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INDOOR ENVIRONMENT PROGRAM

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INDOOR ENVIRONMENT PROGRAM

INTRODUCTION

The Indoor Environment Program examines the scientific issues associated with the design and operation of buildings to optimize building energy performance and occupant comfort and health. Optimizing occupant health and comfort is addressed in various ways by groups within the Program. To examine energy flow through all elements of the building shell, the Energy Performance of Buildings Group measures air infiltration rates, studies thermal characteristics of structural elements, and develops simplified models of the behavior of complete buildings. Potential savings in the infiltration area are 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 building environment. Since ventilation is the dominant removal mechanism for building pollutants, concern continues about the impact of designs or changes in operation that lead to its reduction.

This issue has been an important theme for other projects in 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 production of airborne pollutants. Projects have concentrated on three major pollutant classes: combustion products arising from indoor heaters and other combustion appliances; radon and its progeny, arising from materials (primarily soil) 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 pollutant 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. We continue to explore several important themes:

- A. **Air quality in buildings is dominated by sources.** Problems are more often related to strong indoor sources than to deficiencies in ventilation.
- B. **Air pollution is a buildings problem.** Pollutants concentrations observed in buildings are comparable to those outdoors (when major indoor sources are present, the concentrations indoor 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. We conclude that air pollution is a buildings problem because sources and removal processes are often associated with building structure and operation.
- C. **Ventilation is the best control strategy for indoor pollution.** Ventilation using outdoor air affects all indoor pollutants similarly and is therefore, the best single strategy for pollutant control in buildings. This assertion acknowledges that we cannot identify all pollutant sources in a building. Since such information is often lacking, ventilation remains the best general indoor pollution control strategy.

Evaluation of Several Techniques to Reduce Radon: Preliminary Results from Fourteen Houses*

B.H. Turk, J. Harrison, R.G. Sextro, L.M. Hubbard†, K.J. Gadsby†, T.G. Matthews‡, C.S. Dudeney‡, D.C. Sanchez‡

Fourteen homes with basements and hollow block foundation walls in north-central New Jersey, were selected for this research project. Seven homes were studied by Lawrence Berkeley Laboratory, while the other seven were studied by Oak Ridge National Laboratory and Princeton University. One home from each group of seven did not have a radon control system installed, and served as a control.

Beginning in the fall of 1986, radon concentrations and other parameters in the homes were intensively monitored with continuous, real-time instrumentation. Monitoring continued for 7 to 13 months. We developed diagnostic procedures to guide choice of the appropriate radon reduction technique in each house. Oak Ridge National Laboratory and Princeton also used a modification of these diagnostic procedures. Radon control systems were designed to: (1) effectively and economically reduce indoor radon concentrations below 148 Bq m^{-3} (4 pCi l^{-1}), and (2) allow comparison of a variety of mitigation systems. These were installed beginning in November, 1986. System-types included: subsurface ventilation (SSV) by depressurization (SSD), and SSV by pressurization (SSP) in 11 homes, ventilation of perimeter drain tiles/drain ducts (eight homes), air-to-air heat exchangers (AAHX) in two homes, basement pressurization (three homes), block wall ventilation (three homes), and caulking and sealing openings to the soil (all homes).

Subsurface ventilation by depressurization was very often recommended and successful. SSP was less effective than SSD in all homes where it was evaluated. This contrasts with results from earlier studies in the Spokane, WA area. Drawing air from the cores of block walls and SSV via a connection to perimeter drain (perimeter of basement slab floor) were generally effective due to the efficient ventilation and depressurization of major subslab regions

from which radon normally entered the house. Pressurization of basements with air drawn from upstairs caused satisfactory reductions in indoor radon levels in only one house where the basement could be sufficiently tightened to permit adequate pressurization. The AAHX's reduced radon concentrations to an extent consistent with the theory that concentrations are proportional to the reciprocal of the total ventilation rate when ventilation is not associated with a change in indoor air pressures. This supports previous work indicating that AAHX's are generally adequate only in homes with low initial indoor radon levels and ventilation rates. Finally, caulking and sealing often resulted in a measurable reduction in baseline indoor levels, but never achieved the target concentration.

Intensive Radon Mitigation Research: Lessons Learned*

B.H. Turk, R.J. Prill, R.G. Sextro, and J. Harrison†

Two intensive field studies of radon control have provided an opportunity to conduct follow-on research, and to compare and combine data and results from regions with different soils and types of house construction. The first study near Spokane, Washington involved 14 homes often having foundation walls of poured concrete placed in soils of uniformly high permeability and low to moderate soil gas radon concentrations. The second study was conducted in north-central New Jersey on seven homes that had foundation walls constructed of hollow core blocks. The soils around the New Jersey homes were variable in both permeability and radon concentrations in soil gas.

For control homes (homes that did not receive radon control systems until conclusion of the projects) in both studies, indoor radon levels remained higher than expected in the spring and summer. During these seasons, the warmer outdoor air temperatures are expected to diminish the thermally-caused negative pressure differentials that drive the bulk flow of radon-containing soil gas into the houses. It was discovered that soil temperatures substantially modify the pressure differentials (ΔP s) that drive soil gas entry into basements in both summer and

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winter. Calculations for a one-story house in New Jersey show that warmer soil in winter and cooler soil in summer (relative to the prevailing outdoor temperatures), reduces the magnitude of the basement pressure difference by about 1 Pa. At times during the summer, the cooler soil gas temperatures can cause the ΔP s to be negative, drawing radon into the building.

Another finding is that the forced-air distribution of many residential heating and cooling systems can increase the natural depressurization of the substructure by up to 10 Pa (but generally less) and also transfer large amounts of radon from the substructure to the upper floors. These effects are more pronounced if leaky return air ducts or plenums are located in the substructure.

For the majority of homes in these two studies, subsurface ventilation (SSV) was the most appropriate and effective radon control technique. The data and measurement results indicate that 40% to 90% of the air in SSV exhaust airstreams originates in basements. This suggests that the leakiness of the below-grade substructure surfaces greatly influences the flow resistance to an SSV system.

Air-to-air heat exchangers (AAHX) were generally practical for radon control only in those houses or zones of houses that have low to moderate initial radon levels and ventilation rates. Finally, the success of another mitigation system based on pressurizing the basement depends on achieving a pressure in the basement that is at least 2 to 3 Pa greater than the average wintertime natural depressurization of the basement. Only basements that can easily be maintained air tight therefore are suitable for this system.

Monitoring and Evaluation of Radon Mitigation Systems Over a Two-Year Period*

R.J. Prill

In previous research studies, elevated concentrations of radon were found in a significant percentage of the houses located in Eastern Washington and Northern Idaho. A subsequent study, completed in 1986, developed and evaluated radon mitigation techniques and systems in fourteen houses in the area of the Spokane River Valley. This research reports on the performance of these radon mitigation systems for a period of two years.

Seasonal and annual radon concentrations in all zones and on each level of these houses were measured using mailed alpha-track detectors during the two-year follow-up period. Each house was inspected and the radon mitigation system evaluated during the second heating season of the follow-up study. Some of the systems were modified to eliminate problems which had developed over time.

The alpha-track measurements generally showed an increase in radon levels in a majority of the houses compared to the levels measured immediately after the installation mitigation systems. The greatest increases in radon concentrations occurred in 3 of the 4 houses equipped with basement pressurization systems. In most of the houses equipped with sub surface ventilation systems the radon concentrations also increased over the course of the follow-up period. Radon concentrations in the two houses equipped with air-to-air heat exchangers appeared to depend upon the duration of operation and fan speed settings of the heat exchangers. Factors causing decreased performance of the mitigation system included: (1) a build up of dust and lint on the soil, beneath the slab, at the pipe outlet of subsurface ventilation systems operated in the pressurization mode; (2) noisy and vibrating fans which were turned off by occupants; (3) air-to-air heat exchanger, basement pressurization, and subsurface ventilation system fans which were sometimes turned off or fan speeds reduced by occupants even when there was not a noise problem; and (4) crawl space vents which were closed or sealed.

