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APPLIED SCIENCE DIVISION ANNUAL REPORT

INDOOR ENVIRONMENT PROGRAM

FY 1987

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INDOOR ENVIRONMENT PROGRAM

INTRODUCTION

LBL is a major center of building science research. An important part of that research is the environment defined by the building -- the major focus of the work of the Indoor Environment Program. The Program examines the scientific issues associated with the design and operation of buildings to optimize building energy performance and occupant comfort and health.

Optimizing health and comfort of occupants is addressed in different ways by the groups that comprise the Program. The Energy Performance of Buildings Group examines energy flow through all elements of the building shell. It measures air infiltration rates, studies thermal characteristics of structural elements, and develops models of the behavior of complete buildings. The potential for savings in the infiltration area is great. The heat load associated with natural infiltration is about 2.5 quads/yr costing about $15 billion annually. It may be economic to reduce this by 25%.

This change, however, may produce undesirable effects in the environment of the building. Since ventilation is the dominant removal mechanism for pollutants found within buildings, concern continues about the impact of designs or changes in operation that lead to its reduction.

This issue has been an important theme for the work of the other projects of the Program. Efforts include characterizing the emission of various pollutant classes from their respective sources, studying the effectiveness of ventilation in removing pollutants from indoor atmospheres, and examining the nature and importance of chemical and physical reactions that can affect the occurrence and amount of airborne pollutants. The Program has projects that have concentrated specifically on three major pollutant classes: combustion products, arising from indoor heaters and other combustion appliances; radon and its progeny, arising from materials that contain radium, a naturally occurring radionuclide; and formaldehyde and other organics, arising from a variety of building materials and furnishings. In addition, the Ventilation and Indoor Air Quality Control and Energy Performance of Buildings projects investigate techniques for controlling airborne concentrations, develop devices for monitoring pollutants in laboratories and buildings, and design or carry out field surveys of energy use and indoor air quality in residential and commercial buildings. The Indoor Exposure Assessment project also devotes time to assessing the health effects of indoor pollutant exposures.

It is difficult to generalize the results of on-going research efforts. However, there are several important hypotheses that have evolved from this work that we continue to explore as this research proceeds.

A. **Air quality in buildings is dominated by sources.** Problems that have been seen are more often related to strong indoor sources than to deficiencies in ventilation.

B. **Air pollution is a buildings problem.** The concentrations of pollutants observed within buildings are comparable to those outdoors (when major indoor sources are present, the concentrations indoors are substantially higher). Since people spend 70-90% of their time inside buildings the major portion of their exposure to air pollutants occurs within buildings. Therefore, because sources and removal processes are often associated with building structure and operation, we work from a perspective that air pollution is a buildings problem.

C. **Ventilation is the best control strategy for indoor pollution within a building.** Ventilation using outdoor air affects all indoor pollutants in a similar way. Therefore, it is the best single strategy to employ in buildings for pollutant control. This assertion does not contradict statement A above. Rather, it acknowledges that we do not know and cannot identify all the pollutant sources in a building. If a particular pollutant is known to be a problem, the source of the pollutant should be treated. Since such information is usually lacking, ventilation remains the best general indoor pollution control strategy.

Indoor Radon*

R.G. Sextro, A.V. Nero, K. Garbesi, J. Harrison, J. Hill, D.D. Lee, C. Loureiro, B.A. Moed, W.W. Nazaroff, T. Nuzum, R. Prill, K.L. Revzan, and B.H. Turk

Key elements of the research conducted by the Indoor Radon group are to 1) provide a method of predicting or identifying geographical areas where houses with elevated indoor concentrations might be found; 2) to improve understanding of the mechanisms for production and transport of radon through soils and into buildings; 3) to identify, develop and investigate means of controlling high indoor radon concentrations; and 4) to study the behavior of radon progeny under a variety of indoor environmental conditions.

ACCOMPLISHMENTS DURING FY 1987

Soil as a Source of Indoor Radon

Because soil appears to be the principal source of radon in the indoor environment, particularly in those homes with elevated concentrations, studies of soil and soil properties have been integrated into several projects. One aspect of this research is the use of national data on surficial radium concentrations from the National Airborne Radiometric Reconnaissance This data set and our preliminary work with it are described in more detail in an earlier Annual Report.[1] Current efforts are focussed on assessing the degree of variability in the radium concentration in the surface soil within specific regional or geographic areas, and for the country as a whole. In this latter regard, a preliminary national map has been constructed from the data set, as shown in Figure 1. The data initially gridded at ~1.6 km intervals along the flightlines are regridded to larger, 20 × 20 km spacings in order to provide a map at a usable scale. It is apparent from this map that there are significant regional variations in the radium content of surface soils. In some cases, occurrences of houses with elevated indoor radon concentrations can be broadly associated with these areas. Examples of such areas are eastern Pennsylvania/northern New Jersey and eastern Tennessee/western North Carolina. In other situations, the association between apparent radium content and indoor radon is unknown or not as straightforward. One such example appears to be the relatively high mean indoor radon concentrations in the Fargo, ND area, yet the map suggests that the soil radium concentrations are not elevated significantly.

It is also apparent from the map that calibration anomalies exist between different areas, partly due to the fact that seven different subcontractors were used to collect the aerial radiometric data. Further, there are areas for which the data set contains no data, as indicated by white areas on the map, although most of the quadrangles covering the conterminous U.S. were flown. These problems will be investigated further. Smaller-scale maps for 1° × 2° quadrangles have been produced for selected areas, and offer the possibility of more detailed investigation of the relation between indoor radon and soil radium. Descriptive statistics for each quadrangle area have been compiled and again indicate considerable variation in the radium distribution by region.

Measurements of soil properties around homes have been conducted in conjunction with two field studies of indoor radon. Of particular interest has been both soil radium concentration and air permeability, conducted *in situ*. In the case of studies conducted in the Spokane, WA area, soil air permeabilities were of the order of 10^{-11} m^2, with about a factor of 5 range in these values. The emanating radium content of the soil ranged from 4.4 to 8.8 Bq kg m^{-1}, and the mean soil gas radon concentrations showed a similarly narrow range over 23 sites, from 10.9 to 24.9 kBq m^{-3}.[2]

In contrast to these measurements, soils in the vicinity of the seven study homes in New Jersey exhibit considerably greater variation in air permeability and soil gas radon concentration, both from site-to-site and within a specific site. Based on preliminary data from one home site, the soil permeabilities ranged over 4 orders of magnitude, from 1 x 10^{-8} to < 10^{-12} m^2. Soil gas radon concentratons varied from ~13 to over 3300 kBq m^{-3}, a range of more than 2 orders of magnitude. While this heterogeneity is not surprising, it does indicate that efforts to characterize radon-related soil parameters, either locally or regionally, must be done with caution.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division, and by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under contract No. DE-AC03-76SF00098. It was also partially supported by the Office of Environmental Engineering Technology Demonstration, Office of Research and Development, U.S. Environmental Protection Agency through Interagency Agreement DW89931876-01-0 with DOE, and by the Office of Radiation Programs, Office of Air and Radiation, U.S. EPA through Interagency Agreement DW89932609-01-0 with DOE.

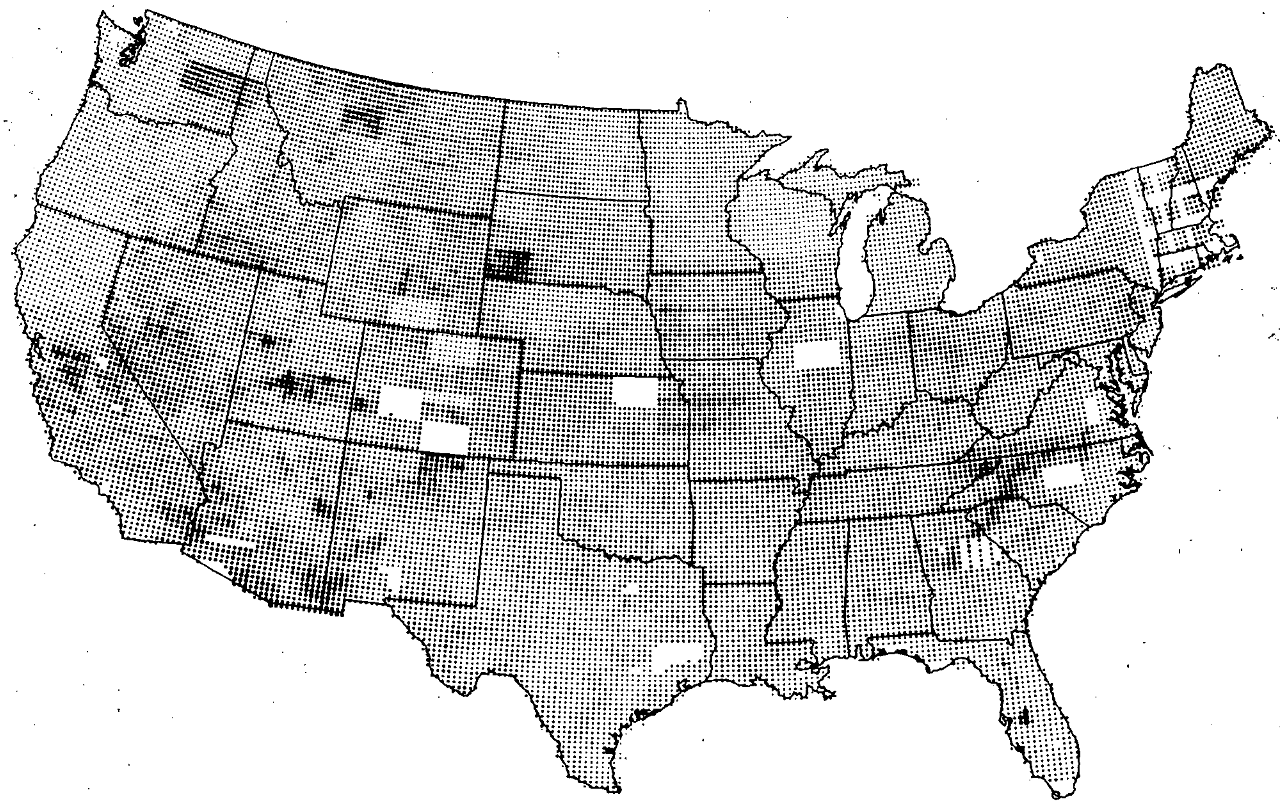

Figure 1. Mean surficial soil radium concentrations for 20 × 20 km areas of the coterminous U.S. compiled from NURE data. The dots vary in size, representing 6 radium concentration intervals: 0 - 20, 20 - 40, 40 - 60, 60 - 80, 80 - 100, and > 100 Bq kg^{-1} of soil [XBL-8711-4927A]

One area of new research recently undertaken by both the Indoor Radon and Indoor Organics groups is the application of research on soils and soil gas transport to studies of the movement of volatile organic compounds through soils and into buildings. There is evidence that in some homes located near municipal land-fill dump sites, soil gas transport may be a source of indoor VOCs. Results of our initial research are described in the chapter on Indoor Organics in this annual report.

Intensive Seven Home Study of Radon Entry and Control

Work was begun during FY86 on a detailed study of radon entry and removal in seven homes in New Jersey.[3,4] There are four components to this research: 1) house and site characterization measurements, 2) continuous monitoring of radon and environmental parameters, 3) diagnostic procedure development, and 4) installation and operation of selected radon reduction techniques. Field work was completed in the homes at the end of FY87 and final reduction and analysis of the data begun. The seven homes chosen for the study were located in north-central New Jersey, within a 25 km radius of Chester, NJ. These houses were one- or two-story detached frame houses with basements. The basement walls in each case were constructed of hollow-core concrete or cinder block. Forced-air heating systems were used in all but one house, where a hot-water heating system was employed. Initial (pre-mitigation) indoor radon concentrations ranged from 700 to 7600 Bq m^{-3} in the basements and from 480 to 2500 Bq m^{-3} in the living space of the homes.

A sampling of data from house LBL11 is illustrated in Figure 2. These data were acquired during a two-week period in November 1986, before mitigation systems were installed in the home. As can be seen, the first three curves—basement radon concentration, pressure difference across the basement walls, and indoor-outdoor temperature difference—appear to behave in a similar manner. The basement radon concentration varies by more than a factor of five within a 2 day period, and exhibits a diurnal variation extending for most of the two week

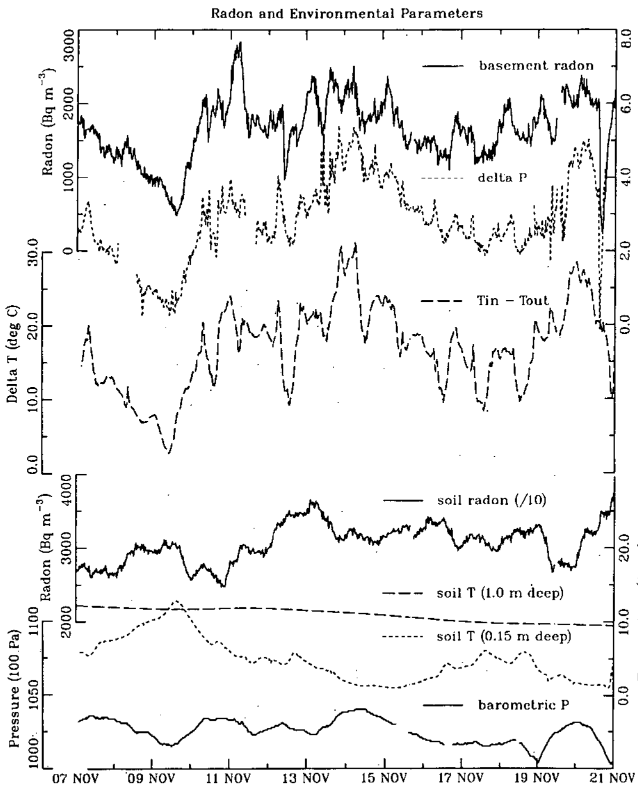

Figure 2. Continuous data on radon concentrations and environmental parameters during a two-week period in November 1986. The data interval is every 30 min. Note that in the case of the differential pressure data, the axis label is in terms of negative pressure. |XBL-873-1256|

period. These same patterns have been observed in some, but not all, of the houses in this study for much of the measurement period.

The average differential pressure between the basement and outside the building shell at ground level has been plotted so that an increasing negative pressure difference is shown as an upward change in the curve. These data exhibit variations similar to the radon concentration data, as does the difference between the indoor temperature at the first floor and the outside temperature. The indoor-outdoor temperature difference is one of the driving forces (the thermal stack effect) responsible for the pressure difference across the building shell. Wind loading on the building shell also contributes to the pressure difference, and might help explain some of the detailed differences in these curves. These data appear to confirm, at a general level, the importance of convective soil gas flow into buildings as a source of indoor radon.

Data from four of the other houses appear to follow a similar pattern, showing a correspondence between the temperature and pressure differentials and the resulting basement radon concentrations. In two of the houses, the preliminary data analysis indicates that peaks in the basement radon concentration apparently lag the corresponding increase in differential pressure, in some cases by a few hours.

Also shown in Figure 2 are radon concentrations in the soil gas, monitored continuously via a probe inserted through the basement floor, soil temperatures measured at two soil depths at a location approximately 1 m from the house, and the barometric pressure data for the same period. Neither the barometric pressure nor the soil-gas radon levels appear to be associated with observed fluctuations in basement radon concentrations. As can be seen, the soil temperatures show a slight downward trend during this two week period, which was a time of seasonal change in the weather.

