cigarette smoking.

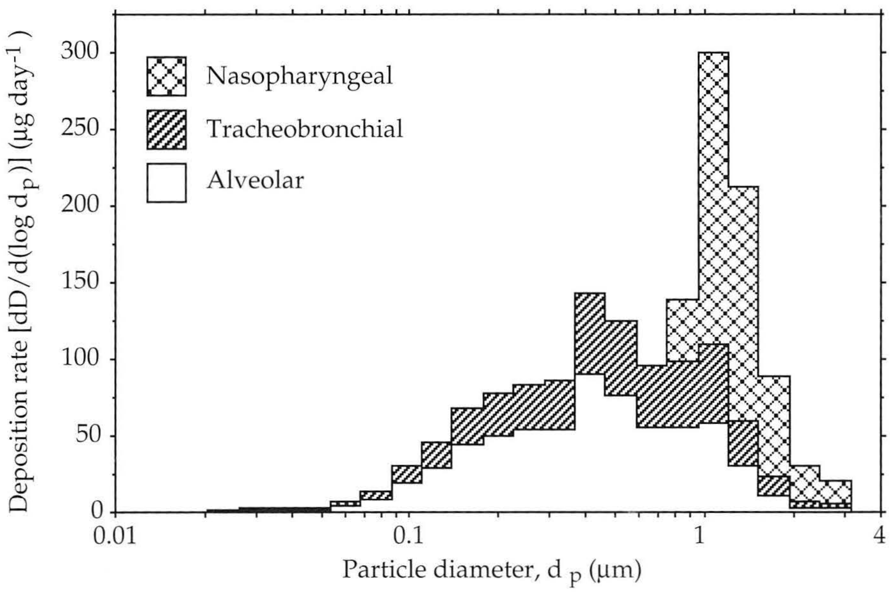

Figure. *Size distribution of deposited mass of environmental tobacco smoke particles in a 6-year-old boy exposed under specific conditions to smoking in a residence. The area between two particle sizes is proportional to the average 24-h mass deposition rate of particles within those two size limits.*

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