Appraisal of the U.S. Data on Indoor Radon Concentrations*

A. V. Nero, K. L. Revzan, and R. G. Sextro

Recent surveys of indoor radon concentrations have suggested that the risk to the U.S. population is much greater than was indicated by earlier surveys. We examine the bases of the discrepancy and show that the interpretations of the recent surveys are in error.

PRE-1984 STUDIES

Results from a number of small surveys were used in 1984 as the basis for developing a U.S. concentration distribution. This analysis discriminated between those surveys undertaken because high indoor concentrations were known or suspected and those that were designed on a

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random basis. Furthermore, data taken in the winter were normalized to an approximate annual-average concentration, and the different data sets were weighted by number of houses, region, and population in order to examine the sensitivity of the resulting distribution to these factors. The resulting aggregate distribution, found to be insensitive to weighting, has an average or arithmetic mean (AM) of 55 Bq m^{-3} . Approximately 2% of homes were found to exceed annual-average concentrations of 300 Bq m^{-3} . The distribution was represented well by a lognormal function with a geometric mean (GM) of 33 Bq m^{-3} and a geometric standard deviation (GSD) of 2.8. The annual-average concentration was, on the average, 72% of that measured in the winter. The inclusion of data from areas where concentrations were expected to be higher on the basis of prior information raised the average concentration substantially, as had been expected. A second important survey entailed year-long radon monitoring in 1984-1985 in the homes of 453 physics faculty at 101 universities throughout the United States. The results correspond well to a lognormal distribution with a GM of 38 Bq m^{-3} and a GSD of 2.36. Both surveys utilized data accumulated in living spaces rather than basements, which is a major distinction from the more recent data sets. The fraction of houses with concentrations above 150 Bq m^{-3} are estimated from the earlier survey at 7%, and from the latter survey at 6%. Because of the difference in GSDs, perhaps due to reliance on a particular subpopulation in the latter survey, the functions diverge at higher concentrations; still, the fractions above 300 Bq m^{-3} are only a factor of two apart.

RECENT STUDIES

In one study, Alter and Oswald find that approximately 60,000 U.S. etched-track measurements are found to average 266 Bq m^{-3} . However, 50,000 of the data are from only 6 states, including some known to have high concentrations. Removing the data from these states yields an average, for the 10,251 remaining data, of 158 Bq m^{-3} . Two alternative methods of obtaining a more representative selection yield averages of 152 and 153 Bq m^{-3} . The authors find this convergence striking, assert that the results provide a rough "exposure" estimate, and conclude that the national "exposure" exceeds the 55 Bq m^{-3} cited previously. In fact, even the three restricted sets of data are likely to overrepresent homes with high concentrations. Further, the parameter of interest for indoor exposures is the annual-average concentration in the living space.

A major difficulty is that a large portion of the measurements are performed in basements. Concentrations in basements average approximately twice those on first floors during the winter, with an even larger ratio during the summer. In fact, for a subset of measurements for which location was recorded, the 44% taken in basements have an average concentration 2.0 times the average from the non-basement readings. If we attempt to correct an apparent average of 155 Bq m^{-3} to a living-space average assuming that 44% have results that are a factor of 2 high,

we find a corrected average of 108 Bq m^{-3} . It is even more difficult to quantify the effect of oversampling in areas or houses where high concentrations are known or suspected. We note that a 25% reduction of the AM yields 81 Bq m^{-3} ; there are indications from the etched-track data themselves and from comparison with the EPA data discussed below that the effect of oversampling is at least this large. Finally, a preponderance of measurements are performed during winter only. As indicated above, annual-average concentrations have been found to average approximately 72% of winter values. Given probable mixes of seasons in which the etched-track measurements were taken, the annual-average concentration may therefore be 80 or 90% of the value above, i.e., approximately 69 Bq m^{-3} . These considerations are enough to indicate that an average less than 75 Bq m^{-3} , reasonably consistent with the earlier surveys, is probable.

Alter and Oswald also find that 23% of the 10,251 data exceed the EPA remedial level of 148 Bq m^{-3} . However, a lognormal function with a GM of 61 Bq m^{-3} and a GSD of 3.2 is found to fit the data below 148 Bq m^{-3} very well, with a considerable excess of data above this point, particularly of very high values. The considerations discussed in the previous paragraph account for this excess.

A second data set has arisen from recent efforts of the EPA in conjunction with 10 states. During the winter of 1986-1987, charcoal detectors were deployed in statistically chosen samples of homes in nine states, plus another state in which volunteers were relied on. Examining the EPA press material, one finds the following information: the number of homes monitored in the main sample varied from 190 to 1787 for the ten states, totaling approximately 10,000. The AM for the main sample was 110 Bq m^{-3} ; 20% of measurements exceeded 148 Bq m^{-3} and approximately 1.1% exceeded 740 Bq m^{-3} . Measurements were performed following the EPA screening protocol so that, as indicated in some of the EPA backup material, these results - taken in winter and, often, in basements - do not represent annual-average concentrations to which people are exposed. Nonetheless, the press reports, following the EPA press release, compared these results directly with the EPA action guideline and indicated that 21% of the homes exceeded the guideline, an inappropriate use of the data.

If the correction from basement concentrations described above is made to the AM of 110 Bq m^{-3} , and the resulting 76 Bq m^{-3} is corrected to an annual-average using the factor of 0.72, an AM of 55 Bq m^{-3} is found. The precise agreement with previous results is fortuitous, but indicates that - if proper adjustments could be made - agreement would be quite satisfactory. Furthermore, these adjustments would drastically reduce the fractions above 148 and 740 Bq m^{-3} , apparently to the vicinity of the early results, which were that 6 or 7% of homes exceed 148 Bq m^{-3} and perhaps 0.1% exceed 740 Bq m^{-3} .

Any two probabilities may be used to define a lognormal distribution. The particular distribution which passes through the given probabilities for 148 and 740 Bq m^{-3} has a GM of 58 Bq m^{-3} and a GSD of 3.0, which implies an

AM of 106 Bq m^{-3} , which is close enough to the actual AM to suggest that the lognormal may be a useful representation of the data. If so, then lognormality is maintained at least to the region of 740 Bq m^{-3} , which contrasts with the data of the Alter-Oswald study. Both the GM and the GSD of the distribution are higher than those of the early surveys, of course, but we have shown that they have been overestimated. Extrapolation of the lognormal indicates that 0.01% of the homes, i.e., 1 home, should exceed 3700 Bq m^{-3} . The actual number is 3, so that we expect that fewer than 3 in 10,000 homes exceed this level, which is a much smaller fraction than has been suggested.

CONCLUSIONS

Monitoring efforts undertaken before 1985 indicate that the radon concentration in U.S. houses averages approximately 55 Bq m^{-3} and that, in approximately 6%, annual-average levels exceed 150 Bq m^{-3} , with perhaps 1-2% having 300 Bq m^{-3} or more. However, several recent large-scale data sets yield average concentrations of 100- 150 Bq m^{-3} , with perhaps 20% of results exceeding 150 Bq m^{-3} , leading to an exaggerated estimate of risk. In fact, these recent data sets overrepresent high-concentration houses or include sampling performed in basements or in the winter only. Adequate information is not available to adjust these results precisely to annual-average indoor concentrations experienced by the population, but plausible corrections yield results that are consistent with the distributions previously found.