Another aspect of this research has been the development and evaluation of a series of diagnostic procedures for identifying the specific means by which radon enters a given house, in order that suitable remedial radon reduction measures can be prescribed and installed.[5]

A general approach for radon diagnostics is shown in Figure 3. The premise for much of this

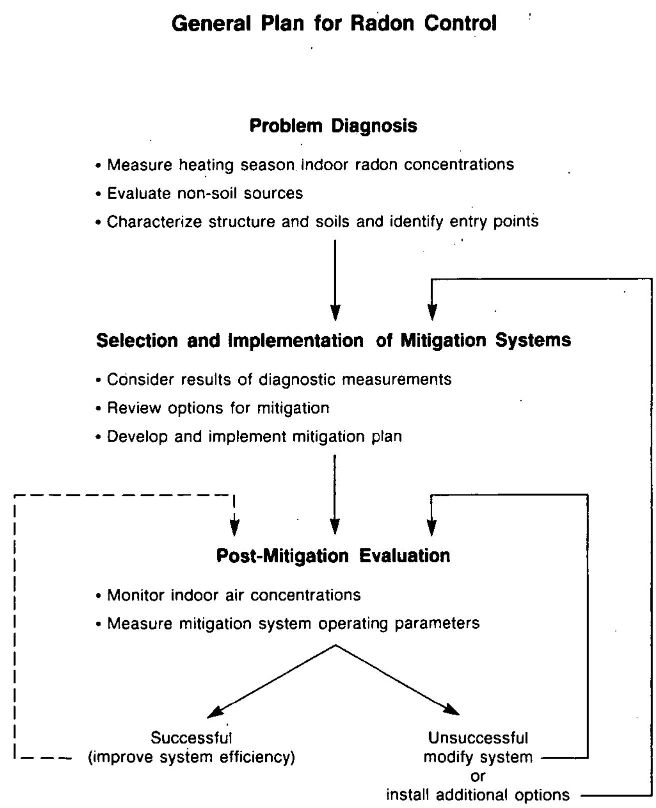

Figure 3. Schematic of a general approach to radon diagnostics and control. |XBL-871-8920|

discussion is that pressure-driven flow of radon-bearing soil gas is the most significant source of radon in houses with elevated radon concentrations, although the procedures do include a general evaluation of non-soil sources, such as water or building materials. An important step in the process is to determine or verify that the average indoor radon concentrations are above guideline values. Because indoor radon concentrations vary with as illustrated in the previous discussion, short-term measurements (< 4 days) are often not adequate to eliminate the possibility of false positives or negatives. This topic is also discussed below in another section of this report. Aspects of control strategies are also discussed in.[6]

Initial evaluation of a house with elevated indoor radon concentrations is based on visual inspection to help locate potential soil gas entry locations. The inspection process is augmented with a building survey questionaire, which can provide further detail and information on potential entry locations, leading ultimately to the specification of a suitable radon control system. In addition to the survey and inspection, tests of air flow communication below the basement floor slab are performed by drilling small holes through the slab at several locations and using a heavy-duty industrial or shop-type vacuum cleaner to depressurize the area below the slab. In this way, the permeability of the subslab zone can be measured, which is important information in assessing potential radon entry locations as well as in determining the viability of using subslab ventilation as a radon mitigation technique.

Alpha-scintillation (Lucas) cells are also important diagnostic tools in evaluating possible entry areas. Samples can be obtained from specific building zones, or using a small volume probe, from behind or within walls, drains or other areas that would indicate possible entry locations. In some cases, the use of a blower door to depressurize the building to ca. -10 Pa will assist in locating entry points. At greater depressurization, air flow through small cracks or other suspected entry points can be visualized with the aid of chemical smoke from commercially available smoke tubes. In some situations a hot wire anemometer may be used to quantify the amount of air movement into the building shell.

A blower door is also useful in determining the effective leakage area of different parts of the building structure. This information is important in establishing the leakage across the building substructure, where soil gas entry is likely, and the leakage of the building superstructure, which helps determine the natural ventilation rate of the building. This latter element can be important in the selection and sizing of heat recovery ventilation or basement pressurization as radon reduction methods.

Certain types of appliances or heating systems can add to the depressurization of the building substructure. By using a sensitive differential pressure instrument, the effect of the operation of these appliances or furnaces may be determined. Forced-air furnaces are very often a source of additional substructure depressurization, largely through leaky return air ductwork or the furnace cabinet itself. The thermal column established by the combustion exhaust through the furnace chimney may also add to the negative pressures. While these are important winter-time sources, attic or whole-house fans may also depressurize the house at times when the furnace system is not used.

Modeling Soil Gas Transport

Because pressure-driven flow is largely responsible for radon entry into buildings, especially those with elevated indoor radon levels, a theoretical model has been developed to simulate this phenomenon.[7] Based on a three-dimensional, finite difference computer code, the model incorporates 1) the generation and decay of radon within the soil, 2) radon migration through the soil due to diffusion and convective flow induced by the pressure difference developed across the building shell, 3) entrance of soil gas into the building via an assumed peripheral crack system at the basement floor-wall joint, and 4) the resultant indoor radon concentration.

Mathematically, the model first establishes a pressure field in the soil surrounding a house with a pressure differential, ΔP, across the building shell. A detailed discussion of the mathematics and the derivations are provided in another report;[7] the main elements of the approach are only summarized here. Using Darcy's law and the continuity equation for the mass balance for the soil gas, one obtains a general expression for the induced pressure field in the soil:

$$\vec{\nabla}\cdot(k\vec{\nabla}p) = 0, \tag{1}$$

where k is the air permeability at point (x,y,z) in the soil and p the induced pressure at the same point. The soil gas velocity field in the soil is then given directly by Darcy's law, namely:

$$\vec{q} = -\left(\frac{k}{\mu}\right)\vec{\nabla}p, \tag{2}$$

where μ is the dynamic viscosity of soil gas. Finally, the flux of radon through the soil is then given by the sum of convective and diffusive flow, where the diffusion term includes both a molecular diffusion term and a mechanical or hydrodynamic dispersion term. Specification of radon migration through the soil under steady-state conditions then allows one to evaluate both the steady-state radon concentration field in the soil, and the resulting radon entry rate into the building.

Numerical methods are used to solve the second order, linear partial differential equations for both the pressure and radon concentration fields, using a finite difference technique employing a discretization method. In order to simplify the task, three zones of permeability are established in the soil block surrounding the house. Within each zone, the permeability is assumed to be constant. These zones correspond to the bulk soil block, a region or layer adjacent to the walls, and a separate region beneath the floor slab. The thickness of these layers adjacent to the building shell can be specified. These separate regions are consistent with actual construction techniques. Next to a basement wall is a region that is backfilled with soil after the wall has been built which often has a higher permeability than the surrounding 'undisturbed' soil. In many houses, an aggregate layer is also established below the basement floor before it is poured in place.

The model allows specification of a number of parameters, including the spatial dimensions of these various permeability zones, the pressure difference across the building shell, and the physical dimensions of the crack system through which radon enters the building. By varying these parameters, the sensitivities and importance of these effects have been investigated. As one example, since the total entry rate of radon into the structure is a combination of the diffusive and convective fluxes, the importance of each component has been evaluated for different soil permeabilities and applied pressures. The results suggest, as expected, that the diffusional component has greater importance for low permeabilities and low applied pressures and that this diminishes with increasing permeability and/or applied pressure. At higher flows, the diffusion component is actually reduced, because the radon concentration gradient at the crack-soil interface is reduced.

Examining the effects of crack width and soil permeability on the pressure field indicates that crack size is important for low permeability soils, but for higher permeabilities, only the smallest crack dimensions affect the pressure field. An example of the calculated pressure profile in the soil is shown in Figure 4 for a crack width of 0.5 mm and a high soil permeability (10^{-10} m^2). A comparison of this result with that for a much lower soil permeability (ca. 10^{-14} m^2) shows that the pressure gradient in the soil is contracted toward the crack as permeability increases. This is due to the fact that flows increase as permeability increases, and the pressure drop across the 0.5 mm gap increases as well, thus reducing the pressure drop in the soil itself. At crack widths greater than 5 mm, the variation in soil permeability has little effect on the pressure gradient in the soil.

Similar analyses can be done for steady-state radon concentrations in the soil. One example is shown in Figure 5 for a very high permeability soil.

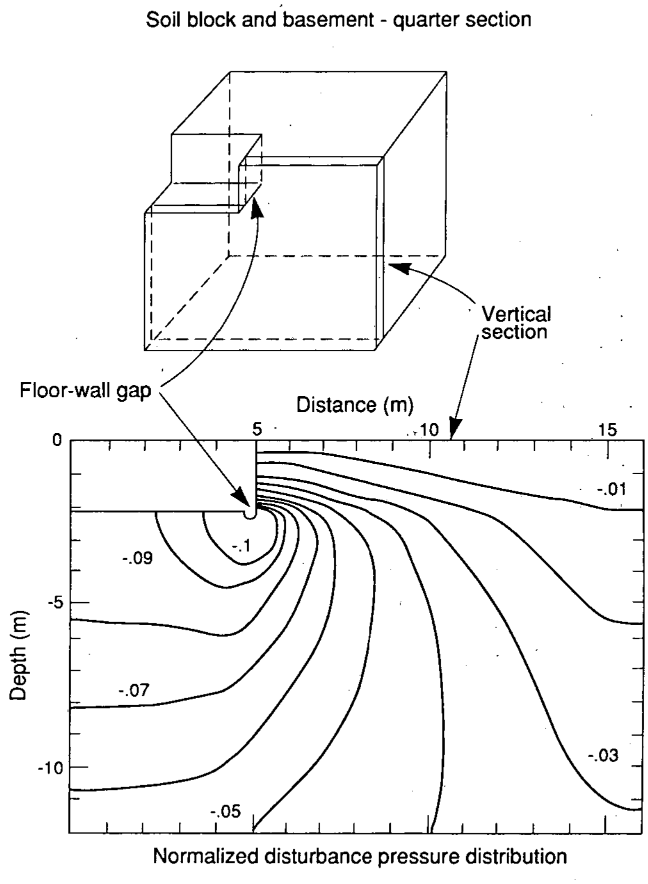

Figure 4. Modeling results for soil pressure gradient. The top portion of the figure is a schematic representation of the basement and the soil block in which it sits. The location of the vertical cross section presented in the lower portion of the figure is indicated. Due to symmetry, only a quarter of the basement and soil block is modeled. The lower portion of the figure shows profiles of the pressure field in the soil surrounding the basement. A 0.5 mm gap between the wall and the floor is assumed, and the soil permeability is 10^{-10} m^2. |XBL-886-11002|

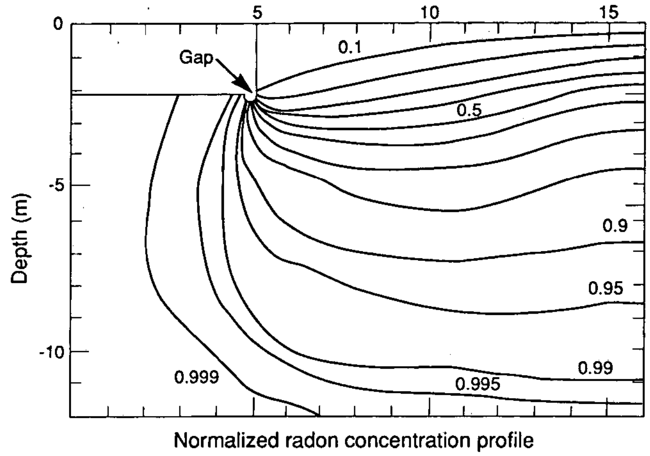

Figure 5. Soil gas radon concentration profiles for the same vertical cross section as indicated in Figure 6. The gap width is 5.0 mm and the soil permeability is 10^{-9} m^2. |XBL-886-11003|

As the figure indicates, the presence of the house affects the soil gas radon concentration at a distance of several meters away from the basement wall. As soil permeability decreases, the effect is less pronounced.

The model has allowed investigation in a systematic way of the interactions among various soil and house parameters. These analysis will be useful in interpreting experimental data obtained in actual houses, and in turn, some of the experimental data can be used to provide validation of components of the model.

The Response of Charcoal Detectors to Varying Radon Concentrations

Radon adsorption by charcoal is the basis for passive sampling devices that provide both an easy and inexpensive method of obtaining quick diagnostic measurements of ^{222}Rn levels. This method is well suited to γ-ray counting and typically requires exposure times of only a few days, unlike α-track devices with recommended exposure times of at least a month. But because Rn desorbs from charcoal as well as it adsorbs onto it, the response of charcoal-based passive samplers to time-variant Rn levels is an important consideration, especially in light of the evidence that typical Rn concentrations undergo diurnal as well as seasonal variations, as illustrated in Figure 3 above.

Two main types of charcoal-based passive samplers have been introduced, an open-faced device and one that incorporates a diffusion barrier that limits the rate of radon accumulation by the device, and at the same time, restricts the back diffusion rate of radon from the device. The operation of these devices, particularly under conditions of varying radon concentration, is not well characterized. Stimulated by our observations of diurnally-varying radon concentrations in homes we have undertaken a study of the the integrating characteristics of charcoal-based radon detectors.[8]

Models describing radon adsorption and desorption by charcoal canisters, both open-face and diffusion-limited, have been assembled. A detailed discussion of the modeling is provided in another report.[8] In general, the models are based on solving the one-dimensional diffusion equation,[9]

$$\frac{\partial y}{\partial t} = D\frac{\partial^2 y}{\partial x^2} - \lambda y, \quad y = f(x,t). \tag{3}$$

where x is the height in the charcoal bed above the bottom of the canister, y(x,t) is the concentration of ^{222}Rn in the charcoal, t is the time, D is the diffusion constant, and λ is the radioactive decay constant for ^{222}Rn.

Assuming that the lid is taken off at time zero, and that the canister previously had no ^{222}Rn in it beforehand, the initial condition is then y = 0 for all x. Additional boundary conditions at the bottom of the canister and when the top is exposed to the Rn in the environment are imposed to help solve the series of equations.

Employing a technique of using a series of linear functions to describe the time-varying radon concentrations in air along with separation of variables, one arrives at a series solution to y(x,t). Hence, knowing y(x,t) for all t, the total amount of ^{222}Rn in the canister at any time T_0 can be found by integrating across the thickness of the charcoal bed.

In the case of the diffusion-limited devices, the picture of the diffusion barrier was simplified somewhat in order to utilize the one-dimensional solution derived for the open-face device, described above. By assuming air in the immediate space after the diffusion barrier and just above the charcoal bed is well mixed and that the diffusion barrier connecting this space with the outside air can be described as an open cylinder, an iterative process is used to deduce the concentration of Rn in this well-mixed air for different times during the exposure. Again, employing the technique of using a series of linear functions to describe this time-dependent Rn concentration the differential equation can again be solved.

A set of experiments was then conducted to provide an empirical determination of the modeling parameters, such as diffusion coefficients, adsorption coefficients, and diffusion barrier dimensions. The parameters for the various detectors, both open face and diffusion barrier, were determined by first loading the canister with ^{222}Rn and then measuring the desorption from the canister into a space with low Rn concentrations over a period of a few days. These experiments were done by counting the 609 keV peak from ^{214}Bi, a radon decay product, with a 3 x 3 NaI detector in a low-background lead-shielded counting enclosure through which air was circulated.

In a second set of experiments, conducted in a chamber, several canisters of each type were placed in the two rooms of the chamber. One room had a high ^{222}Rn content, averaging between 3.5 and 7 kBq m^{-3}, and the other with a lower ^{222}Rn content, averaging between 200 and 1000 Bq m^{-3}. The actual ^{222}Rn concentrations were measured over time using continuous radon monitors. Several canisters were switched from room to room during the middle of the exposure to expose them to high-low, and low-high variations. Results of the experiment are summarized in Table 1. As can be seen from the table, comparisons between the model and the measured charcoal device concentrations are quite good, for both the open face and the diffusion barrier devices. These results also indicate that the diffusion-limited charcoal detectors do in fact integrate better than their open face counterparts.