Parametric Modelling of Temporal Variations in Radon Concentrations in Homes*

K.L. Revzan, B.H. Turk, J. Harrison, A.V. Nero, R.G. Sextro

The radon concentrations in the living area, the basement, and underlying soil of a New Jersey home have been measured at half-hour intervals over the course of a year, as have indoor and outdoor temperatures, wind speed and direction, and indoor-outdoor and basement-subslab pressures; in addition, periods of furnace operation have been logged. We generalize and extend an existing

radon entry model in order to demonstrate the dependence of the radon concentrations on the environmental variables and the extent of furnace use. The model contains parameters which are dependent on geological and structural factors which have not been measured or otherwise determined; statistical methods are used to find the best values of the parameters. The non-linear regression of the model predictions (over time) on the measured living area radon concentrations yields an R^2 of 0.88.

Theory

We assume that a house is divided into two zones, the basement and living area, of which only the former is in contact with the soil; the house is assumed to be depressurized as a result of temperature differences between inside and outside and the flow of wind around the structure. On the basis of a highly simplified model, we represent the soil gas radon concentration, C_s , as

$$C_s = p_1 (1 - \exp[-p_2/\Delta p_s]), \quad (1)$$

where the p_n are parameters which depend on the properties of the soil and on the nature of the openings between basement and soil and Δp_s is the pressure across the soil.

From the mass-balance, assuming the outdoor radon concentration to be negligible, the steady-state radon concentration in the basement is

$$C_b = (f_{sb}C_s + f_{lb}C_l) / (f_{bo} + f_{bl}), \quad (2)$$

where C_b , C_l , and C_s are the radon concentrations in the basement, living area, and soil, respectively, and f_{sb} , f_{lb} , f_{bo} , and f_{bl} are the flows from soil to basement, living area to basement, basement to outside, and basement to living area, respectively, and where the outside concentration and diffusive entry have been neglected. Similarly, the steady-state living area concentration is

$$C_l = f_{bl}C_b / (f_{lo} + f_{lb}), \quad (3)$$

where f_{lo} is the living area to outside flow.

We now assume that the flow from living area to basement, f_{lb} , is entirely due to furnace operation, that the flow from basement to living area is the sum of f_{lb} and a term directly proportional to the flow from the living area to the outside, and that the basement to outside flow is a constant multiple of the living area to outside flow, so that

$$C_b = \frac{f_{sb}C_s(1 + p_3A_f)}{(p_4 + p_5A_f)f_{lo}}, \quad (4)$$

and

$$C_l = (p_6 + p_7A_f)C_b / (1 + p_7A_f) \quad (5)$$

where A_f is the fraction of the time the furnace is in operation. When the furnace is not in operation, C_b is the quotient of a source term and the outside to basement flow; when the furnace is in operation, assuming the fur-

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nance flow to dominate other flows between the two interior zones, the denominator becomes the total flow into the house. With the furnace off, the house can be represented by the two zone model; with the furnace on, the air of the two zones is mixed and the house is effectively a single zone.

If we now represent the flows appearing in equations 4 and 5 by

$$f_{sb} = p_8 \Delta T + p_9 u^2; f_{ls} = (p_{10} \Delta T + p_{11} u^2)^{0.5}, \quad (6)$$

where ΔT is an appropriate temperature difference and u is the wind speed, and if we further assume that Δp_s is proportional to f_{sb} , then we have a model in which the only independent variables are the temperature difference, the wind speed, and the fractional furnace operation. There are 3 parameters in the equations determining C_s (1 and 6), 6 in those determining C_b (1, 4, and 6, with terms collected), and 2 in that determining C_i (5).

Results

We shall apply the model to a two-story dwelling with a basement located in north central New Jersey, which was selected as the control for a year-long study of the effectiveness of remedial action in six other houses in the same general area. The basement is almost entirely below grade; it contains a forced-air furnace whose ductwork has been observed to be leaky. Radon concentrations were measured in the soil below the basement slab, in the basement itself, and on the first floor using continuous radon monitors. Environmental measurements included indoor, outdoor, and soil temperatures, wind speed and direction, barometric pressure, and precipitation. Differential pressures were measured between the top and bottom of the basement slab, between the first floor and the basement, and across the four walls separating the basement from the outside air. Furnace operation was measured on a binary (on/off) basis. Data was collected for 10 months, beginning on 18 September 1986; all data was logged automatically at half-hour intervals. The comparison between theory and experiment is, however, based on three-day averages of the data.

A linear regression shows that Δp_s is directly dependent on ΔT , u , and possibly on A_f , but it is impossible to determine statistically which of the variables must be included in the equation. The best results occur when we use the basement temperature, the soil temperature at 70 cm depth, and the furnace activity; the R^2 is 0.82. If the same variables are used to predict C_s , we find an R^2 of 0.62. The model accounts for the general tendency of the data, but is insufficient to account for the day-to-day fluctuations. There may be inhomogeneities in the soil gas concentration in the vicinity of a house, in which case a spot measurement could be unrepresentative of the average and the model would not be expected to predict well.

The basement concentration data can be divided into three distinct periods: two periods of warm weather during which relatively large fluctuations in concentration

occurred and the winter period, running from December 4 through March 12, during which the fluctuations were relatively small. The difference in character between the warm and cold weather periods may be due to freezing of the soil. When we model the basement concentration using equations 4, 6, and 7 with C_s equal to its measured value, the fit is quite poor, suggesting that the soil gas measurement is not representative. When we use equation 1 to represent the soil gas, the fit to the data for the full year is poor, but some success is found in fitting distinct equations to the data for the warm and cold weather periods taken separately. The best fit to the warm weather data is obtained when the basement-outside temperature difference and the wind speed are used in both the source and removal terms; the R^2 is 0.63. The best fit to the cold weather data is obtained when the basement-soil temperature difference and the furnace activity are used in the source term; the R^2 is 0.70. The comparison of theory and data for the basement reveals the inadequacy of the theory; one major flaw may be the inability of the theory to represent the flow across the building shell (the air exchange) correctly.

When the measured values of C_b are used in equation 5, we find p_1 and p_2 to be 0.24 and 5.1, respectively, with an R^2 of 0.93; we regard this result as confirming the theory leading to that equation. When the calculated values of C_b are used, we find an R^2 of 0.88, which is satisfactory, but we note that the prediction of the basement concentrations is not good, and the result may be fortuitous.

Technique for Measuring the Indoor ²²²Rn Source Potential of Soil *

W.W. Nazaroff and R.G. Sextro

Elevated indoor radon concentrations are often caused by high rates of entry of radon generated in soil within a few meters of a building's substructure. The potential of soil for generating high indoor radon concentrations depends on two factors: (1) the rate of release of radon from soil grains into the pore space of the soil, and (2) the volume of soil that can contribute its emanated radon to indoor air. The aim of this work is to develop techniques for measuring these factors and a method for combining

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the results into a single indicator of the indoor radon source potential of soil.

The experimental method entails installing a sampling probe into the soil. A pump is used to extract air from the soil through the probe, and a sample of this air is analyzed to determine its radon content. From this measurement, the rate of release of radon into the soil pores can be determined. The difference in air pressure established by the pump is measured between the tip of the probe and the atmosphere, and the rate of air flow through the probe is also measured. From these parameters, and the dimensions of the probe, the permeability of the soil is computed. This characteristic indicates how much soil may contribute radon to the interior of a building.

A theoretical analysis of radon transport in soil is developed as a basis for interpreting the experimental data and for combining the results into a single indicator of radon source potential. In the analysis, it is first argued that, for homogeneous soil, molecular diffusion may be neglected compared with bulk flow as a radon transport mechanism in cases in which the source potential is high. Then, equations for the pressure field and the radon flux are formulated and solved numerically for two idealized soil cavities with reduced air pressure (1) an isolated sphere, and (2) a long cylinder with a horizontal axis. The first case represents the soil sampling probe, and the latter case is a model for a house in which there is a leakage path from the soil around the basement perimeter, such as a floor-wall gap or crack.

In a preliminary field test, the measured indoor radon source potential in soils adjacent to four New Jersey houses was found to correlate well with the measured average indoor radon concentrations.

Successful preliminary tests suggest that this may be a useful basis for setting priorities in efforts to identify individual houses with high concentrations. The method could also be used to determine whether construction practices in an area need to be modified to prevent elevated radon concentrations in future housing. Further survey work must be conducted comparing measured indoor radon concentrations with the indoor radon source potential of nearby soil. Ultimately, the demonstration of a strong empirical correlation between the higher observed indoor concentrations and the source potential is both sufficient and necessary to justify the use of this method for appraising the risk of high indoor radon concentrations from soil.

Mapping Surficial Radium Content as a Partial Indicator of Radon Concentrations in U.S. Houses

K.L. Revzan, A.V. Nero, R.G. Sextro

In connection with the problem of indoor radon, we discuss the use of data from the National Aerial Radiometric Reconnaissance to develop maps of radium in soil, at various resolutions, for the contiguous 48 states. We examine the relationship between the results of measurements of radon in houses and the indications of the U.S. map, noting that some, but by no means all, of the areas known to have elevated radon concentrations appear as areas of higher radium concentration than their surroundings and that there are other areas, in which measurements of high radon levels have not been made, which are suggested as deserving of interest. We discuss mapping techniques for smaller areas and possible methods of dealing with apparent discrepancies between adjacent areas.

Results of Mapping

An important factor determining radon concentrations in houses is the radon concentration in the pore spaces of the underlying soil. For that reason, a useful first step in the identification of areas of elevated radon is the development of a map of soil gas concentration or, what is equivalent, a map of radium concentration in soil, for the U.S. Though such a map cannot exclude any area of the country from the possibility of having houses with high radon levels (since, for example, high permeability soil may allow transport of sufficient soil gas of low radon concentration to produce a high indoor concentration), it can suggest certain areas which are likely to have large numbers of those houses.

The necessary data for a radium map was obtained by the National Aerial Radiometric Reconnaissance (NARR), which measured the gamma radiation from the top 0.5 m of soil or rock in order to discover uranium deposits. From the data of this survey, obtained and processed by a number of subcontractors, a database of manageable size was developed, in which we have stored the average radium concentration for each 1.6 km along the survey flightlines. A map of the contiguous 48 states was then

*This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Pollutant Characterization and Safety Division, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy (DOE) under Contract No. DE-AC03-76SF00098. It was also supported by the Office of Radiation Programs of the U.S. Environmental Protection Agency (EPA) through Interagency Agreement DW89932609-01-0 with DOE. This report has not been subjected to EPA review. Its contents do not necessarily reflect the views of EPA, nor does mention of firms, trade names, or commercial products constitute endorsement or recommendation for use.

created, on which a dot has been placed in each 20×20 km area, the size of the dot representing the average radium concentration in that area.

The map reveals that certain areas appear sufficiently different in character from their surroundings to lead to suspicion that there might be problems involved in attempting to compare data obtained by different subcontractors despite their use of the same calibration procedures. The problem is perhaps most clearly exhibited in the Rawlins and Greeley quadrangles of Wyoming and Colorado. The means of Ra for the two quadrangles are 6.3 and 8.1 Bq kg⁻¹, while the mean Ra of the six surrounding quadrangles is 33.3 Bq kg⁻¹. Other possible calibration anomalies appear in southwestern South Dakota, eastern Washington and western Idaho, and San Jose, California. The average radium concentration of the territories surveyed by individual subcontractors ranges from 20 to 32 Bq kg⁻¹, but the variation may be explained, at least in part, by the different areas of the country flown by each; the question of the importance of subcontractor performance remains open.

The following areas, which the map reveals as having high radium concentrations compared to their surroundings, have also been found to have high radon concentrations in homes: eastern Pennsylvania-northern New Jersey (Reading Prong), eastern Tennessee-western North Carolina, western Washington-eastern Idaho (Spokane-Cour d'Alene), and western Florida (phosphate-bearing land). Apart from Florida, where the situation is well understood, and Tennessee, the mean levels of radium in these areas, while higher than their surroundings, are not high in absolute terms, and the nature of the relationship between the means of radium in soil and radon in houses remains to be established.

One region is known to have high radon concentrations but does not appear to have high radium levels: the Red River valley of North Dakota. While the map shows the valley to be somewhat higher in radium than the territory to the east and west, the level is the same as that of the territory to the south, so that it is difficult to infer that this might be a region of interest. There are a number of areas which, conversely, have high radium concentrations but in which high radon levels have not been found: central California, southern Arizona-New Mexico, a number of regions in the Rocky Mountain states, central New Hampshire-southern Maine, and, most conspicuously, southwestern South Dakota. Some of these are known to be areas in which uranium deposits occur; some, as we have suggested, may stand out because of calibration problems; some may be worthy of investigation.

The Statistics of Radium in Soil

On the basis of the 22,172 average radium concentrations used for the U.S. map, the geometric mean (GM) is 25 Bq kg⁻¹, the geometric standard deviation (GSD) is 1.6,

the arithmetic mean (AM) is 27 Bq kg⁻¹, and the arithmetic standard deviation (ASD) is 12 Bq kg⁻¹. These parameters are useful for making comparisons among regions, but they are misleading in that each datum is treated as if it were itself an observation rather than as an average of original observations. Since we have retained the number of observations, the AM, and the ASD for each 1.6 km flightline datum, it is a simple matter to calculate an ASD for each 20×20 km region and then, to calculate an ASD for the contiguous U.S. On the basis of the original 24,591,855 measurements, this ASD is 21 Bq kg⁻¹. Calculation of the GM and GSD on the same basis involves approximations, since we have not retained the GM and GSD of the observations in our database. If we assume the data to be lognormally distributed, however, we may use the AM and ASD to calculate a GM and GSD: 21 Bq kg⁻¹ and 2.0, respectively.

If we now consider that each original observation itself represents an integration of several hundred square feet and that large areas of the country remain unobserved due to the relatively large distances between flightlines, it is apparent that the actual GM of observations of radium in soil made at ground level, each representing an area the size of a house, is likely to be somewhat greater than 2.0. The GM of measurements of radon concentration in houses in the U.S. is approximately 2.8. Suppose that the indoor radon concentration is the product of the soil gas radon concentration, represented by the radium concentration, and some other lognormally distributed factor or combination of factors. Given the fact that the logarithms of GSDs add in quadrature, two factors contributing equally to the variation in radon would each have a GSD of 2.1, which is very close to the calculated GSD for radium. On this basis, the observed variation in radium in soil accounts for roughly half the observed variation in indoor radon.

It is clear, however, that we must look to factors other than radium in soil to explain the radon concentration data. In part of Eastern Pennsylvania, for example, we find a GM indoor radon concentration of 120 Bq m⁻³ (with a GSD of 3.4), which is a factor of 3.6 higher than the national GM. The GM radium for this area is generally 20-40 Bq kg⁻¹, with a high of 56 Bq kg⁻¹; the GSD is generally 1.5-2.5. If the relationship between radium and the other factors affecting radon in houses were to be the same in Eastern Pennsylvania as in the contiguous 48 states as a whole, the GM radium should be on the order of 75 Bq kg⁻¹ and the GSD should be 2.4.

Conclusions

We have shown that, on a national basis, as much as half the variation in radon from region to region may be accounted for by the level of radium in the soil, but that there are regions for which the radium concentration does not account for the relatively high observed radon.

Indoor Atmospheric Chemistry: Interactions of Radon with other Gaseous Pollutants*

J.M. Daisey, R. Sextro, A.T. Hodgson, N. Brown, and D. Lucas

Research was initiated on the radiolytic interactions of radon and radon progeny with other gaseous indoor pollutants. The objectives are to chemically characterize the gaseous and particulate products generated by the radioactive decay of radon and its progeny, to determine formation rates and size distributions of the aerosols and resultant equilibrium factors and to elucidate reaction mechanisms.