This work has also demonstrated the limitations in using charcoal canisters to obtain integrated readings over short periods of time when the actual ^{222}Rn concentrations are changing.

PLANNED ACTIVITIES FOR FY 1988

A significant portion of the radon group research effort will be focussed on analysis of the large data set collected from the field study in New Jersey. Radon entry data will be analyzed and performance

Table 1. Response of Various Charcoal Canister Devices to Time-varying Radon Concentrations and a Comparison of Model and Measurement Results

Device	Exposure Condition*	Avg. [Rn]** (k) (1)	Charcoal Device Measured (2)	Charcoal Device Model Prediction	[(2) - (1)] / (1) (%)
Open-face Devices:					
OF#1:	H1	7.25	5.74	6.18	-21
	H1-3	5.48	3.48	3.52	-36
	H1-4	4.88	2.81	2.85	-43
	L1-4	0.81	0.34	0.30	-58
	L1,2H3,4	2.37	2.48	2.59	+5
	H1,2L3,4	3.33	0.74	0.56	-78
OF#2:	H1-4	4.88	3.29	2.52	-33
	H1,2L3,4	3.33	0.35	0.28	-90
	L1,2H3,4	2.37	2.44	2.48	+3
Diffusion Barrier Devices:					
DB#1:	H1	7.25	7.07	7.18	-3
	H1-3	5.48	5.03	5.00	-8
	L1,2H3	2.11	2.18	2.29	+4
	H1,2L3	4.37	3.37	3.59	-22
DB#2:	H1',2L3,4	2.92	2.55	2.41	-12
	L1',2H3,4	2.41	2.78	2.55	+15

* The exposure times were divided into four periods of almost the same duration. The letters H(igh) and L(ow) designate in which of the two rooms the detectors were placed. Period 1′ is slightly shorter than period 1.

** Average during exposure period determined from continuous radon monitor data of the radon reduction systems will be evaluated. Empirical models linking observed radon concentrations with parameters thought to influence radon transport will be developed. Other research will include continued investigation of the use of the NARR data set, coupled with other regional data sets on soils, house construction characteristics, etc., to provide a model for estimating regional variability in indoor radon.

Further investigation of radon transport through soils and into structures will be initiated this fiscal year. This work will consist of experimental studies of radon movement in soils using small structures with controlled leakage characteristics. In addition, the modeling of gas transport through soils will be expanded to incorporate more realistic, heterogeneous soil conditions.

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Field Surveys of Indoor Air Quality*

B.H. Turk, D.T. Grimsrud, J. Harrison, and R.J. Prill

Four field studies examining indoor air quality funded by the Bonneville Power Administration (BPA) were completed in FY 1987. The studies included (1) a comparison of new energy-efficient homes with new standard construction homes, (2) monitoring of existing single family dwellings undergoing weatherization to reduce energy consumption, (3) mitigation of excessive radon concentrations in 15 residences, and (4) a survey of 38 commercial and institutional buildings. All buildings were located in and around the Oregon cities of Portland and Salem; Spokane, Washington; and Coeur D'Alene, Idaho. Because of regulatory pressures from the Pacific Northwest Electric Power Planning Act, BPA instituted recommendations for energy conservation that have included methods for reducing the amount of outside air entering buildings. These studies examine whether concentrations of some indoor pollutants increase in response to the reduced ventilation and cause greater health-related risks.

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ACCOMPLISHMENTS DURING FY 1987

New Energy-Efficient Homes

Model Conservation Standards (MCS) for the construction of new energy-efficient houses include specifications calling for air infiltration packages leading to infiltration rates as low as 0.1 ach. These homes have air-to-air heat exchangers installed to raise the ventilation above 0.5 ach. Twenty-nine MCS homes were monitored along with 32 new homes, built according to standard construction practices, that served as controls. The goals of the study include comparing pollutant concentrations and installed ventilation rates in the two groups of houses along with an evaluation of pollutant source strengths.

The average air leakage area measured by fan depressurization for the MCS houses was approximately 46% lower than for the Control homes. However, measured ventilation rates, determined with a passive perfluorocarbon tracer (PFT) technique are virtually identical for both groups of houses, with a geometric mean of 0.30 ach for MCS houses and 0.26 ach for Control houses, yet are still lower than the design of 0.6 ach. From the data, it is estimated that the AAHX was responsible for providing an average 0.2 ach of additional ventilation to the natural infiltration in the MCS houses.

In general, indoor concentrations of radon and formaldehyde exhibited greater dependence on the region in which a house was located than on the construction practices by which it was built. Differences in radon levels between MCS and Control houses by region or for all houses are not considered significant. Radon concentrations were higher in homes in the Spokane/Coeur d'Alene region (geometric mean 96 Bq m^{-3}) due to the local highly-permeable, gravelly soils. Portland area homes had a geometric mean of 41 Bq m^{-3}. Eleven percent of all houses in this study exceeded the BPA mitigation action level of 185 Bq m^{-3} while 16% were above the EPA guideline of 150 Bq m^{-3}. Eighteen of the 61 houses (30%) had indoor formaldehyde levels above 100 ppb, a frequently cited guideline. The combined MCS and Control houses in the Portland area had a geometric mean formaldehyde concentration of 92.8 ppb, while Spokane area homes had a geometric mean of 59.5 ppb. This difference was much greater than that between all MCS and Control homes (82 ppb vs. 72 ppb). The regional difference is likely a result of different emission characteristics of pressed-wood products used in the two areas. Indoor formaldehyde concentrations also tended to be lower in older structures suggesting that emission rates of free formaldehyde decrease as construction materials age.

Water vapor concentrations were surprisingly similar both between groups of houses and between regions, even though outdoor concentrations were considerably higher in the Portland area. Average indoor concentrations ranged only from a low of 6.29 g/Kg in Spokane area MCS houses to a high of 6.81 g/Kg in Portland area MCS houses. Control house group averages were between these extremes. Water vapor levels in Control house bedrooms were significantly higher than in other locations in these homes. There were no significant spatial differences in the water vapor concentrations in the MCS houses, presumably due to the more uniform distribution of ventilation air by the AAHX.

Existing Homes

One hundred existing homes built prior to 1980 were tested and screened for HCHO, H_2O, and Rn using mailed passive samplers. Sixteen other homes were screened only for radon during a 30 minute visit by a technician using a continuous radon monitor. Forty eight of these homes with measurable levels of HCHO or Rn were then selected for more intensive monitoring to evaluate the effects of house tightening weatherization retrofits on the concentrations of these indoor air pollutants.

In the Phase I screening sample, 45 homes were located in the Spokane, WA-Coeur D'Alene, ID area and 71 homes were located north of Portland in Vancouver, WA. The majority of these homes had pollutant levels below most currently recommended guidelines and standards. Only one newly remodeled home had HCHO concentrations above 100 ppb (136 ppb), while 98% of the homes were below 80 ppb and the total group had a mean of 36 ppb.

The mean water vapor concentration was 6.15 gKg^{-1}, very similar to that measured in the new home study. Radon, however, appears to be a pollutant of concern in the Spokane River Valley area of Washington and Rathdrum Prarie of Idaho. The average heating season concentration for 46 new and existing homes in this area is 490 Bq m^{-3} Approximately 43% of these residences had concentrations above 300 Bq m^{-3}, the National Council on Radiation Protection and Measurements guideline. Concentrations were monitored in 14 of the 46 homes over the summer using passive samplers and were observed to decline by factors of up to 16 from heating season values. An examination of soils, domestic water supplies, and building materials strongly suggests that the high concentrations are due to the local subsurface soil composition and structure.

The more intensive monitoring of the 48 homes to be weatherized in Phase II began in December. In each home, equipment was installed to monitor temperatures, windspeed and direction, and radon concentrations continuously. Passive monitors for pollutants and ventilation were also deployed along with instruments for making time-weighted average measurements of carbon monoxide (CO) and respirable suspended particles (RSP). This equipment was operated for a 7-10 day period before and after each stage of weatherization, which could have included wall insulation and "house doctoring" along with caulking, weatherstripping and storm windows.

Analyses of measurements show that the standard BPA weatherization package reduced the leakage in the forty houses by approximately 12 percent while wall insulation had no measurable effect. House doctoring, an intensive weatherization technique, reduced leakage another 26%.

Preliminary examination of the pollutant concentration measurements reveals that concentrations of water vapor and formaldehyde increased following weatherization by 17 and 4 percent, respectively, while radon decreased by 18%. These results will change when adjustments are made for corresponding changes that were seen in the concentrations measured in the eight control houses during the course of the study.

Detailed analysis of the results of the study continues in FY88.

Radon Mitigation

As part of a series of surveys of the effects of weatherization on indoor air quality in the Pacific Northwest, radon concentrations were measured in 46 residential buildings in the Spokane River Valley in eastern Washington and northern Idaho. Approximately 57% of these homes exceeded the 185 Bq m^{-3} guideline established by the Bonneville Power Administration (BPA) for remedial action. The average in these 46 residences was 490 Bq m^{-3}. Fifteen of these homes were subsequently selected for research on remedial techniques, with the objectives of evaluating several possible mitigation measures and of reducing the long-term average radon concentration during the heating season to below 185 Bq m^{-3} in each house.

A number of diagnostic procedures were utilized to assist in identifying the likely radon entry locations. Because pressure-driven flow of radon-bearing soil gas is generally thought to be the predominant source of radon in houses with elevated indoor concentrations, several procedures were directed toward this source.

Continuous monitoring of indoor radon concentrations, indoor and outdoor temperatures, and wind speed and direction was established in each home to provide data on premitigation baseline conditions as well as provide a means of evaluating the radon mitigation systems. In addition, seven-day-average ventilation rates were measured at the same time, using the passive perfluorocarbon tracer (PFT) technique. Local meteorological data on winds, precipitation and barometric pressure were obtained from the National Weather Service.

Several mitigation techniques were evaluated in the course of the study. Heat-recovery ventilation (an air-to-air heat exchanger, or AAHX) was employed in three houses; in two of these systems ventilation air was supplied and exhausted from the basement respectively. Reductions of about 60, 67, and 75% were achieved. In general, the AAHX units were sized to add about 1 ach of ventilation. Since the units, when properly balanced, have a neutral effect on the pressure distribution across the building shell, the radon source strength should not be affected and the radon concentration should therefore be related inversely to the ventilation rate. Use of an AAHX to control radon appears to be best suited for those cases where initial indoor concentrations are not excessive (<750 to 1500 Bq m^{-3}) and/or where the initial building ventilation rate is low.

Subsurface ventilation (SSV) systems were implemented in five homes, in a variety of configurations. In general, the systems consisted of 7.5 cm diameter PVC pipes inserted in one or more (up to four) locations through the basement floor slab, or in one case, ESP119, along the exterior of the foundation wall, to a point below the wall footer. The pipes end approximately 30 cm below the floor in a 60 cm diameter dry sump 60 cm deep, backfilled with clean gravel. For the interior systems, the pipes are routed either singly or in a manifold through the top of the basement to the outside of the house. Here, the pipes are connected to a centrifugal blower, sized to develop more than 125 Pa at more than 25 L/s flow.

The effects of SSV operated in a depressurization mode were dramatic for four of the five houses, with almost all configurations leading to concentrations below the 185 Bq m^{-3} guideline adopted by BPA. In three of the five houses, the SSV system was used to pressurize the soil below the slab. In all three cases, the first floor radon concentrations dropped further. In house ESP111, subsurface depressurization resulted in a factor of two reduction in first floor radon concentration, while subsurface depressurization produced a concentration reduction of more than a factor of 10 over baseline conditions. It appears that in highly permeable soils, characteristic of this region, pressurization of the soil below the basement slab dilutes the soil-gas radon concentrations. Thus, even though the pressure differential across the building substructure is increased somewhat by the sub-slab pressurization, the soil gas that enters has a reduced radon concentration. This system requires further study, particularly in situations were the soil permeabilities are lower than in the Spokane River Valley.

Basement overpressurization was used for four homes. The basements in each home were first sealed, including leakage paths between the basement and first floor. The basements were pressurized with a 100 - 200 L/s fan, using heated air from the first floor. This technique caused first-floor radon concentrations to be reduced below 185 Bq m^{-3}.

Basement pressurization and subslab ventilation were compared in one house, ESP120. This particular house had stone basement walls and a partially finished basement. The substructure leakage area was large; an estimated 20 percent of the total air infiltration into the house was soil gas, resulting in the relatively high indoor radon concentrations observed. This large substructure leakage may help explain why basement pressurization was somewhat more successful than subsurface ventilation.

Sealing techniques, by themselves, yielded only slight reductions in indoor radon concentrations, due in part, to the difficulty in gaining access to all the wall and floor surfaces in finished basements. Sealing the membrane between the crawlspace and the first floor produced modest reductions in first floor radon concentrations. Ventilation of the crawlspace areas also helped reduce radon levels. With the addition of mechanical ventilation to the crawlspace in one house, further radon concentration reductions were observed.

Commercial and Institutional Buildings

A survey of 38 commercial and institutional buildings involved monitoring of ventilation rates and indoor air pollutant concentrations. The objectives were to (1) inventory these parameters in non-residential, non-industrial facilities, (2) furnish data to assist in establishing energy conservation and ventilation guidelines and, (3) examine relationships between indoor air quality and ventilation rates. Pollutants monitored included formaldehyde, water vapor, radon, nitrogen dioxide, respirable suspended particles, polycyclic aromatic hydrocarbons, carbon dioxide, and carbon monoxide. Neither volatile organic compounds (other than formaldehyde) nor airborne microorganisms were monitored in this study because of budget limitations. Two buildings were monitored twice for a total of 40 building assessments. Buildings ranged in age from 6 months to 90 years, in size from, 28 to 34,000 m^2, and in occupancy from 25 to 2500 people. From 6 to 20 pollutant sampling sites were located in each building during the two week (10 working day) monitoring period. Sampling was started at the beginning of each working day and stopped at the end of occupancy for an accumulated minimum of 75 hours. Selected RSP filters were analyzed for up to 16 polycylic aromatic hydrocarbons (PAH) including benzo(a)pyrene (BaP). Carbon dioxide (CO_2) was monitored at up to two locations for a one day period, while CO was sampled at up to seven locations for one 7-10 hour day. Twice daily observations of the ventilation system were recorded for use during a later tracer decay ventilation test. Data were also collected that describe building construction, materials, occupancy, smoking policies, and activities. Ventilation rates were measured in all buildings with a one time tracer dilution and decay test conducted over one 12-hour period during unoccupied hours. The ventilation systems were set up to mimic the conditions of the two week pollutant monitoring period, while a centrally located gas chromatograph with an electron capture detector monitored the decay of sulfur hexafluoride (SF_6) at up to nine building locations.

In general, measured ventilation rates were high and pollutant concentrations were generally quite low and seldom exceeded commonly recognized standards and guidelines.

High water vapor concentrations may have caused problems of occupant comfort at sites in six buildings, most of which were monitored during higher temperature summer months.

Carbon dioxide eight-hour averages ranged from a low of 340 ppm to a high of 840 ppm with a peak 15 minute reading of 1290 ppm in one classroom. Readings rarely exceeded 800 ppm.

Only 29% of the eight-hour time-weighted average carbon monoxide measurements were above the minimum detectable level of 2 ppm.

Nitrogen dioxide levels at only two of 245 sites exceeded the EPA ambient (outdoor) annual air standard of 50 ppb. Most sites with elevated concentrations were exposed to outside air containing NO_2 from vehicular exhaust.

Of all pollutants monitored, respirable suspended particle (RSP) concentrations most frequently exceeded conservatively recognized guidelines, with occurrences usually related to nearby tobacco smoking. Building mean RSP ranged up to 67 $\mu g/m^3$. It is estimated that approximately 34% of the smoking sites in a similar sample would have RSP concentrations above the annual EPA limit of 50 $\mu g/m^3$ for suspended particles whole diameters are less than 10 μm (a larger subset of suspended particles than RSP).

Polycyclic aromatic hydrocarbon concentrations, including benzo(a)pyrene, were positively correlated to RSP concentrations and, thus, to nearby smoking with a maximum B(a)P concentration of 9.67 ng/m^3, considerably above the U.S. ambient urban concentration of 2 ng/m^3.

Formaldehyde concentrations were quite low. The averages in only 21 buildings were above the 20 ppb detection limit. It is estimated that only 3% of all similarly selected sites would have concentrations above the ASHRAE 100 ppb guideline.

The geometric mean of all radon measurements was 20 Bq m^{-3}, similar to levels found outdoors, with only one building having concentration of concern at 290 Bq m^{-3}. The latter condition is likely due to open soil in the basement and a network of underground service tunnels allowing ready entry of the gas.

The one-time ventilation measurements from all buildings average 1.5 ach and ranged from a low of 0.2 ach to 4.1 ach. Buildings with low ventilation rates were not usually associated with indoor air quality problems, although local ventilation (i.e., ventilation rates in specific regions or rooms) may fall below ASHRAE recommendations of 5 cfm/occupant in non-smoking areas and 20 cfm/occupant in smoking areas.

Correlation is weak between pollutant concentrations and ventilation rates (both with outside and recirculated air). This is probably due to a larger variability in source strengths between buildings than ventilation rates.

PLANNED ACTIVITIES FOR FY 1988

Analyses of data from all the projects will be completed and journal articles containing the major results of the studies will be written.

Volatile Organic Contaminants In Indoor Air*

J.M. Daisey and A.T. Hodgson

Energy conservation has become an integral part of current building practices in the U.S. Reductions in ventilation rates have been found to be a particularly cost-effective means of conserving energy. However, decreased ventilation in combination with increased uses of synthetic building materials and consumer products in new and renovated buildings have been associated with increased complaints about "sick building syndrome" and related losses of work days. Emissions of volatile organic compounds (VOC) from materials used to finish interiors of buildings are suspected to play a significant role in "sick building syndrome." The major sources of these compounds have not been fully identified nor are the factors controlling their indoor concentrations well understood.

The goals of the Indoor Organic Chemistry Group are to identify the airborne contaminants that contribute to "sick building syndrome," to identify their sources and to develop a fundamental understanding of relationships between building materials, energy-conserving construction practices and ventilation so that effective mitigation strategies can be developed. This research has targeted VOC which include irritants and carcinogens and which have been shown in previous work in this laboratory to be emitted from widely used interior building materials. In FY1987, the specific research objectives were:

1. To program the temperature and humidity controllers of the Environmental Chamber and evaluate Chamber performance;
2. To investigate relations between ventilation rate and VOC source strengths in both field and laboratory experiments;
3. To develop a conceptual framework for theoretical models to describe emission rates of VOC from interior building materials as functions of ventilation rate, material age, chamber temperature and mixing and loading;
4. To investigate the effectiveness of portable air cleaners in reducing NO_2 and VOC in indoor environments;
5. To analyze the data from field experiments on personal exposures to methylene chloride from paint removers to determine exposures for various use scenarios and

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environments, to evaluate mitigation strategies and to evaluate the predictive capability of the mass-balance exposure model;

6. To determine indoor concentrations of extractable organic matter and polycyclic aromatic hydrocarbons in respirable particles collected in woodburning homes in Wisconsin.

ACCOMPLISHMENTS DURING FY 1987

Environmental Chamber

The temperature and humidity controllers for the Environmental Chamber were programmed and Chamber performance was evaluated. Background decay rates for NO_2 and six VOC were found to be 0.1 h^{-1} when the Chamber was operated in static mode. Decay rates were also found to be very reproducible in duplicate Chamber experiments.

Measurements of VOC in Large Buildings

A long-term study of a new office building in Portland, OR was begun in collaboration with R. Grot of the National Bureau of Standards. The objectives of the study are: 1) to determine long-term temporal changes in source strengths of VOC over a period of a year; 2) to identify the major sources of VOC in the building; 3) to determine short-term temporal changes in the source strengths of VOC as a function of building ventilation rates; 4) to determine temporal variations in the concentrations and source strengths of VOC over one week.

The building has seven office stories with three return air shafts. The three basement levels, used as a garage, have a separate ventilation system. Occupancy of the building was begun in April, 1987 before the building was completed. The building was completely occupied by the end of August, 1987. The major interior finish materials in the building are the same on each floor. No smoking is permitted on the office floors. Continuous ventilation measurements are being made by R. Grot using SF_6. The range of ventilation rate for the building is 0.5 to 2.0 air changes per hour.

A survey of the building was completed, the major interior finish materials were inventoried and samples of VOC were collected in the building during two field experiments. Major finish materials in the building include carpet tiles, carpet spray adhesive, rubber tile floor and adhesive in the stairwells, vinyl base cove and adhesive, painted gypsum board walls, office furniture and partitions. The VOC samples were analyzed by gas chromatography-mass spectrometry (GC-MS) to identify and quantify individual VOC. A portion of each sample was also analyzed for total hydrocarbons (THC $> C_4$) using a flame ionization detector with no chromatographic separation. Twenty-three individual compounds, C_9 through C_{12} aliphatic hydrocarbons, were identified.

The sums of the concentrations of the individual VOC in the building, which were quantified with GS-MS, averaged approximately 0.5 mg-m^{-3} in both August and October. By comparison, the average concentrations of the THC were about ten to twenty times higher. The latter measure includes many branched-chain hydrocarbons for which analytical standards are not available and which therefore cannot be individually quantitated. The concentrations of the THC, which were 4-10 mg-m^{-3}, are in the range in which irritant effects have been observed in subjects exposed to a synthetic mixture of 20 VOC in a chamber.[1] Some of the compounds in that mixture were present in the Portland building, although at lower individual concentrations. Specific source strengths for the sum of the individual VOC and for THC, were calculated from a single-equation mass-balance model. Based on the THC concentrations, the specific source strengths for the building were in excess of 4 mg-kg^{-1}-h^{-1}. No significant change in specific source stengths was observed between August and October.

Development of Models

Previous work in this laboratory showed that a six-fold increase in the ventilation rates in two large buildings decreased the concentrations of VOC by only one-half to one-third.[2] It was hypothesized that the emission rates of VOC were dependent upon the concentration gradient between the source and the indoor air as a driving force. This effect was also noted in small chamber measurements of VOC emissions from an assemblage of carpet and carpet adhesive. There is a need to develop quantitative models for this phenomenon so that the effects of ventilation changes can be reliably predicted and so that emissions measurements in small chambers can be reconciled with those made in large chambers and in buildings. An understanding of this effect is also important for the development of standard methods of measuring emissions rates. During FY 1987, a conceptual framework for a model was developed in collaboration with M. Sherman. The effective ventilation concept developed by Sherman and Wilson, will provide the basis of the model.[3] Experiments were designed to determine whether material bulk resistance or air resistance dominate the rate of emissions of VOC from a given material. The base cove or carpet adhesive from the Portland building will be used for the planned experiments.

Efficiencies of Portable Air Cleaners for the Removal of NO_2 and VOC

An increased public awareness of indoor air pollution has resulted in the development of a substantial market for portable air cleaners for use in residences and offices. Portable air cleaners are designed primarily for removal of suspended particles such as pollen and tobacco smoke. Recently, some manufacturers have claimed that their devices also remove gaseous pollutants such as oxides of nitrogen and sulfur and VOC. There is, however, little information available to consumers on the performance of these devices, other than that provided by the manufacturers.

A study was undertaken to determine if portable air cleaners, equipped with charcoal filters, have any efficacy for the removal of NO_2 and VOC at concentrations similar to those found in buildings. Experiments were conducted with four portable air cleaners using the 20-m^3 Environmental Chamber operated in static mode. For each air cleaner, the Chamber was spiked with NO_2 and a mixture of six VOC. The air cleaner was operated in the chamber for several hours. The concentration of NO_2 was continuously monitored and samples for subsequent analysis of VOC were periodically collected. Decay rates due to operation of the air cleaner were calculated as the difference between the decay rates in the Chamber with the air cleaner in operation and the Chamber background decay rate.

Table 1 presents the effective cleaning rates (ECR) for the VOC and NO_2. This is the product of the removal rate times the volume of the Chamber (20 m^3) and provides a measure of the effective volume of air from which NO_2 and VOC are removed by the air cleaner in one hour. This measure is useful for evaluating the effects of air cleaners in rooms of different sizes or for comparing air cleaning to ventilation as an indoor air quality control technique. Duplicate experiments were conducted with the Air Cleaner D to assess experimental variability. The same filter was used in both experiments.

There were substantial variations among the air cleaners with respect to the ECR for NO_2 and VOC. For Air Cleaners A and D, the ECR ranged from 31 to 51 m^3-h^{-1} for five of the VOC. The ECR for NO_2 averaged 75 m^3-h^{-1} for Air Cleaner D and 42 m^3-h^{-1} for Air Cleaner A. Since Air Cleaners B and C had very low ECRs, they have very little utility as control devices for NO_2 and VOC.

The ECR for NO_2 decreased from 79 to 71 m^3h^{-1} in the second experiment with Air Cleaner D. This difference was statistically significant ($p=0.01$). The ECR for the n-heptane, 2-butanone and toluene were also lower and significantly different ($p \leq 0.05$) in the second experiment. Differences in ECRs for the remaining VOC were not significantly different.

Of the three air cleaners, Unit D had the highest removal rate for NO_2. Unit B had the lowest removal rate for NO_2, which was only about 2.5 times greater than the background decay rate. None of the air cleaners effectively removed dichloromethane, an organic solvent commonly used in paint removers and other consumer products. The vapor pressure of this compound at 25°C is 427 mm and is four times higher than that of the compound with the

Table 1. Effective Cleaning Rates for NO_2 and VOC.

	Effective Cleaning Rate (m^3h^{-1} ± 95% C.I.)				
				D	
Compound	A	B	C	Exp 1	Exp 2
NO_2	42 ± 1	5.14 ± 0.08	6.2 ± 0.2	79 ± 1	71 ± 2
Dichloromethane	2 ± 1	0	0	0	0
2-Butanone	31 ± 4	0	8 ± 2	49 ± 13	37 ± 4
n-Heptane	47 ± 1	3.1 ± 0.6	18 ± 1	51 ± 2	41 ± 3
Toluene	43 ± 3	3.2 ± 0.6	17 ± 1	45 ± 2	41 ± 2
Tetrachloro-ethylene	41 ± 2	2.5 ± 0.6	14 ± 1	44 ± 2	41 ± 2
Hexanal	37 ± 6	4.6 ± 0.9	10	39 ± 6	18 ± 4

next highest vapor pressure, 2-butanone (95.5 mm). Air Cleaners A and D both had ECRs for the remaining VOC of about 40 m^3-h^{-1}. These two devices operate at high flow rates and incorporate relatively large amounts of charcoal. Air Cleaner B did not remove 2-butanone and had low removal rates for the remaining VOC.

Exposures to VOC from Use of Consumer Products

Usage of consumer products in buildings and residences can be a major source of VOC in indoor air. High exposures to methylene chloride (CH_2Cl_2) from the use of paint removers and aerosol finishes are of particular concern since this compound is metabolized to CO leading to elevated levels of carboxyhemoglobin and possible anoxic stress. In addition, this compound has recently been reported to be a carcinogen in animals.

Source strengths and personal exposures to CH_2Cl_2 were previously characterized in the Environmental Chamber at two ventilation rates for typical applications of paint removers and aerosol finishes.[4] This investigation was extended in 1987 to include field measurements of personal exposures to CH_2Cl_2 from paint removers in residential environments for a variety of use scenarios.[5] The objectives of the field measurements were to identify practical ways to minimize personal exposures resulting from the use of paint removers and to evaluate the mass-balance model previously developed for predicting exposures in the residential environment.

A total of 21 experiments were conducted outdoors and indoors in a garage, a basement workshop, and in large and small rooms of a house. In the work areas, ventilation patterns and rates were varied by opening windows and doors and by the use of a household fan. Finishes were removed from uniformly-prepared panels or from chairs. The personal exposure of the worker was determined by continuous measurement of CH_2Cl_2 in a pumped breathing zone sample.

Personal exposures resulting from the outdoor use of paint remover were very low (6-36 ppm-h). Exposures from the use of paint removers indoors without mechanical exhaust ventilation were considerably higher, 190 to 2090 ppm-h. In each indoor location, an open window or exterior door reduced exposures by one-half relative to the closed condition. Exposures were greatly reduced by a fan placed near the work area, exhausting through an open window (11-142 ppm-h).

A single-equation mass-balance model was used to produce estimates of theoretical exposures for experiments conducted indoors. The efficacy of the model for predicting exposures was evaluated by comparing the theoretical and measured personal exposures. The model performed best for small-volume work areas with low ventilation rates. In general, the model had an accuracy of ± 50 percent when applied to experiments conducted in enclosed work areas without an exhaust fan.

Effects of Woodburning Stoves on Indoor Air Quality

Deterioration of outdoor air quality due to residential woodburning has been widely documented. To date, most studies of indoor air pollution have focused on total or respirable particulate matter concentrations and have sought to assess the impact of woodburning stoves on indoor air quality by comparing indoor and outdoor levels. In a pilot study, the effects of woodburning on indoor particulate air pollutants were examined by comparing air quality during woodburning and non-woodburning periods. Concentrations of respirable particulate matter (RSP) (D_{50}=3.5um), dichloromethane-soluble (DCM) and acetone-soluble (ACE) particulate organic matter and eight polycyclic aromatic hydrocarbons (PAH) were compared in seven Wisconsin homes.[6]

There were no significant differences between RSP concentrations during the woodburning and non-woodburning periods. Concentrations of the total organic-soluble matter (DCM plus ACE), however, averaged 10.4 $\mu g/m^{-3}$ during woodburning periods which was approximately twice the average concentration during non-woodburning periods. The concentrations of total measured PAH were 2 to 46 times higher when the woodstoves were in operation. The source strength for the sum of the DCM plus ACE fractions was estimated to be 1.5 mg-h^{-1}. This is consistent with the range of the source strengths of total particulate matter reported for airtight woodburning stoves.[7]

Soil-Gas Transport: A Mechanism of Indoor VOC Exposure

Human exposures to toxic VOC from hazardous waste sites can occur through several routes. Most investigations have focused on exposures which occur through ingestion of contaminated water or inhalation of outdoor air contaminated by releases of VOC from such sites. Another potentially significant exposure pathway is pressure-driven flow of VOC contaminated soil gas into building substructures and the subsequent distribution of VOC throughout the building. This flow is driven by the pressure gradient established across the building substructure and soil by thermal differences between indoors and outdoors, by wind loading on the building superstructure, and, in some instances, by the operation of mechanical systems (e.g., unbalanced exhaust ventilation).

Evidence of the importance of this pathway is provided by work at LBL that has shown that this is the major pathway of exposure for radon, but there has been almost no research on the significance of this pathway for VOC. In the fall of 1987, field experiments were conducted at a house with a full basement located near a landfill in California. The objectives of these experiments were: 1) to determine the identities and concentrations of VOC in soil gas, indoor and outdoor air and well water at the site; 2) to measure source strengths for VOC entering the house by gas-phase migration through the soil; and 3) to measure the source strengths of VOC due to the use of heated well water for showers.

The field experiments were completed and all samples have been analyzed for VOC. The data from the field experiments are now being analyzed. Some preliminary results, however, are available. The major VOC identified in the soil gas and well water were Freons 11 and 12, tetrachloroethylene, and 1,1,1-trichloroethane. These compounds were also found in the house. Source strengths of these compounds increased in the basement as the house was depressurized, supporting the hypothesis that VOC can be transported into a building by this mechanism. Exposures to the VOC from soil-gas transport will be compared to those from uses of VOC-contaminated water.