Three environmental chamber experiments were conducted for the purpose of determining appropriate experimental parameters. These experiments were conducted in collaboration with P.K. Hopke and M. Ramamurthi, University of Illinois.

The chamber was spiked with a mixture of volatile organic compounds (VOC) and radon. VOC and radon decay rates, over and above chamber background (determined in a separate chamber experiment), were monitored for 42 hours. The activity size distribution of the ultrafine aerosol was measured with a multi-screen sampler. Four VOC were used: n-hexane, toluene, 2,3-dimethyl-2-butene, and limonene. The 2,3-dimethyl-2-butene had a net decay rate of 0.007 h^{-1} . The limonene decayed at a net rate of 0.004 h^{-1} . The decay rates for the other two compounds were not significantly different from those measured in the absence of radon. In this experiment, there was no evidence of formation of ultrafine aerosol; however, it was determined that n-butanol from the condensation nucleus counter had back diffused into the chamber. This compound is a free radical inhibitor and contamination of the chamber with the n-butanol probably accounts for the lack of particle formation in contrast to the first experiment.

A molecular beam mass spectrometer is being modified and evaluated to allow for the detection and quantification of ions produced by the radioactive decay of radon and its progeny in indoor air. The apparatus had previously been used to measure neutral species in transient combustion events, using electron-impact ionization and analog signal detection and averaging methods. Many significant changes are needed in the beam system to permit the detection of the low concentrations of ions that are expected in these experiments.

Initial Efficiencies of Air Cleaners for the Removal of Nitrogen Dioxide and Volatile Organic Compounds*

J.M. Daisey and A.T. Hodgson

The objective of this research was to investigate the effective cleaning rates (ECRs) of selected portable air cleaners for removing NO_2 and volatile organic compounds from air when first exposed to concentrations typical of those found indoors. The ECR represents the air volume per unit time from which a contaminant has been removed and is useful in evaluating the cleaning effect in rooms of different sizes. We used NO_2 and VOC because they have documented adverse health effects and are commonly found at elevated concentrations in residences.

Four portable air cleaners were selected for study. All incorporated some activated carbon. Two devices designated PF1 and PF2 had multiple stage filter cartridges employing glass fiber mats for particle removal. The PF1 air cleaner had a layer of finely divided carbon impregnated in a fibrous mat and had the least amount of carbon. The PF2 unit had a layer containing activated carbon pellets (115 g) and a catalyst (99 g). The ES unit had a HEPA filter for particle removal, and contained the largest amount of activated carbon ($\sim 130 \text{ g}$) which was combined with potassium permanganate ($\sim 90 \text{ g}$). The fourth device, EP, removed particles by electrostatic precipitation rather than filtration and had 55 g of activated carbon.

Experiments were conducted in a 20-m^3 environmental chamber operated without mechanical ventilation. The chamber was ventilated and then the NO_2 and VOC were added to the chamber and mixed. The air cleaner was turned on and the rate of decay of the compounds was determined. Removal efficiencies for NO_2 were determined at an initial chamber concentration of $\sim 500 \mu\text{g m}^{-3}$. Six VOC, representative of five major classes of VOC typically found in indoor environments were used: n-heptane, an aliphatic hydrocarbon; toluene, an aromatic hydrocarbon; dichloromethane (methylene chloride) and tetrachloroethylene chlorinated hydrocarbons; hexanal an aldehyde; and 2-butanone (methyl ethyl ketone) a ketone. The average initial chamber concentrations for these compounds ranged from 130 to $680 \mu\text{g m}^{-3}$.

None of the air cleaners removed dichloro-methane. The initial ECRs for NO_2 and the remaining five VOC (averaged for the VOC) for the four air cleaners are shown (figure). The ES and PF2 devices were reasonably effective.

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Effective Cleaning Rates of 4 Air Cleaners
for NO₂ and 5 VOC

Figure Initial effective cleaning rates of four air cleaners for NO₂ and five VOC (average). Effective cleaning rate for the PF2 air cleaner after 150 hours of operation in a house is also shown.

tive initially in removing NO₂ and the five VOC. Removal rates were equal to one air change per hour or more for a room of about 40 m³. The PF2 device, which had a catalyst as well as carbon, had the highest ECR for NO₂ and was almost twice as effective in removing NO₂ as was the ES unit. These two devices had relatively high air flow rates and the most carbon. The PF1 and the EP devices, had much lower ECRs for the removal of NO₂ and VOC and would not effectively remove these pollutants from even a small room.

The PF2 air cleaner was subsequently operated, with the same filter, for 2.5 months (150 hours) in an older residence of non-smokers who used a gas range for cooking. The air cleaner was then tested a third time in the chamber. The figure compares the ECRs in the first and third experiments. For NO₂, the ECR was reduced to about one-third of the initial value. For the five VOC removed by the air cleaner, the ECRs after field operation were about half the initially measured values. The product literature for this device states the estimated filter life is about 1000 hours.

Further investigation is needed to determine ECRs and efficiencies over periods of extended use for air cleaners which have relatively high ECRs. Investigation of possible chemical reactions occurring with extended use is also warranted.

Volatile Organic Compounds in Large Buildings*

J.M. Daisey and A.T. Hodgson

There have been increasing numbers of complaints about discomfort and illness in new and newly renovated office buildings. This increase in complaints has been correlated with reduction in ventilation for energy efficiency and increased uses of synthetic building materials and furnishings. Exposures to volatile organic compounds (VOC), originating from materials and furnishings and various products used in large buildings are suspected to play a role. However, there has been relatively little research to characterize VOC in large buildings, to identify their sources, to evaluate temporal and spatial variations in VOC concentrations or the effects of building ventilation on concentrations.

The purposes of the ongoing study of VOC in large buildings are: 1) to develop a data base of concurrent measurements of VOC concentrations and ventilation; 2) to investigate both short- and long-term temporal variations in source strengths of VOC; and 3) to develop methods to identify major sources and estimate their contributions to indoor VOC concentrations.

To date, simultaneous measurements of VOC and of ventilation have been made in four large office buildings, a museum-teaching facility and a school. Concentrations of total organic carbon in these buildings have ranged from less than 1 to 11 mg·m⁻³.

Temporal variations in indoor concentrations of VOC and the effects of ventilation on VOC have been under detailed investigation in a large seven-story office building in Portland, OR in collaboration with R. Grot, National Institute of Standards and Technology. The first measurements were made in August, 1987, before the building was completely finished but after it was partially occupied. Subsequent VOC samples have been collected on three occasions over a period of a year. In addition, samples of major materials used to finish the interior have been collected and screened for VOC emissions.

The concentrations of VOC and total organic carbon in the Portland building have varied considerably over the study, with the highest concentrations observed when the ventilation rate was lowest. The concentration and ventilation rate data were used in a single-equation mass balance model to estimate specific source strengths and to determine if these had declined as expected over time. The results showed that the source strengths of the individual VOC and of total organic carbon remained relatively

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constant over the course of the study. The dominant source of the VOC in this particular building appears to be, not the interior finish materials, but a solvent-using activity in the building. Efforts to estimate the contribution of this activity to indoor concentrations are in progress. The emission of total organic carbon in this building was estimated to be over 2.5 kg per 8-hour day.

Development of a Sampling and Analysis Method for Polycyclic Aromatic Compounds in Indoor Air *

J.M. Daisey, L.A. Gundel, A.T. Hodgson, and F.J. Offermann†

Research was initiated to develop a method for sampling and analyzing vapor- and particulate-phase polycyclic aromatic hydrocarbons (PAH) and nitro-PAH in indoor air. Many of the PAH and nitro-PAH are carcinogens in animals but there have been few indoor measurements of these compounds. Efforts to measure these compounds in indoor air have been hampered by the lack of sensitive, validated sampling and analytical methods. For indoor air, the sampling rate must be much less than the air exchange rate so that the act of sampling has a minimal impact on the concentrations of indoor pollutants which are removed by the sampling.