PLANNED ACTIVITIES FOR FY 1988

- Complete field experiments on the spatial and temporal variations in source strengths of VOC in the Portland office building and begin to analyze the data with respect to ventilation rate.
- Conduct Chamber experiments on emissions of VOC from building materials.
- Continue work on the development of models for the mass transport of VOC from building materials and for source identification of indoor air pollutants.
- Prepare a paper on the results of the pilot study on a tracer method for sources of indoor particulate matter.
- Complete Chamber experiments on the portable air cleaners; prepare a report and a paper on the results of the experiments.
- Analyze the results of the field experiments on pressure- driven flow of VOC-contaminated soil-gas; prepare a report and a paper on the results.
- Conduct pilot studies of the heterogeneous reactions of NO_2 on interior materials found in buildings.
- Serve as a member of the National Research Council's Committee on Advances in Assessing Human Exposures to Airborne Pollutants.

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Indoor Exposure Assessment*

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The Indoor Exposure Assessment Project has three major research themes: 1) to continue the development of a macromodel to characterize the frequency distribution of exposures to indoor pollutants; 2) to compile a data base of field measurements of indoor pollutants; and 3) to conduct assessments of the health risks associated with exposures to indoor air pollutants. Conceptually, the first two projects supply the exposure data needed for the third project of assessing health risks from indoor air pollutants.

In FY 1987, modeling efforts assessing the distribution of indoor exposures to combustion pollutants were continued; the concentration of indoor pollutants (CIP) data base was expanded; and the overall assessment of carcinogenic risk from indoor exposures was advanced.

MACROMODEL TO ASSESS INDOOR EXPOSURE DISTRIBUTIONS

Accomplishments During FY 1987

A major effort of the Indoor Exposure Assessment Project has been to utilize available information on the behavior and occurrence of indoor pollutants as a basis for assessing, in a systematic way, the distribution of public exposures to important classes of indoor pollutants. An important manifestation of this effort has been the development of elements of a model that calculates such exposure distributions, based on mass-balance principles and on available data on the factors affecting indoor concentrations. Initial efforts of the project focussed on the problem of estimating exposures to combustion emissions, and these efforts have expanded with the participation of other contractors supported by the Department of Energy's Office of Environmental Analysis. (These were K. Novak at Brookhaven National Laboratory, L. Green at Mueller Associates, Inc., and A. Smith-Reiser at Energetics, Inc.).

Many previous efforts have focused on specific aspects of indoor air pollution due to combustion sources.[2] However, there does not exist a cohesive model that can characterize the distribution of indoor combustion pollutant concentrations in residences on a regional, national, temporal, and/or source basis. It is the goal of this project to develop, calibrate and verify such a distributional model, initially for combustion emissions, then for other pollutant classes. Such a model will be a useful tool to 1) quantify the impact of combustion sources on indoor air quality (IAQ), 2) identify high-risk populations exposed to high indoor pollutant concentrations, 3) direct policy decisions regarding energy conservation, new housing codes, and source emission rates, 4) identify key parameters to target for control/mitigation efforts, 5) assist in the quantification of pollutant exposures for epidemiology studies, and 6) direct data collection efforts of future national/regional IAQ field studies.

The model is based on, and is an expansion of, mass balance principles commonly used in IAQ studies. Keys to the model include the characterization of building stock parameters relevant to IAQ (e.g., house volume, air exchange rate), the investigation of the market penetration of combustion appliances and other indoor combustion sources, and the development of source usage models. The macromodel takes advantage of existing laboratory and field research on appliance pollutant emission rates and pollutant-specific building penetration factors and reactivity rates. The model also utilizes existing

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regional and national data (from utilities, state agencies, federal agencies and trade organizations), when available, for model inputs. The model utilizes deterministic and Monte Carlo simulation techniques to combine all of the inputs yielding indoor pollutant concentration distributions.

The first phase of this project is to develop the model from mass balance principles and incorporate existing data into the model. Initial efforts in the development phase focus on carbon monoxide (CO), nitrogen dioxide (NO_2), and respirable suspended particle (RSP) levels in single-family residences.

The second phase of this project is to calibrate the model. Calibration can take two forms. First, the equations in the model may need adjusting or expanding based on field studies designed to test one or more parts of the model. For example, the equation describing the usage of primary space heating appliances may need modification based on a field study designed to test that part of the model. This first type of calibration can be considered to fall under the general category of model improvements. This second type of calibration activities fall under the general category of data improvement. For example, a field study designed to measure the pollutant emission rate distribution of gas wall furnaces would provide additional information to calibrate the model. Sensitivity analyses will be used to rank the relative importance of various information gaps to efficiently guide calibration efforts involving field studies.

The final phase of the project is to conduct a verification of the entire model by comparison wit data developed over a period of years. Although specific aspects of the model will have been tested as part of the calibration efforts, the complete model will still need validating in order to establish its adequacy for the purposes intended.

Although the initial modeling efforts concentrate on three combustion pollutants, the model is being developed with explicit attention to future expansion of the model to describe other indoor air pollutants concentrations from a wide variety of sources.

This effort is essentially an expansion of previously published ideas directed at efficiently utilizing monitoring and modeling efforts to understand the indoor combustion-related air pollution picture[3,4]. The indoor pollutant concentration distributions developed as part of this study can be combined with activity patterns to assess residential exposures to combustion pollutants. Exposure to residential indoor pollutants is part, often the dominant part, of a person's total exposure[5].

Preliminary modeling and data collection efforts have identified several information gaps that need to be filled. An important information gap is the distribution of venting factors for partially vented appliances such as wood stoves and malfunctioning vented appliances. Other information gaps include appliance (or source) usage rates and some pollutant emission rates. Although the pollutant emission rates of several combustion appliances have been tested in the laboratory, field studies need to be conducted to verify or modify the laboratory results. Different appliance types, ages, and models and different frequencies of maintenance can cause appliances in the field to have different pollutant emission characteristics than the few appliances that have been tested under laboratory conditions. Numerous other, yet less significant, information gaps have also been identified.

The preliminary modeling results do support many intuitive notions regarding populations exposed to the highest indoor pollutant concentrations. High indoor CO concentrations are associated with poorly tuned unvented gas or kerosene space heaters, malfunctioning vented appliances, and leaky wood stoves. High indoor NO_2 concentrations are associated with unvented gas or kerosene space heaters and malfunctioning vented appliances. High indoor RSP concentrations are associated with leaky wood stoves and indoor cigarette smoking. Houses with multiple combustion-pollutant sources with independent source usage patterns, such as houses with leaky wood stoves and cigarette smokers, have the highest indoor pollutant levels. Houses with only gas cooking ranges are not associated with relatively high indoor pollutant concentrations unless they are used to heat the house or are maltuned.

Planned Activities for FY 1988

The planned activities for FY 88 are: 1) complete the initial development of the model to assess indoor exposure to combustion-generated pollutants; 2) conduct sensitivity analyses and micro/macro comparisons of the model to rank information/modeling gaps; and 3) explore the potential for generalizing the model and expanding it to include combustion pollutants other than CO, NO_2, and RSP (e.g., polycyclic aromatic hydrocarbons, dinitropyrenes or other organic mutagens), radon, and non-combustion organic contaminants such as those arising from building materials, furniture, and consumer products.

CONCENTRATIONS OF INDOOR POLLUTANTS (CIP) DATA BASE

During the last ten years public and governmental concern regarding indoor air quality in this country and elsewhere has greatly increased. This concern has resulted in hundreds of field experiments being carried out to monitor pollutant concentrations and other relevant parameters in a wide variety of building types and geographic locations.

The results of this research have been published in a variety of different journals, conference proceedings, and reports. This diversity of source material, combined with the rapid growth in the amount of research being carried out, has made it apparent that a centralized collection of these data in an easily accessible form would facilitate the transfer and distribution of knowledge regarding indoor quality, both within the research community and to other involved entities, such as architects, builders and energy utilities.

The goal of this project is to create a computerized data base of the results of field studies devoted to monitoring indoor air quality in occupied buildings in the United States and Canada.

Accomplishments During FY 1987

A major update to the Data Base was prepared during FY 87. Seventy-four new bibliographic references were added, and forty-one new summary data sets. Several minor enhancements to the software were made, including the ability to output data to a text file as well as to a screen and printer.

Software was written to support user entry and editing of summary search data. When distributed, this would make it possible for the user to enter not only their own bibliographic data, but also summary data and text.

The first draft of a technical reference manual was prepared. This manual is designed to provide a journeyman programmer with enough information to modify and extend the data base system. It includes file specifications, heavily commented source code, a subroutine tree, and other useful information.

The CIP Data Base (Version 3.1) has been implemented in a microcomputer environment running MS-DOS, using dBase III, and a commercial dBase III compiler, Clipper. Copies of the CIP Data Base are distributed on floppy diskettes to individuals for their own use, avoiding the time-sharing and phone charges of mainframe data bases, and allowing customization and additional data entry by the user. Periodic updates to the data base are distributed to users, also on floppy diskettes. The system is shipped to the user on 7 floppy diskettes, together with a 45-page user manual, and a printout of the bibliographic database in a 3-ring binder. User support is provided both over the phone by project staff and via a periodic newsletter distributed to all users. Updates to maintain the currency of the data base are distributed 1-2 times a year.

The CIP Data Base is a stand-alone system, with menu-driven functions and on-line help to facilitate entry, retrieval, and searching. Both bibliographic information and summary text and data are retrievable. Some of the available search parameters are author, pollutant range, title, keyword, year of publication, geographic region, country, state or province, building type, building material, instrumentation used, sampling method used, climate, and ventilation system and rate.

The CIP Data Base organizes reports of experimental work into two components, a bibliographic data base and a data base of summary data and text. Each has its own structure, search, and retrieval/display capabilities. Below is a brief specification of the system:

Required Microcomputer: IBM PC/XT/AT,
  or a compatible
Language: compiled dBase III using Clipper
  (Nantucket Software)
Operating system: MS-DOS & PC-DOS,
  Version 2.0 or later
Minimum Hardware configuration required:
  1 Floppy disk drive and
  1 Hard disk drive
Required Memory: 352 Kbytes
User training required: Minimal
Documentation: On-line/interactive + extensive
  external documentation
Data structures: 8 database files, 4 permanent,
  4 temporary; 7 indexes, 6 permanent,
  1 temporary; 1 ASCII text file
  per summary dataset.

Planned Activities for FY 1988

Additional updates to the data base will be distributed during the fiscal year. The updates will include published work and final reports through June or July, 1988, and will, in particular, include the papers from the International IAQ conference in Berlin 1987. In addition, the user community will continue to be supported. There are 200 current users of the CIP Data Base.

RISK ASSESSMENT

The purpose of this work is to utilize exposure information as a basis for estimating the health risks due to various classes of indoor pollutants.

Accomplishments During FY 1987

Earlier work in this area has made sufficient progress in examining risks of major pollutant classes that, together with other information, it is now possible to assemble tentative pictures of risk for certain health endpoints, at least for diseases like lung cancer, that are usually fatal.

The LBL effort has previously examined data on indoor radon concentrations as a basis for estimating the distribution of indoor concentrations, and hence exposures, in U.S. homes.[6] This indicates that the average indoor concentration is approximately 1.5 pCi/l (55 Bq/m^3) in single-family homes and that approximately 7% (or 4 million houses) have annual-average concentrations exceeding 4 pCi/l (150 Bq/m^3). Together with various epidemiological data, this leads to an estimate of the average lifetime risk of lung cancer due to radon exposures of about 0.4%,[7] with long-term occupants of houses with 150 Bq/m^3 incurring a risk exceeding 1% and those living at higher concentrations having proportionately higher risks.

This defines a spectrum of risk from radon (see Figure 1) that is much higher than the risks associated with typical environmental pollutants, i.e., those in outdoor air and in water supplies, and that compares with occupational risks or with risks associated with personal choices - e.g., accidents in homes or cars or, in the extreme, cigarette smoking. Similarly, analysis of organic chemicals indoors leads to an

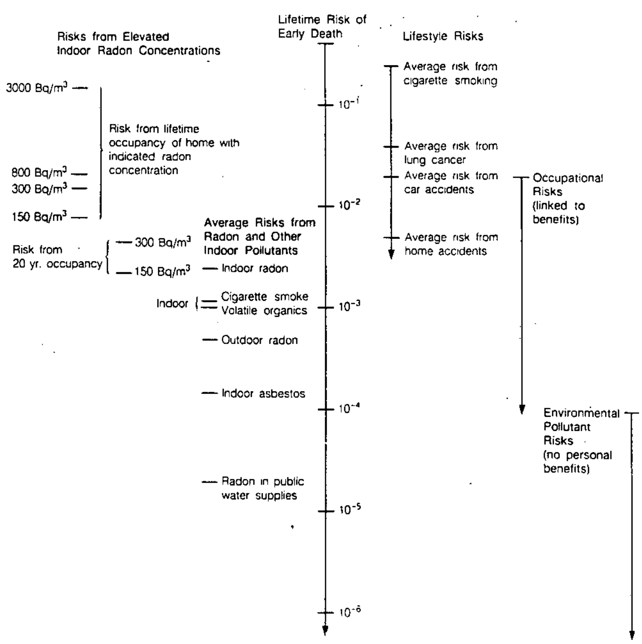

Figure 1. Comparison of risk of premature death for various exposures and settings. (XBL 871-9909B)

estimated average risk of cancer of 0.03-1% due to indoor exposures (depending on the form of dose-response model used).[8,9] This again is a large risk compared with other environmental situations.

This picture of risk of premature death due to indoor exposures can be filled out by noting the estimated effects of two other pollutants about which there has been much concern: environmental tobacco smoke (ETS) and asbestos.[10] Although controversial, midrange estimates of the risk of lung cancer to the average nonsmoker, due to breathing ETS, is comparable to the middle of the estimated range for organic chemicals just noted. Estimates of the risk from asbestos exposure, arising primarily indoors, are somewhat lower. Nonetheless, estimated risks from all of these indoor pollutants just named exceed 10^{-4}, which is larger than most environmental risks. This more complete, albeit tentative, picture of the risks of indoor pollutants provides a direct basis for considering the importance of indoor pollutants and influences the design of strategies to control indoor air pollution levels by contributing to fuller development of our general perspective on risks due to pollutant exposures.

Planned Activities for FY 1988

We will 1) reexamine radon risk estimates in the light of new data on U.S. radon concentrations and reanalysis of the full body of epideiological data, 2) undertake a general evaluation of our current state of knowledge on organic chemicals and their importance, and 3) begin to include results from combustion exposure modeling in assessment of indoor risks.

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Ventilation and Indoor Air Quality Control*

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The Ventilation and Indoor Air Quality Control Project conducts research on techniques for limiting the concentrations of pollutants in indoor air - these include methods of ventilation, air cleaning, and minimizing pollutant source strengths. Objectives are to evaluate existing and proposed technologies and to develop new technologies. Evaluation criteria include the influence of a technology on indoor pollutant concentrations, the associated energy requirements or savings, and costs. Research is performed through a combination of laboratory experiments, field studies, modeling, and analysis of the work performed by others.

During FY 1987, project staff focused on the following four efforts: 1) a laboratory evaluation of exhaust-air heat pump performance; 2) modeling the influence of different residential ventilation techniques on indoor radon; 3) a laboratory study of thermal decomposition of tracer gases; and 4) detailed field studies of ventilation within commercial buildings. Summaries of activities in the four areas are provided below.