The approach being taken in this research is to develop and validate a sampler consisting of a filter followed by an XAD-4 resin bed to collect, respectively, particulate and vapor phase PAH and nitro-PAH. Approximately 25 m³ of air will be sampled in 12 hours. After solvent extraction, the vapor phase compounds will be analyzed by gas chromatography-mass spectrometry and the particulate phase compounds will be analyzed by high pressure liquid chromatography with fluorescence detection. The methods will be field tested in selected houses.

The Role of Heterogeneous Reactions of NO₂ in Indoor Air *

J.M. Daisey and L.A. Gundel

Concentrations of NO₂ in indoor air can be one to two orders of magnitude greater than those in outdoor air if combustion sources such as gas stoves are present. Indoor surfaces have been shown to remove NO₂, and in a few instances, to convert it to NO. The purpose of this study was to determine if heterogeneous reactions of NO₂ on surfaces of materials in indoor environments could produce other secondary pollutants which might be hazardous or which might initiate further indoor atmospheric chemistry.

Experiments were conducted in a specially designed and constructed anular reaction vessel containing selected indoor materials: wool or nylon carpet, polyurethane foam or wallboard paper. NO₂, at concentrations of 1 ppm or less, was passed through the vessel in dry or humid (50% relative humidity) air. Concentrations of NO₂, NO, HONO, and HNO₃ were measured downstream of the reactor. An annular denuder was used to collect the acidic gases, HONO, HNO₃.

Each material removed a large fraction of the incident NO₂. The polyurethane foam removed all of the NO₂ in the air stream during the initial exposure period, but after about 5 hours was saturated. Nylon and wool carpet removed about 35% and 50%, respectively, of the incoming NO₂. NO was produced in varying amounts on all of the four materials investigated.

Significant quantities of gas phase nitrous acid (HONO) were produced from the interaction of NO₂ with both the foam and the wool carpet. Much smaller quantities of nitric acid (HNO₃) were produced. The excess of HONO over HNO₃ indicates that a direct reaction with these materials, rather than a disproportionation in sorbed surface water, has occurred. On foam, in humid air, at least 7% of the initial NO₂ (560 ppb) was converted to HONO, at a rate of about 0.5% per hour. For wool carpet, the conversion rate was only about 0.1% per hour.

The results of the experiments on heterogeneous reactions on surfaces of indoor materials have demonstrated that nitrous acid can be generated in indoor environments at substantial rates. The presence of this secondary pollutant may lead to subsequent indoor atmospheric chemistry and/or may pose some health hazard in itself.

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Transport of Volatile Organic Compounds from Soil into a Residential Basement*

A.T. Hodgson, K. Garbesi, R.G. Sextro, and J.M. Daisey

For residents of nearby houses, landfills are potentially important sources of exposure to toxic volatile organic compounds (VOC). Even municipal landfills accepting only nonhazardous material have been found to contain air concentrations of VOC high enough to cause concern. If not properly contained, VOC can migrate through the soil by aqueous or gas-phase transport. Gaseous compounds in the soil around houses are available for transport into these houses.¹

Our investigation sought to identify the mechanisms involved in transport of VOC from soil gas into the basement of a house situated in an area of contaminated soil. The study site was a single-family house adjacent to a covered municipal landfill in California. We had found previous evidence of migration of gas and VOC to the site from a landfill 70 m from the house at its closest point. The house was built over a basement which was almost entirely below grade. The foundation and basement consisted of a cement-block wall built on a cement slab. Experiments were conducted at the site over a four month period during the dry season.

Thirty soil probes were installed around the house at distances ranging between 0.5 to 12 m from the basement wall. The majority of these probes terminated at a depth of 1.5 m. The in situ permeability of the soil measured at the soil probes averaged $2 \times 10^{-10} \text{ m}^2$.

Samples of soil gas, outdoor air, and indoor air for qualitative and quantitative analyses of VOC were collected on multisorbent samplers and analyzed by gas chromatography-mass spectrometry. The VOC identified in soil gas were predominantly halogenated and oxygenated compounds, a number of which have been detected in landfills. The dominant compounds in soil gas were Freon-11, Freon-12, tetrachlorethylene, dichloromethane, and acetone. Many of the compounds in soil gas were also measured in indoor air but at much lower concentrations. Since the house was unfurnished and unoccupied and had no other obvious sources, soil gas was assumed to be the primary source of most of these compounds.

The entry rate of soil gas into the basement was estimated as a function of basement depressurization. Pure SF_6 was injected into the soil around the house to provide a source of labeled soil gas. One month later, after the SF_6 had diffused over most of the site, the soil-gas concentrations of SF_6 and Freon-12, a soil-gas contam-

inant, were measured at the soil probes nearest the basement. Then, with the basement closed, the exhaust fan was operated to produce pressures in the basement of -20, -30, -40, and -50 Pa relative to ambient pressure. Concentrations of SF_6 and Freon-12 in basement air were continuously monitored throughout the experiment. The entry rate of soil gas at each depressurization stage was estimated from the concentration data using a simple mass-balance model, assuming steady-state conditions. The slopes of the regression lines of entry rate versus basement depressurization diverged for SF_6 and Freon-12 undoubtedly due to differences in their distributions around the house and the consequent uncertainties in the average soil gas concentrations of the two compounds. However, the regressions suggest that for this house the entry rate of soil gas due to pressure-driven flow would be less than $1 \text{ m}^3/\text{h}$ at a typical basement depressurization of a few Pascals resulting from wind and an indoor-outdoor temperature differential. For comparison, the infiltration rate of outdoor air for the house at typical winter conditions would be about $500 \text{ m}^3/\text{h}$.

Since the basement of this house was well coupled with the soil and the soil was moderately permeable, the pressure-driven entry of soil gas was probably limited by the low below-grade leakage area of the basement. However, for houses with greater below-grade leakage areas, soils of equal or greater permeability, and low infiltration rates, the relative contribution of pressure-driven inflow to the total inflow of air can be much higher. Therefore, it is concluded that advective transport can result in elevated indoor concentrations of soil-gas VOC in those houses which have high relative inflow rates of contaminated soil gas.

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The Indoor Environment of Commercial Buildings*

D.T. Grimsrud, J.T. Brown, W.J. Fisk, J.R. Girman

The primary focus of research in indoor air quality has been on residential buildings. This report, by contrast, concentrates on commercial (office and institutional) buildings and is intended for a broad audience ranging from

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those who have no previous background in indoor air quality to those with considerable indoor air quality experience.

A recurring theme throughout the report is the sick building syndrome. This troublesome phenomenon, an attribution of the source of general feelings of irritation and malaise to the occupant's building, can cause significant economic damage to the building owners and tenants if the productivity of the workforce declines. Considerable uncertainty exists regarding the cause or causes of sick building syndrome. Current research on indoor air quality issues in commercial buildings concentrates on sick buildings; however, one must be careful not to overemphasize this topic. The health outcomes associated with the sick building syndrome tend to be short-term irritation effects. Longer-term, chronic effects associated with exposure to pollutants in commercial buildings may be equally or more important. These are not addressed typically in any study focused on the sick building syndrome. Where long-term effects are understood, they are discussed in this report.

The report is divided into seven chapters. The introductory chapter is followed by a discussion of the effects of initial design decisions that affect air quality. Many of these design decisions pertain to the ventilation systems. The mechanical ventilation systems, rare in residences but common in commercial buildings, have been identified by some as major causes of problems in the indoor environment. Their influence on indoor air quality is treated in chapter three.

Pollutants present in commercial buildings are discussed in chapter four. The discussion is organized by pollutant classes arranged in order of the expected pervasiveness of the pollutant problem. The long pollutant chapter is followed by the three final shorter chapters examining human factors, investigative procedures, and general corrective procedures to be considered when problems are discovered.