ACCOMPLISHMENTS DURING FY 1987

Exhaust Air Heat Pumps

In a residential mechanical ventilation technique that is being introduced in the United States, an exhaust fan draws air from various indoor locations at a controlled rate. This air is blown through the evaporator of a small exhaust-air heat pump (EAHP) and is then exhausted to outside. Makeup air is drawn into the building through unplanned cracks and holes and, optionally, through adjustable-size, strategically-placed slot ventilators installed in the exterior walls. The EAHP extracts heat from the exhaust airstream and transfers this heat, plus the energy consumed by the heat pump's compressor, to the domestic hot water. Some EAHPs contain a fan coil (i.e., either a second condenser or a hot water coil plus a fan) so that heat can also be delivered to the indoor air, reducing the load on the furnace system.

During FY 1985 and FY 1986, we developed and utilized a computer model to evaluate this ventilation technology.[1,2] During FY 1987, we completed

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laboratory evaluations[3] of two EAHP systems that are now (with some modifications) being marketed in North America. System performance was monitored over a wide range of operating conditions. One of the systems (Unit A) was evaluated with and without operation of a fan-coil condenser. In the following discussion, we consider only the results of evaluations of Unit A.

The experimental results indicate that the coefficient of performance (COP) of Unit A, when used to heat water, can be correlated linearly to the average temperature of water in its tank. This correlation, which holds for a wide range of hot water demand volumes and schedules, reflects the configuration of the condenser which wraps around almost the entire vertical cylindrical surface of the water tank. When Unit A was operated with its fan coil condenser, its COP varied linearly with the temperature of air entering the fan coil.

Based on the data, simple empirical models of EAHP performance were developed. The COP of Unit A, when used to heat water (COP_w) is described by the relation

$$COP_w = -0.077\ \overline{T}_{tank} + \begin{cases} 6.55 & \text{for } R_{ex}=150 \\ 6.67 & \text{for } R_{ex}=200 \\ 7.00 & \text{for } R_{ex}=300 \end{cases} \qquad (1)$$

where: $\overline{T}_{tank}$ is the average (in space and time) temperature of water within the tank (°C), R_{ex} is the exhaust air flow rate (kg/h), and the temperature and relative humidity of the air entering the evaporator, are 21 °C and 50%, respectively. The COP can also be correlated to the more commonly utilized hot water delivery temperature (i.e., the temperature of water at the top of the hot water tank), since this temperature is approximately a constant 5.5 °C greater than $\overline{T}_{tank}$. When Unit A is operated with its fan-coil condenser to heat air, its COP can be characterized by the expression

$$COP_{FC} = -0.073\ T_{in} + \begin{cases} 4.14 & \text{for } R_{FC}=200 \\ 4.64 & \text{for } R_{FC}=300 \\ 5.04 & \text{for } R_{FC}=400 \end{cases} \qquad (2)$$

where: T_{in} is the temperature of air entering the fan coil (°C) and R_{FC} is the flow rate of air through the fan coil (kg/h). Finally, when both condensers are utilized (with the fan coil condenser used only when there is no demand for water heating), the average COP (COP_{combi}) can be expressed by the relation

$$COP_{combi} = X_w\ COP_w + X_{FC}\ COP_{FC} \qquad (3)$$

where: X_w and X_{FC} indicate the fraction of total operating time during which the water-heating condenser and fan-coil condenser are utilized, respectively. These correlations can be used to estimate energy savings; however, they are valid only for the range of operating conditions in our studies.[3]

Unit A has an average COP that is approximately 30% greater than the COP used in our previous modeling efforts.[1,2] Using a modified version of the TRNSYS (Transient System Simulation) Program, and this higher COP, we developed revised estimates of yearly energy savings and cost of conserved energy for EAHP systems with fan coils installed in all-electric well-insulated houses (built to a model conservation standard) located in three Pacific Northwest cities: Portland, Spokane, and Missoula. Considering the relatively large predicted energy savings of 5700 to 8090 kWh, and estimated costs of conserved energy of 3.5 to 4.6 cents/kWh which are comparable to current electricity prices, this method of ventilation appears to be fairly attractive in the Pacific Northwest. Our studies also pointed out the potential advantages of a modified EAHP control system which gives priority to fan coil operation until water temperatures fall below a certain value. With such a control system, we estimate that energy savings might be increased by 15 to 20%.

Influence of Infiltration, Balanced Ventilation and Exhaust Ventilation on Indoor Radon

Most U.S. houses are ventilated primarily by infiltration, the natural leakage of air though cracks and holes in the building envelope, which is driven by wind and indoor-outdoor temperature differences. To obtain better control of the ventilation rate and to reduce energy demands, mechanical ventilation of houses that have a more air-tight envelope (to reduce infiltration) is sometimes employed. The two common mechanical ventilation options are: 1) balanced (equal supply and exhaust) mechanical ventilation with heat recovery using an air-to-air heat exchanger, and 2) mechanical exhaust ventilation as described in the previous summary.

Models suitable for examining the influence of these three ventilation options (infiltration, balanced ventilation, and exhaust ventilation) on radon (Rn) entry rates and indoor Rn concentrations were developed primarily in FY 1986. One model applies for a house with a basement surrounded by homogeneous soil with the only penetration to the soil being a wall-floor gap at the junction of the basement floor and walls. The second model applies for a house with a crawl space when the crawl space has sufficient vents to outside so that air pressures within the crawl space are not influenced by pressures within the house.

A detailed description of the models is provided elsewhere.[4,5,6] The major parameters calculated are: 1) the magnitude of the pressure difference which causes soil gas (containing Rn) to enter through the wall-floor gap, or crawl-space air (containing Rn) to enter through the floor above the crawl-space; 2) the entry rate of soil gas or crawl-space air; 3) the Rn entry rates (based on assumed values of soil gas or crawl-space Rn concentration; 4) the building ventilation rate (using an infiltration/ventilation model); and 5) the indoor Rn concentration (using a single-zone mass balance equation).

Soil gas and crawl space air can be drawn into a house due to pressures caused by wind and the stack effect, irrespective of the method of ventilation. However, the method of ventilation influences Rn entry rates for two primary reasons. First, mechanical exhaust ventilation (but not balanced mechanical ventilation) depressurizes a house slightly which increases the driving force (pressure difference) for Rn entry. Second, the tightening of a building envelope to reduce infiltration, which generally accompanies mechanical ventilation, usually includes a tightening of the floor located above the crawl space. A reduction of the leakage area in the floor inhibits the flow of crawl-space air into the house. Each of these factors is accounted for in the models.

During FY 1987, we used the models and hourly weather data for Spokane, Washington to estimate average Rn entry rates and indoor radon concentrations for the heating season (September 16-April 30) assuming that there is negligible window opening during this time period. The calculations are performed using effective leakage areas (ELAs) and mechanical ventilation rates that vary depending on the method of ventilation so that the heating-season average ventilation rate is always approximately 0.55 air changes per hour (ach).

For a house with a basement we performed calculations with a range of soil permeabilities and soil gas radon concentrations. These calculations indicate that pressure-driven entry of soil gas and, thus, Rn should not be a problem when the soil surrounding the basement has a permeability of 10^{-12} m^2 or less. Soil permeabilities in this range or lower are common - for example, clays and silts have a permeability less than 10^{-13} m^2. Thus, from the perspective of indoor Rn, any of these methods of ventilation should be acceptable if the soil has a low permeability. Even if the permeability is in the range of 10^{-11} m^2, soil gas entry and the method of ventilation should not be important unless the soil gas has an unusually high concentration of Rn. However, if the soil permeability is in the range of 10^{-10} or $10^{-9} m^2$, our calculations indicate that exhaust ventilation, compared to infiltration at the same rate, could increase average indoor Rn concentrations by a factor of approximately 1.7 and by hundreds of Bq m^{-3}. In such situations, exhaust ventilation should be avoided unless other measures are taken to reduce Rn entry.

For a house with a crawl space, calculations were performed for three different distributions of leakage area: uniformly distributed, high floor ELA, and low floor ELA. Three crawl-space Rn concentrations were also used for calculations. Based on the calculations, a large fraction of the air that enters a house can come from the crawl-space, particularly when ventilation occurs by natural infiltration. In such instances, the indoor Rn concentration will be a substantial fraction (e.g., 50% to 100%) of the crawl-space Rn concentration. Therefore, control of crawl-space Rn concentrations (usually by crawl-space ventilation) is more important than choosing a particular type or rate of ventilation for the house. The different techniques of ventilation do lead to substantially different Rn concentrations, in a house with a crawl space. Both the mechanical ventilation options, when combined with house tightening that includes reducing the ELA of the floor, lead to substantially lower indoor Rn concentrations than the traditional reliance on infiltration. Such results are expected, because with mechanical ventilation and house tightening a larger proportion of the air that enters the house will not pass through the crawl space. Balanced ventilation leads to the lowest indoor Rn concentrations - about a factor of three lower than with natural infiltration.

The models have been used to investigate the effects of varying other parameters. One particularly interesting result for a house with a basement, is a predicted increase in indoor Rn concentrations as the rate of exhaust ventilation is increased above approximately 0.5 h^{-1}.

Thermal Decomposition of Tracer Gases

Gaseous tracers, such as sulfur hexafluoride and various halocarbons are commonly injected into the air within buildings in order to measure ventilation rates and study air flow patterns. Depending on the instrumentation utilized to measure tracer gas concentrations and the specific tracer(s) selected, maximum tracer gas concentrations may be less than 100 parts per billion or as high as several hundred parts per million. Typically, one uses tracers that are essentially non-toxic (i.e., tracers that are expected to cause no adverse health effects at concentrations substantially above those encountered during the studies).

The authors previously developed a multi-tracer measurement system for detailed studies of ventilation in commercial buildings. The tracers that can be utilized with this system are sulfur hexafluoride and refrigerants 13B1, 115, 12, and 114 (SF_6, $CBrF_3$, $CClF_2CF_3$, $CClF_2$, and $CClF_2CClF_2$). Available threshold limit values (maximum average concentration for an 8-hour workday) for these tracers are 1000 to 200,000 times greater than the maximum anticipated concentrations of tracers in our experiments; therefore, no adverse health effects are expected due to exposure to these tracers. However, it is known that these tracers and similar compounds that are commonly present in indoor air can decompose when they pass through a combustion zone or are otherwise heated to a sufficiently high temperature. The halogen acids (i.e., HCl, HF, and HBr) are generally considered to be the predominate decomposition products. Some production of phosgene ($COCl_2$), carbonyl fluoride (COF_2, carbonic chloride fluoride (COClF), and free halogens (Cl_2, F_2, Br_2) have also been suggested. Because any of these potential decomposition products are considered to be highly toxic, the possibility of thermal decomposition of tracer gases is a significant concern.

Experiments were conducted to determine approximately the rates of tracer gas decomposition caused by electric and gas range-top burners. A mixture of the five tracer gases was injected into a mechanically ventilated, artificially mixed, stainless steel chamber containing the ranges. Tracer decay rates were monitored with and without range burner operation. Additional experiments were directed at the potential for decomposition when these tracers passed through a lighted cigarette - in this case our concern is with the inhalation of decomposition products by the smoker. The concentrations of tracer gas in the air surrounding a cigarette smoking machine (which smoked the cigarette) were measured and compared to the concentrations of tracer gases in the main-stream smoke which was collected in a small sample bag. The same experiment was also conducted without lighting the cigarette.

The techniques used for this study yield results with a high uncertainty but these results are still valuable given the lack of other data. More accurate and complete data could be obtained by actual monitoring of decomposition product concentrations.

Based on the experimental results, our best estimate is that an 825W electric range-top heating element caused no tracer decomposition and that a natural gas burner (~7400 kJ/h) caused all the tracer within 2.8 to 4.2 m^3 of air (depending on the tracer) to decompose during each hour of burner operation. These volumes of air correspond to 120% to 190% of the minimum amount of air required for complete combustion of the natural gas. Considering the precision of repeated experiments, we also derived estimated upper limits (i.e., probable overestimates) of the volumes of air from which tracer is decomposed each hour - these are 1.7 m^3 and 5.3 m^3 for the electric and gas burner, respectively.

In tests with burning cigarettes, we measured repeatable (in two tests) 20% to 30% lower tracer gas concentrations in the mainstream smoke than in the air surrounding the cigarette and essentially a 0% loss of tracer when the cigarette was not lighted. These 20% to 30% losses could be due entirely to tracer decomposition; however, we can not rule out losses due to sorption of the tracers on tobacco smoke aerosols.

To estimate the decomposition product concentrations that might result from tracer gas decomposition, one can utilize the estimates of decomposition rates given above, simple mass balance models for a building or room with a known ventilation rate, estimates of the extent of range burner operation or smoking, and the principle of conservation of halogen atoms. In the case of smoking, the ratio of air inhaled through cigarettes to total air breathed, approximately 0.002 if twenty cigarettes are smoked in an eight-hour period, should also be factored into the calculations. The resulting estimated decomposition product concentrations are highly dependent on the tracer gas concentration, which can range over a factor of 1000 depending on the experimental techniques. Through such calculations we concluded that use of the five tracers noted above in commercial buildings, with maximum tracer gas concentrations of 0.2 ppm for SF_6, 0.5 ppm for refrigerant 13B1, and 1.0 ppm for the other refrigerants, should not result in adverse health effects. However, we adopted procedures to minimize the possibility of accidental releases of tracer (which might result in very high tracer gas concentrations). We also consider the possible sources of thermal decomposition in each building prior to deciding whether to study the building. Since tracer gas concentrations, the actual tracers utilized, building volumes, sources of thermal decomposition, and ventilation rates vary widely, it is recommended that the hazards associated with tracer decomposition be considered on a case-by-case basis. Further studies of this issue, to reduce uncertainties, are also recommended.

Commercial Building Ventilation Studies

The approximate building-average ventilation rate has been measured by the research community in roughly 50 U.S. commercial buildings primarily by monitoring the rate of decay of a tracer gas concentration. However, it is important to obtain more detailed information on ventilation within commercial buildings - for example, to monitor: 1) ventilation rates and the related local ages of air at different locations within buildings; 2) values of ventilation effectiveness which indicate overall patterns of air flow between locations of supply and exhaust; and 3) rates of interzone air flow or mixing. These factors influence the efficiency and capability of ventilation systems in supplying and removing heat and removing pollutants and, thus, influence indoor air quality and building energy requirements.

Using recently introduced tracer gas experimental techniques and methods of processing tracer gas data [7], it is possible to obtain much of this more detailed information on commercial building ventilation. (The specific information that can be obtained depends on the building and experimental methods employed.) In prior fiscal years, we identified a group of five gases that are suitable for use as tracers and that can be monitored using one instrument, developed measurement and calibration procedures, developed and evaluated methods of tracer gas injection and sampling, and conducted tests of measurement precision and accuracy [8]. During FY 1987, multi-tracer experimental systems for use in buildings were fabricated and monitoring was completed in two buildings.

There are three major components of the experimental system. The core of the system is three cart-mounted gas chromatographic systems for measuring tracer gas concentrations; each system samples air through one to three sample lines. These cart-mounted systems are generally placed in the building mechanical room(s) and used to monitor tracer gas concentrations within the major air handling units (AHUs) - for example: the concentration in the return/exhaust air stream and upstream and downstream of a point of tracer gas injection into the supply air stream. The second component, four tracer gas injection systems, consist of adjustable-speed peristaltic pumps which draw tracer gas from large storage bags and inject tracer through flow meters and into the AHUs. Injection rates are very stable and can be varied over approximately two orders of magnitude. The third major component of the monitoring system consists of 15 small, silent, local samplers which collect samples of air/tracer at a constant rate in one-liter sample bags. The time at which sampling initiates and terminates is programmable. These samplers are used primarily to collect samples at breathing level from various locations (e.g., offices) within the occupied space. Syringe samples of air are also collected manually at each sample location at the end of the sample collection period.