Pacific Northwest Existing Home Indoor Air Quality Survey and Weatherization Sensitivity Study*

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

The study reported in this paper had the following objectives:

1) survey indoor pollutant concentrations in unweatherized Pacific Northwest housing,

2) study the effect of weatherization on indoor pollutant levels.

SCREENING SURVEY

A screening survey of indoor air quality in 111 unweatherized houses was followed by staged weatherization in 40 of these 111 structures. Study sites were located in two of the three major climate areas of the Bonneville Power Administration (BPA) region. Houses in Portland and Vancouver, WA are found in the mild, coastal region while houses in Spokane and Coeur d'Alene, Idaho are located in the high plateau desert region east of the Cascade Mountains. Passive samplers to measure concentrations nitrogen dioxide, water vapor, formaldehyde, and radon were mailed to homeowners who put them in place using the shipping box as the sampler holder. Extensive telephoning was required to assure that instructions were followed. The screening survey results indicate that indoor concentrations of nitrogen dioxide (geometric mean of 5 ppb), formaldehyde (geometric mean of 37 ppb), and water vapor (arithmetic mean of 6.7 g/Kg) were significantly below levels of concern. However, the survey led to the discovery of elevated indoor radon levels in houses in the Spokane River Valley/Rathdrum Prairie of Washington and northern Idaho. The geometric mean concentration for 43 houses in that area was 4.4 pCi/L, compared with other regional and national studies that range from geometric means of 0.8 to 1.0 pCi/L. The high indoor radon levels found in the Valley/Prairie are due to the convective flow of radon-bearing soil gas from a highly permeable soil into the houses.

WEATHERIZATION STUDY

Forty-eight houses from the screening survey were chosen for the weatherization sensitivity phase of the study. Eight of the houses remained unweatherized during the study and acted as control structures; monthly measurements of pollutant concentrations were made in these houses to track the impact of non-weatherization factors on pollutant concentrations. The remaining houses underwent a variety of staged weatherization retrofits: all 40 houses received the standard BPA weatherization package, 14 houses also received wall insulation, while five of the forty houses also received house doctoring. Building and pollutant measurements were obtained using passive samplers where possible, and real-time instrumentation where necessary. Spokane/Coeur d'Alene houses were more tightly sealed against air leakage, both before (geometric mean specific leakage area of $4.9 \text{ cm}^2/\text{m}^2$) and after weatherization (geometric mean of $4.1 \text{ cm}^2/\text{m}^2$) than the Vancouver area houses (geometric mean of 5.3 and $4.9 \text{ cm}^2/\text{m}^2$, respectively). BPA's standard weatherization program reduced the specific leakage area of the 40 weatherized structures approximately 12.5%. The reduction due to wall insulation (6%) was not statistically significant. House doctoring resulted in an additional reduction in leakage area of 26%.

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Ventilation rates measured using passive sampling techniques and perfluorocarbon tracers (PFT) had a geometric mean of 0.37 h^{-1} before weatherization, 0.39 h^{-1} after weatherization, and 0.30 h^{-1} after house doctoring; however, these ventilation rates have not been corrected to account for different environmental conditions during the various measurement periods. The PFT-measured ventilation rates averaged approximately 20% lower than ventilation rates calculated using the measured leakage areas, weather data and a predictive model developed at LBL. The PFT technique yields results for a specific set of environmental conditions. The leakage area measurement combined with predictions accounts for environmental conditions but has significant uncertainties due to the reliance of an imperfect model. Because, ventilation rates scale with leakage area, we use the change in the leakage area of the house as the best measure of the change in the ventilation produced by weatherization.

Changes in pollutant concentrations were not well correlated with changes in ventilation rates. Factors other than ventilation, including pollutant source strengths, occupant effects, and environmental conditions are more important in influencing indoor pollutant levels.

While not correlated with changes in ventilation, pollutant concentrations did change. Measured data from this study showed increases of 11% in water vapor concentrations, 1% in formaldehyde concentrations, and reductions of 6% in NO_2 and 43% in radon concentrations when the means of the pre- and post-weatherization samples are compared. However, these results represent measurements made during different environmental conditions. Therefore, the results must be corrected to standard conditions if meaningful comparisons are to be made. Simplified models were developed to evaluate the impact of environmental conditions on indoor air pollutants. The models were used to recalculate radon, water vapor, and formaldehyde concentrations from before and after weatherization to corrected standard conditions. The concentrations adjusted to standard conditions show an increase of 8% in post-weatherization water vapor concentration relative to pre-weatherization conditions; a decrease of 3% in formaldehyde concentrations, and a decrease of 33% in radon concentrations. Only the changes in the radon concentrations are statistically significant. Where the radon data are separated by substructure type we find that only in crawl-space houses, where ventilation is added to crawl-spaces during weatherization, were the indoor radon levels significantly reduced. Radon levels in houses with other substructure types may have decreased also, but the changes are not statistically significant.

The impact of weatherization on indoor air quality is rather modest with the exception of its impact on radon concentrations. In a house with a crawl space, the standard BPA weatherization package improves indoor air quality by reducing radon concentrations.

The findings from this study showed that indoor pollutant concentrations were low except for radon concentrations in existing houses in the Spokane area. The standard weatherization measures reduced the specific leakage

area and therefore the ventilation in these houses by 12%. A poor correlation was seen between ventilation changes and changes in pollutant concentrations. Finally, weatherization had a modest effect on pollutant concentrations other than radon. Weatherization caused radon concentrations to decrease significantly in crawl space houses.

Commercial Building Ventilation Measurements Using Multiple Tracer Gases*

William J. Fisk, Richard J. Prill, and Olli Seppanen

Indoor air quality and the efficiency of ventilation depend, in part, on the rate of supply of outside air and also on the spatial variability of ventilation and the indoor flow patterns. For example, some rooms may be over-ventilated and others under-ventilated. Another concern is the possibility that fresh air supplied at ceiling-level short circuits to ceiling-level return grills such that the occupied region is poorly ventilated. Such a flow pattern would be inefficient. Conversely, a displacement or piston-like flow pattern in the floor-to-ceiling direction would generally be efficient since the air exiting the building would typically have an above-average concentration of pollutants.

Three new parameters are used to describe the ventilation process in detail. The first parameter is the age of air which equals the amount of time the air has been in the building. The second parameter is the air exchange efficiency which equals the age of the air that exits the building divided by twice the spatial-average age of indoor air. The air exchange efficiency equals 0.5 when the indoor air is perfectly mixed--values below and above 0.5 indicate short circuiting and displacement flow patterns, respectively. The third parameter is the source of air fraction which equals the fraction of air at some location that entered the building through a particular air handler or by infiltration.

To measure these new parameters, we simultaneously label each incoming stream of outside air with a different tracer gas. Outside air may be labeled directly by injecting a tracer gas at a constant rate directly into the stream of outside air, or labeled indirectly by injecting the tracer into the mixture of outside air and recirculated indoor air. Tracer injection is continued until concentrations in the air exiting the building are stable. Using cart-mounted gas chromatographic systems, tracer gas concentrations are monitored versus time in the major ducts of the air han-

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03 76SF00098.

dling units. During the period of injection, small local samplers in occupied spaces pump air/tracer samplers at a constant rate into one-liter sample bags yielding samples with time-average tracer concentrations. When tracer concentrations have stabilized, a syringe sample is collected at the location of each local sampler and operation of the local sampler is terminated.

Previously-established data analysis procedures based on age distribution theory have been modified to account for the use of multiple tracer gases. Source of air fractions are determined from ratios of steady-state tracer gas concentrations to measured (or predicted, if the outside air is labeled indirectly) concentrations of the same tracer gases in the streams of incoming outside air. Ages of air are determined from the source of air fractions and numerical integrations of the real-time tracer gas concentrations or by equivalent computations using the data collected at local samplers. Finally, the spatial average age of the indoor air is estimated by averaging the ages measured at numerous indoor locations.