Although a variety of tracer gas procedures can be employed, a tracer gas step-up has been used in all studies conducted to date. In this procedure, a distinct tracer gas is injected at a constant rate into each stream of outside air entering the building or into each associated supply airstream. (With injection into the supply airstream, good mixing between the recirculated air and outside air is necessary for accurate measurements.) Injection and monitoring is continued until tracer concentrations reach steady-state values.

Straightforward calculations based on tracer gas mass balances are employed to determine such parameters as the flow rates of the outside air and supply airstreams and the percent outside air in the supply airstream. Through the application of age distribution theory [7,8], ages of air (i.e., time elapsed since the air entered the building), local ventilation rates (reciprocals of local ages of air), and values of ventilation effectiveness are computed. Through other calculations we can determine the fraction of air at each monitoring point which enters the building through a particular AHU.

To provide an example of the information obtained in these studies, we discuss the results obtained from one of three tests in a complex of three interconnected two-story office buildings (No. 2, 3 and 4) located in Palo Alto, California. In this complex, Buildings 2 and 3 are served by one roof-mounted, variable air volume AHU and Building 4 is served by a similar AHU located within its basement. Air is supplied through ceiling-mounted diffusers and returned through ceiling-level return grills both located in virtually every office. During the monitoring, outdoor temperatures were sufficiently high so that the AHUs were automatically set to maximize recirculation of indoor air, thus bringing a minimum of outside air into the buildings.

The experimental results indicate that approximately 95% of the air within Buildings 2 and 3 enter through the AHU which serves these buildings and that approximately 92% of the air within Building 4 enters through the Building 4 AHU. Thus, there is only a small amount of air flow between the buildings. These results reflect the limited connections between buildings - only one hallway connects adjoining buildings - and indicate that there are no large flow imbalances which drive air flow between buildings. Based on the data obtained from the local samplers, ages of air and local ventilation rates vary over a moderate range. For example, the ages of air measured with eight local samplers in Buildings 2 and 3 vary between 1.0 and 1.5 h with an average age of 1.3 h. Lesser variability and a somewhat higher age of air is observed in Building 4 where ages of air measured with five local samplers range between 1.5 and 1.8 h with an average value of 1.7 h. The lowest measured local ventilation rate (recipricol of local age of air) of 0.4 h^{-1} is from a hallway which connects buildings. Values for ventilation effectiveness [7,8] can be computed by taking the ratios of age of air in the return duct determined by numerial integration of tracer concentrations as a function of time (1.3 h for Building 2 and 3 and 1.7 h for Building 4 to the average age of air within the building as measured with the local samplers. Ventilation effectiveness values of 1.0 (1.3 ÷ 1.3) and 1.0 (1.7 ÷ 1.7) result from these calculations. Ventilation effectiveness values close to unity, indicate that the air within each zone (Buildings 2 and 3 as one zone and Building 4 as the other zone) is relatively well mixed (e.g., there is not a large amount of short circuiting of air between locations of supply and exhaust).

Other calculations indicate that at the end of the monitoring period, supply air flow rates, outside air flow rates, and percent outside air were approximately 36000 ft^3/min, 10000 ft^3/min, and 28% for Buildings 2 and 3, and 16000 ft^3/min, 3800 ft^3/min, and 24% for Building 4. Finally, the data indicate that there is insignificant leakage of air into these buildings, i.e., virtually all air enters through the AHUs.

PLANNED ACTIVITIES FOR FY 1988

Our largest effort during FY 1988 will be to continue the use of multiple tracer gases to study ventilation within commercial buildings. In a related effort, we will initiate an assessment, based on reviews of available information and modeling, of a technique of ventilation, called displacement ventilation, which is gaining acceptance in Scandinavia. A third effort will be to conduct a follow up study of the effectiveness of radon mitigation systems previously installed in Spokane-area houses. Finally, field studies of selected radon mitigation techniques in central Florida housing will be initiated if funding for this study is received.

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Energy Performance of Buildings*

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The Energy Performance of Buildings Group (EPB) carries out fundamental research into the ways energy is expended to maintain desirable conditions inside buildings. Our results form the basis of design and construction guidelines for new buildings and retrofit strategies for existing buildings. Our primary areas of research are air infiltration and retrofit research. In this article, the work carried out over the last year is split into five overlapping sections: 1) building energy retrofit research, 2) air infiltration, 3) air leakage, 4) International Energy Agency support, and 5) appliance performance testing. The emphasis in our work is on whole building performance. We collect, model, and analyze detailed data on the energy performance of buildings, including the micro-climate, the building's thermal characteristics, the mechanical systems, and the behavior of the occupants. Because of the multidisciplinary approach we work closely with other groups, both at the Laboratory and elsewhere.

BUILDING ENERGY RETROFIT RESEARCH (BERR)

While new buildings—both residential and commercial—are responding to higher energy prices and stricter energy codes by becoming more energy efficient, the existing stock represents a large area for energy conservation activity. Of the three buildings sectors, single-family, multifamily, and commercial, multifamily has had the least level of activity, and presents some of the greatest challenges. Over one quarter of the U.S. housing stock is in multifamily buildings. The Office of Technology Assessment estimates that while current levels of retrofit activity in multifamily buildings are likely to save 0.3 quads of energy (320 petajoules) by the year 2000, the *potential* savings are more than three times as much. The reasons for this untapped energy savings are complex, and involve institutional as well as technological barriers. While we know something about the performance of retrofits in single-family houses, we have very little understanding of the interactions and performance of retrofits in multifamily buildings. The measured savings from retrofits in multifamily buildings are typically 25-50% less than the predicted savings, with a large spread around the mean.

The Building Energy Retrofit Research project was initiated to address these problems in all three building sectors, single-family, multifamily, and commercial. The Department of Energy has designated LBL as the primary lab for carrying out research in the multifamily sector, although we continue to work in all three sectors. Several of the projects in this area overlap with projects in other areas such as federally-assisted housing, infiltration diagnostics and measurement, and appliance field testing, and are reported in these sections.

Accomplishments During FY 1987

The BERR work can be broken down into four areas: 1) development of a monitoring protocol, 2) development of new diagnostic techniques, 3) analysis of retrofit performance in multifamily buildings, and 4) analysis of behavior of occupants, owners, and managers.

Monitoring Protocol

The need for a standardized set of procedures for monitoring buildings has led to the development of a monitoring protocol for multifamily buildings. An earlier draft of the protocol was used to specify the monitoring procedures used during field tests in multifamily buildings in Chicago, Minneapolis, and St. Paul. The experience gained at these monitoring sites has been incorporated into subsequent drafts of the protocol. The objective of the protocol is to provide a comprehensive standard for data collection and evaluation of retrofit performance. A primary goal for the protocol work is the development of an ASTM and ASHRAE standard for building monitoring. At present the protocol is being reviewed as a draft standard by ASTM. The ASHRAE version is being incorporated into a chapter on monitoring protocols for the *Handbook of Fundamentals.*

New Diagnostic Techniques

While the protocol provides a guideline for long-term monitoring, practitioners and researchers also have a need for short-term diagnostic tests to understand the characteristics of the building shell and mechanical systems. Diagnostics for energy use in multifamily buildings that have been developed or are currently under development include tests of

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boiler efficiencies, distribution losses, shell and inter-apartment leakage (see air leakage section), and appliance efficiencies (see appliance field testing section).

Our diagnostics work in FY 87 included development and analysis of two single-family diagnostic techniques. The first single-family diagnostic was the testing of a technique for measuring air leakage in duct work, specifically, the supply and return side leakage and driving pressures in a central air distribution system (see air leakage section for a more detailed description). The second single-family effort was to test a single-channel wood-stove heat output monitor developed by our group. In collaboration with Pacific Power and Light, we analyzed data taken using this sensor as part of the Hood River Conservation Project (HRCP).[1] The analysis showed that the average efficiency of the wood stove in the field was only 27%, significantly lower than the 50% efficiency that was assumed based on laboratory measurements and estimates based on occupant-reported wood use.

Retrofit Performance in Multifamily Buildings

Our previous year's monitoring work in multifamily buildings in Chicago and St. Paul, Minnesota, has provided a large source of data on the energy characteristics of these buildings. Our work this year has been to develop models that can use this data to evaluate the performance of the retrofits.

Two models are currently under development. The first models the air flow through combustion appliances (i.e., heating and hot water systems) that exhaust through a common chimney, a situation that is typical in multifamily buildings (see Figure 1). The model can be used to predict the performance of retrofits such as vent dampers or flow restrictors based upon the physical configuration and operating characteristics of the system.[2] The second model being developed characterizes the seasonal efficiency of multifamily boilers, taking into consideration the venting issues described above, as well as heat losses through the boiler jacket and to the ground. This model should be capable of providing the data necessary to make recommendations for boiler retrofit or replacement.

As a follow-up to our previous year's collaborative work on monitoring energy use in new Swedish apartment buildings we conducted a study on the appropriate analysis techniques for analyzing the energy consumption data from these buildings.[3]

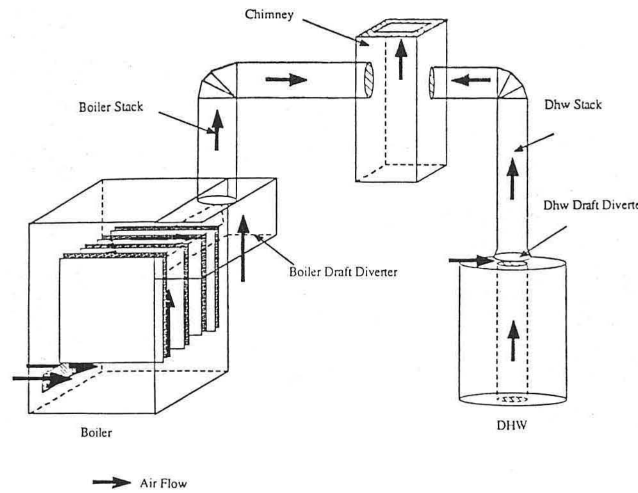

Figure 1. Schematic of air flow paths through two combustion appliances vented through a common chimney. (XBL 8711-4648)

Behavior Studies of Building Occupants, Owners, and Managers

An important aspect of retrofit performance is the related behavioral aspects. Building owners have to make decisions on what retrofits to select, residents modify the retrofits to suit their needs, and building managers take actions that affect the performance of the retrofits. We carried out two projects this year that looked at behavioral effects, the first on the role of apartment managers in determining the energy use in multifamily buildings, and the second, a case study of the energy decision makers in a speculative commercial office building.

The study of apartment managers surveyed several groups and building organizations that have addressed the problems of improving energy efficiency in multifamily buildings through better operations and maintenance. Motivation and feedback were found to be the two key elements in ensuring adequate attention by the building managers. We undertook case studies to examine the basic problems confronting apartment managers, and solutions to some of these problems were documented.[4]

The case study of the two commercial buildings evaluated the role of tenants, managers, and owners in determining energy consumption. Built in the late 70's to showcase new energy technologies, these buildings, known as Enerplex, (see Figure 2) have been intensively monitored and studied to ascertain how they use energy.[5] Our study focused on how

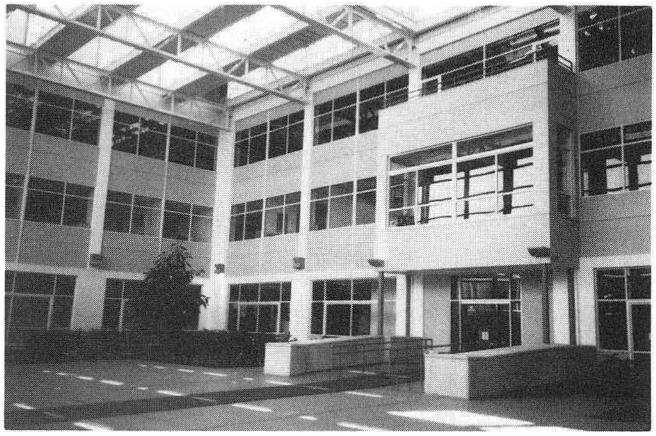

Figure 2. Enerplex office buildings incorporating advanced energy technologies and design strategies. (BBC 8711-9503)

decisions by the owners, tenants, and managers circumvented the intentions of the architects and engineers, resulting in a three-fold increase in actual energy use compared to predicted energy use.[6]

Planned Activities for FY 1988

Our new work will include an investigation of the performance of retrofits in cooling climates. Other plans for the coming year are to continue analyzing the data that has been collected on the monitored buildings, specifically looking at the data on boiler efficiencies. In addition, we will be working with Princeton University in testing new diagnostic techniques as well as preparing a multifamily audit.

AIR INFILTRATION

With improved insulation of the building shell, heat loss from ventilation—whether controlled or by infiltration—has become an even more important fraction of a building's overall heat loss. Infiltration is the flow of outside air driven by wind pressure and thermal buoyancy into the building. Our infiltration is divided into three main areas: 1) infiltration modeling, including the development of a multizone airflow model, 2) multigas tracer measurements, and 3) wind tunnel measurements of the wind pressure distribution on building surfaces.

A number of computer programs have been developed to calculate air flow patterns in buildings. Awareness of the airflow pattern in a building is particularly important when (1) determining indoor air quality for the different zones in a building, (2) evaluating smoke distribution during a fire, and (3) calculating space conditioning loads. Sizing space conditioning equipment is also dependent upon accurate air flow information.

To treat the true complexity of the air flows in a multizone building, extensive information is needed regarding flow characteristics and pressure distributions both inside and outside the building.[7] To reduce the input data required by detailed infiltration models, simplified models have been developed. Most of these, including the one developed at LBL,[8] simulate infiltration associated with single-zone structures.

A high percentage of existing buildings, however, have floor plans that characterize them more accurately as multizone structures. Although multizone models exist, these models need inordinate amounts of input data. Therefore, a simplified multizone model capable of providing the same accuracy as the established single-cell models is being developed at LBL.[9]

Accomplishments During FY 1987

Infiltration Modeling

The first phase of a simplified model for predicting multizone air flows was completed this year. Extensive testing and validation are required however, before the model can be generally used. We plan to validate the model in the coming year through multigas tracer measurements both in the lab and in the field, as well as through a collaborative effort with the *Laboratoire d'Energie Solaire (LESO)* at the Ecole Polytechnique Federale de Lausanne in Switzerland and the EEC Laboratory in Varese, Italy.

In another application, the single-zone infiltration model developed at LBL was used to validate a commonly used rule of thumb that the annual average air change rate is equal to the number of air changes at 50 Pascals divided by 20. Using a set of simplifying assumptions to derive a divisor for this air change rate, typical values ranged from 17 to 23 in various parts of the US (see Figure 3).[10]

Multigas Tracer Measurements

We have designed and assembled a multigas tracer system which is based on a residual gas analyzer using a mass spectrometer (see Figure 4). The system is capable of measuring six different gasses in six independently controlled zones with a complete cycling time of less than five minutes. The system automatically controls the concentration of the tracer gas in each of the zones by using a control

LEAKAGE/INFILTRATION RATIO

Figure 3. A graph of the United States indicating zones of various leakage/infiltration ratio. (XBL 864-1546)

scheme that keeps the concentrations of the tracer gases stable in the zones.

The multigas tracer system can be used to measure the real-time air flows between different zones in a building, as well as between the different zones and the outside. Although this system could be used as an audit technique, it would probably be too expensive for most field applications. Its primary purpose is to validate mathematical models and diagnostic techniques which, in turn, can be used in more general situations. In addition to using it for validating the multizone infiltration model, we will use the system to validate models of effective ventilation (see below). Other uses include the measurement of air flows in combustion appliances, which was previously not possible using standard spectroscopy techniques.

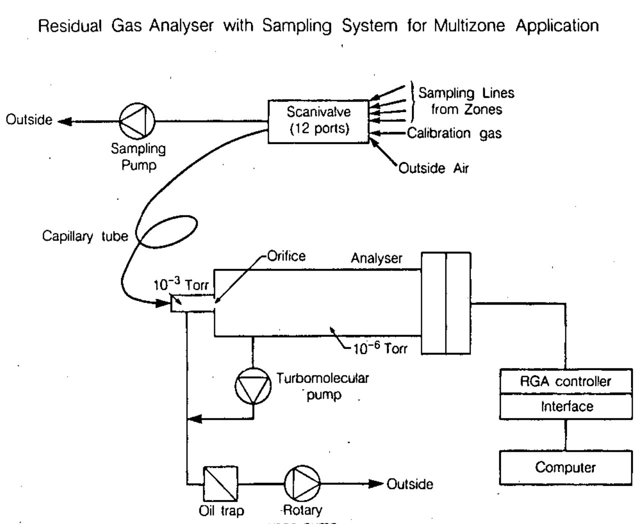

Figure 4. Multitracer gas system for measuring air flows between different zones in a building. (XBL 8711-4647)

Effective Ventilation

The degree to which incoming air mixes with the air in a room depends on the geometry of the space and the ventilation system. This concept has conventionally been called *ventilation efficiency*, and is used in calculating ventilation rates needed for diluting pollutants and ensuring sufficient air quality. In the last year we have expanded the notion to include the fact that time varying ventilation will behave differently from a steady ventilation rate of the same average; we have called this concept *effective ventilation.*

The concept of effective ventilation is especially pertinent to the passive ventilation measurement technique (e.g., perfluorocarbon tracers). This technique is in fact a measurement of the average effective ventilation which can be misinterpreted when the average ventilation is desired.[11] The effective ventilation concept is even more important in multizone environments because of potential mixing problems. The multigas tracer capabilities allow a field measurement of real-time concentration which in turn will provide a verification of the effective ventilation model, and could be used to make a quantitative field test of the perfluorocarbon technique.

Planned Activities for FY 1988

Multizone Modeling

The bulk of the multizone infiltration modeling work will be done in two parts: 1) cooperative validation work at the EEC Laboratory in Varese; and 2) preparation for the COMIS workshop in FY89. COMIS (Conjunction of Multizone Infiltration Specialists) is a year-long international workshop scheduled to take place at LBL during FY89. Experts from approximately 10 different countries will work together to complete the problem of predictive modeling of air flow in multizone buildings. The intended outcome is a general purpose computer code for use by designers, policy makers, researchers, and others.

Multigas Tracer Measurements

In the coming year we plan to start using the Multigas Tracer Measurement System (MTMS) in the field. These measurements will be done in single-family and multifamily buildings and will allow verification of the effective ventilation concept and provide input data for the multizone infiltration models.

Effective Ventilation

The effective ventilation work will expand to include multizone environments as well as to examine the transport of specific pollutants, such as radon. The comparison of effective ventilation predictions to the measurements using the multigas tracer measurement system will begin after completion of the field measurements.

AIR LEAKAGE

The process of air flowing through unintentional openings is called air leakage. In buildings, air leakage occurs through openings in the building envelope, in mechanical systems, and in between building zones. Air leakage flowrates depend both on the air tightness of the building component as well as on the pressures driving the flow. The fan pressurization technique, i.e., blower-door testing, has evolved over the past ten years as the standard technique for characterizing the air tightness of building envelopes. We have started developing techniques to measure the air tightness of mechanical systems (such as air ducts) as well as the air tightness of internal partitions between zones (such as in multifamily buildings). For all three types of air leakage, the measurement and study of air tightness allows us to characterize buildings, better understand ventilation and space conditioning, evaluate the performance of mechanical systems, and estimate the effectiveness of air-tightness retrofits.

Our air leakage research can be divided into three areas: leakage characterization, measurement techniques, and consensus standards. Our leakage characterization effort involves collecting and analyzing measured leakage data, as well as understanding the fluid dynamics of air leakage. As part of our measurement technique research we have developed an alternative technique for measuring building envelope airtightness, AC Pressurization, and are presently developing techniques for measuring the air leakage in residential duct systems and multizone buildings. Finally, we are transferring our experience by participating with professional societies in the formation of consensus standards.

Accomplishments During FY 1987

Air leakage research efforts in FY 87 focused on the development of measurement techniques covering three types of leakage: envelope, duct-system, and multizone. The envelope leakage research has concentrated on quantifying the effects of wind on both fan pressurization and AC pressurization measurements. Wind-induced pressure variations add uncertainty to the measurement, which we measure using a portable test building, the Mobile Infiltration Test Unit (MITU). Our experiments with MITU have shown that the effects of wind on fan pressurization measurements can be significantly attenuated by using a four-wall pressure averaging probe developed in Canada. The MITU tests also indicated that the leakage area measured by AC pressurization did not vary with the wind, up to wind speeds of 8 m/s (18 mph). As this result is encouraging, an analytical examination of the effects of wind on AC pressurization is planned.

A theoretical and experimental investigation of a new envelope leakage measurement technique was initiated in FY 88. This technique, known as pulse pressurization, determines the leakage characteristics of the envelope from the decay of the building pressure from an elevated value down to its steady-state value. Preliminary experiments performed in MITU showed that the the technique has the potential for wider application, although further demonstration of the theory and development of a practical prototype remain to be performed.[12]

As part of a larger multifamily retrofit research project, initial experiments were performed with three potential multizone leakage measurement techniques. Rather than testing an actual apartment building, as was done in FY 86, the experiments were performed under controlled conditions in a single-family house that had been divided into two zones with a panel having known leakage characteristics. Two of the techniques tested used blower doors, whereas the third technique was based upon the AC pressurization apparatus. The two blower techniques differed in the way the pressure differences between the two zones were varied, and the manner in which the data was analyzed. The results of these tests will be analyzed, and recommendations developed in FY 88.

One of the major accomplishments of FY 87 was the measurement of supply and return side leakage in a central air distribution system and the characterization of the pressures driving the leakage in that system. Determining the split of duct-system leakage between the return and supply sides of the fan is important both because the energy penalties associated with this leakage can vary by a factor of four depending upon the leakage split, and because the indoor air quality implications depend upon this split.

During FY 87 we also made use of the air tightness database that was compiled during the past several years.[13] This database, which contains 1100 measurements on 750 houses in 110 different zip codes, was used to estimate the total leakage area of duct systems, which was found to average 190 cm^2 for 90 California houses.

As part of our work with professional committees and organizations, we were involved with two standards-writing organizations: the American Society for Testing and Materials (ASTM) and the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE). We participated in several activities in ASTM during FY 87, including the modification of Standard Test Method E-779, "Determining Air Leakage Rate by Fan Pressurization" to include effective leakage area as part of the standard. Standard E-779, after public review, was published as an official ASTM standard in FY 87. We are now participating in four new standards in ASTM. We are continuing to work with ASHRAE standard project 119P, which is intended to promote energy conservation by setting maximum values for air leakage in detached single-family residential buildings.

Planned Activities for FY 1988

Air leakage research efforts in FY 88 will focus on analysis, interpretation, and documentation of the experiments performed in FY 87. These efforts include analysis and further testing of the multizone, duct, and pulse-pressurization measurement techniques.

The other focus of air leakage research in FY 88 will be in leakage characterization. The objective of this work is to develop a workable physical model for air flow through large apertures submitted to dynamic pressure conditions. This more basic work has application both to our two dynamic leakage measurement techniques, AC pressurization and pulse pressurization, as well as to the dynamic flows associated with natural ventilation. In addition to our experimental examination of flow profiles this work will also include theoretical modeling efforts in collaboration with the Royal Institute of Technology in Sweden.

The standards work will also continue during FY 88. In particular, during FY 87 ASHRAE standard 119 was put out for public review, and is expected to be published in FY 88.

IEA SUPPORT

In response to the 1973-74 oil crisis, the OECD countries formed the International Energy Agency. As part of the implementation agreement, technical annexes were created to enable countries to work together on problems of mutual interest. To date, thirteen technical annexes have been formed. Our group has been representing the U.S. on Annex V, the Air Infiltration Centre.

Accomplishments During FY 1987

The U.S. has been one of the most active members of the Air Infiltration and Ventilation Centre (AIVC). As the U.S. representative, we provide interested parties with information material, e.g., the quarterly published Air Infiltration Review, which is sent to over 640 U.S. researchers and professionals. We also distribute the AIVC Technical Notes to interested parties.

During FY 87 the Air Infiltration and Ventilation Centre responded to approximately 120 inquiries from the U.S. and delivered over 600 copies of technical papers held in their library of some 2,200 ventilation-related papers.

Planned Activities for FY 1988

There are two new annexes being considered by the Executive Committee; one on moisture and the other on the fundamentals of air flow patterns. LBL is qualified to participate in either.

APPLIANCE PERFORMANCE TESTING

Gas and electric utilities use a large array of information for forecasting future energy demands. This project is concerned with the projection of energy demand due to major appliance operation in single-family residences. These are gas and electric domestic hot water heaters, refrigerators, central air conditioners, and central gas furnaces. Although some data is available for residential end-use energy consumption there is no data base available on major appliance field performance. Future energy demand is dependent on knowledge of actual appliance efficiencies changes due to factors such as long-term degradation.

Accomplishments During FY 1987

We have conducted a project in conjunction with Pacific Gas and Electric, the California Energy Commission, and DOE to develop and test procedures that are applicable for field appliance performance testing. A major goal of the study was to compare the measured and the rated efficiencies of the target appliances.[14] Another goal of the study was the development of simple techniques for a large-scale survey of appliance efficiencies.

Methods development, conducted in early 1986, investigated several techniques for duplicating laboratory appliance efficiency indicator measurements in the field. A total of 61 single-family residences located in north-central California were monitored during the summer of 1986 and winter of 1987.

Refrigerators

For refrigerators the only efficiency indicator is the monthly energy consumption, based on a week-long measurement of energy consumption and freezer compartment and ambient temperatures. Figure 5 compares normalized specific energy consumption with unit age and with the applicable California standards, where specific consumption is the measured electricity consumption adjusted for volume, allowing all volumes of refrigerators to be compared in the same figure. Newer units clearly consume less energy than the older units.

Domestic Hot Water Heaters

A large amount of scatter is evident in Figure 6, which compares measured recovery efficiency with unit age and with the applicable California standards. There is no clear trend of efficiency with age. Some 30-year old units are as efficient as 1-year old units. Some of the low values are attributable to thermosiphon loops or other loss mechanisms which would not be found in a laboratory test setup, although they may be common in the field.

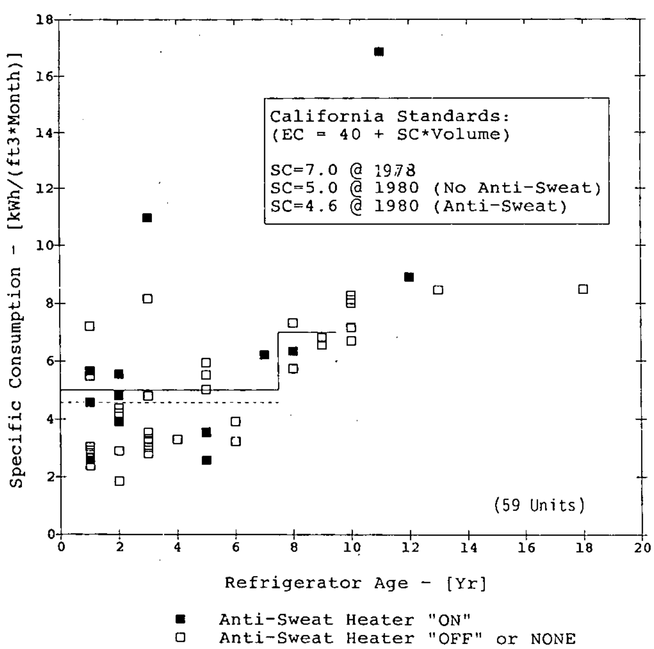

Figure 5. Refrigerator electricity consumption by age of refrigerator. (XBL 8711-4646)

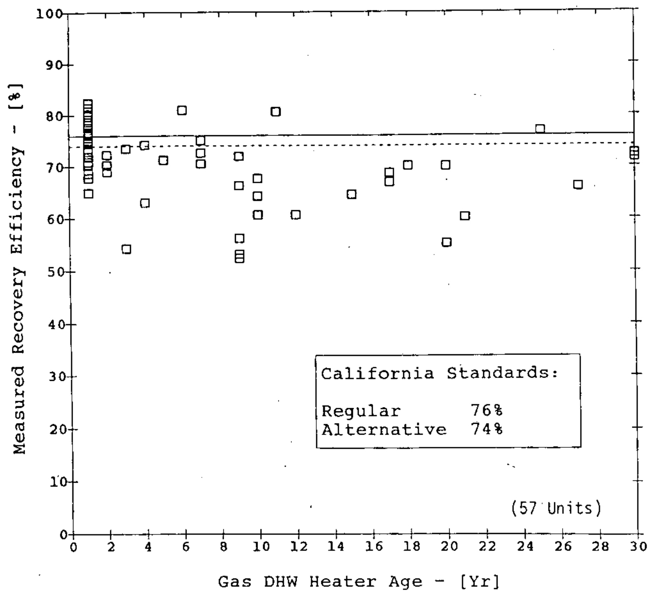

Figure 6. Measured recovery efficiency of gas water heaters by age of appliance. (XBL 8711-4645)

Central Air Conditioners

This study attempted to determine the Energy Efficient Ratio (EER) and Seasonal Energy Efficient Ratio (SEER) indirectly by measuring the heat rejection at the outside condenser coil. This technique was chosen due to the difficulties associated with field measurement of latent heat removal. The outside coil is more accessible for sensor installation and does not have latent heat loads. Three different methods of measuring condenser unit air flow rate were used. The high turbulence and pressure sensitivity of the the fans resulted in condenser-coil air flow measurement uncertainties on the order of 25%. Given this level of uncertainty in the data, it is clear that the experimental methods require considerable improvement.

Central Gas Furnaces

Figure 7 shows the variation of measured furnace efficiency with unit age, and its relationship with the applicable California standards. The older unit steady-state efficiencies cluster around 75%, while newer units seasonal efficiency is generally better than the requirement.

Planned Activities for FY 1988

The project was completed in FY 1987, and the only additional work will be the publication of the results.

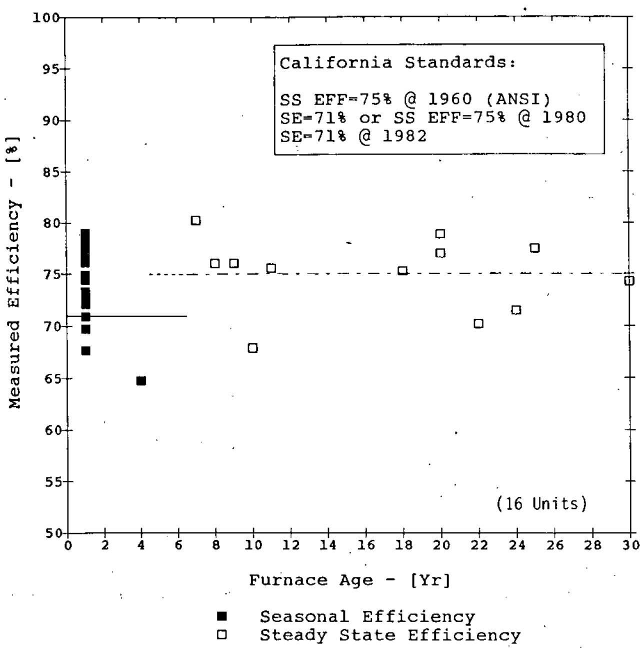

Figure 7. Measured efficiency of gas furnaces by age of appliance. (XBL 8711-4644)

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Indoor Radon

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