The results of investigations in a complex of three interconnected office buildings and in an isolated office building are summarized. Within regions of these buildings that are served by a single air handler that supplies a mixture of outdoor and recirculated indoor air, the measured ages and source of air fractions varied by 30% or less from the region-average values. Monitoring at different heights above floor level provided no evidence of either short circuiting or displacement flow patterns within a room. Age of air varied more substantially between physically-isolated regions of a building (e.g., different floors with no mechanical recirculation between the floors) and between regions served by different air handlers. In the complex of buildings, air exchange efficiency values were close to 0.5, suggesting relatively uniform mixing of the indoor air in regions served by a single air handler. In the isolated building, air was supplied and removed from physically-isolated regions, and the air exchange efficiency was 0.7. Monitoring in additional buildings is required before general conclusions can be drawn regarding these aspects of ventilation in commercial buildings.

Indoor Exposure Assessment*

G.W. Traynor, A.V. Nero, S.R. Brown, M.A. Apte, and B.V. Smith

The Indoor Exposure Assessment Project has three major research themes: 1) to continue the development of a macromodel to characterize the frequency distribution of indoor pollutant concentrations; 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 data needed for the third project of assessing health risks from indoor air pollutants.

In FY 1988, 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 CONCENTRATION DISTRIBUTIONS

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. Initial efforts of the project focussed on the problem of estimating exposures to combustion emissions. This effort has resulted in the development of a macromodel that can predict indoor pollutant distribution across houses for carbon monoxide (CO), nitrogen dioxide (NO₂) and respirable suspended particles (RSP).¹

The model development was completed in FY 88. 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

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exchange rate), the investigation of the market penetration of combustion appliances and other indoor combustion sources, and the development of source usage models. The model utilizes deterministic and Monte Carlo simulation techniques to combine all of the inputs yielding indoor pollutant concentration distributions.

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.

The planned activities for FY 89 are: 1) finalize the formal report on the development of the model; 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, NO₂, 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 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.

A major update to the Data Base was prepared during FY 88. New bibliographic references, summary data sets were added. Several minor enhancements to the software were made.

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.

Additional updates to the data base will be distributed during the fiscal year. The updates will include all available published work and final reports. In addition, the user community will continue to be supported. There are over 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.

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.² This indicates that the average indoor concentration is approximately 1.5 pCi/l (55 Bq/m³) in single-family homes and that approximately 7% (or 4 million houses) have annual-average concentrations exceeding 4 pCi/l (150 Bq/m³). 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%,³ with long-term occupants of houses with 150 Bq/m³ incurring a risk exceeding 1% and those living at higher concentrations having proportionately higher risks.

This defines a spectrum of risk from radon 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 estimated average risk of cancer of 0.03-1% due to indoor exposures (depending on the form of dose-response model used).^{4,5} 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.⁶ Although controversial, midrange estimates of the risk of lung cancer to the average nonsmoker, due to breathing ETS, are 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.

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

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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. In this article, the work carried out over the last year is split into four overlapping sections: 1) Existing Buildings Efficiency Research, 2) Air Infiltration, 3) Air Leakage, and 4) Wood Burning. 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.

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EXISTING BUILDINGS EFFICIENCY RESEARCH

As 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 untapped 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 Existing Building Efficiency Research Program was initiated to address these problems in all three building sectors, single-family, multifamily, and commercial. The U.S. Department of Energy has designated IBL as the primary lab for carrying out research in the multifamily sector, and while the emphasis in the past years has been in coordinating research in this sector, we continue to work in single-family and commercial buildings. A review of the work in all three sectors is available.¹

Protocol Development

The need for a standardized set of procedures for monitoring buildings has led to our developing a monitoring protocol for residential buildings. An earlier draft of the protocol was used to specify the monitoring procedures during field tests in multifamily buildings in Chicago and Minneapolis/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.

Development of Audits and 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. In addition to having a tool box of basic diagnostic techniques, the practitioner needs a strategy for how to use them.

The *Multifamily Audit* currently under contract to Princeton University gives the necessary information for determining appropriate retrofits for an individual building.² Based on material developed by Princeton and IBL, the audit outlines the steps to evaluate, select, and analyze the performance of the retrofits in a multifamily building. A draft of the audit was prepared in conjunction with the joint Princeton/IBL diagnostic demonstration (March, 1988) and a final copy will be available by 1989.

Diagnostics for energy use in multifamily buildings that have been developed or are currently under development include tests of boiler efficiencies, distribution losses, shell and inter-apartment leakage, and household appliance efficiencies.

Following the development of air leakage diagnostics, we tested a ten-unit apartment building to determine air flows between units and to the outside. Results from these tests showed that the individual apartments were quite leaky to the outside, but had very little leakage between units, in contrast to the older buildings we had been studying previously.

Analysis of Retrofit Performance in Multifamily Buildings

We developed two models in the past year based on data collected from earlier monitoring projects in Chicago and Minneapolis. 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. 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.³

The second model characterizes the seasonal efficiency of multifamily boilers, taking into consideration the venting issues described above, as well as jacket and ground heat losses. Jacket losses from the older brick-set boilers were as high as 12 percent. Newer, steel-case and sheet-metal boilers had jacket losses of 2-4 percent. More than 80% of the losses were found to occur in off-cycle. This model is capable of providing the data necessary to make recommendations for boiler retrofit or replacement.⁴

Institutional Barriers

The widespread adoption of many retrofits is hindered by institutional barriers, including split financial incentives between owners and tenants, lack of information on the part of building managers, and a wide range of behavioral issues. We evaluated three projects this year that looked at institutional barriers, the first on the role of apartment managers in determining the energy use in multifamily buildings, a second study on how to improve information about energy use and savings to homeowners and renters based on their utility bills, and a third project that looked at how decisions are made that affect the energy use in new office buildings.

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 innovative solutions to these problems were documented.⁵

One of the difficulties in retrofit research is finding simple ways to evaluate the performance of the retrofits.

Often the only feedback available to homeowners who have undertaken retrofits is to compare utility bills from before and after the retrofit. While energy researchers can weather-normalize the pre- and post-retrofit energy consumption, homeowners will typically compare only their costs, receiving potentially misleading information.

In work carried out by the Center for Environmental Studies, Princeton University, we collaborated on a project to provide a sample of households in New Jersey with a home energy report which showed their monthly household energy consumption, weather-normalized, for a two-year period. The households were then surveyed to determine whether they found this information useful, whether it helped them determine if their previous retrofits were successful, and whether the information would encourage them to take further steps in conserving energy. The results of this feedback study showed that while most households appreciated having the information, and found it quite interesting, many were unable to grasp the concept of weather normalization. Several of the households, however, thought that the information would help them keep track of how much energy they were using.⁶ In 1988 we started a similar study to focus on providing information to tenants in multifamily buildings.

We completed the evaluation of two innovative office buildings designed to showcase new energy technologies. The work was carried out in collaboration with Princeton University, and focused on the design process and how decisions affecting energy performance were made. As part of the study we evaluated the tenants' satisfaction with the buildings.⁷ An off-shoot of this work will be our involvement in FY '89 in evaluating a sample of new energy-efficient buildings in the Pacific Northwest.

AIR INFILTRATION AND VENTILATION

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. Our air infiltration and ventilation work is split into three areas, multizone modeling, ventilation and moisture analysis, and support for the International Energy Agency's ventilation annexes.

Multizone Modeling

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.⁸ To reduce the input data required by detailed infiltration models, simplified models have been developed. Most of these, including the one

developed at LBL, 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, the vast majority are not readily available to the end user.⁹ 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.¹⁰

The first validation of the simplified model for predicting multizone air flows was completed this year.¹¹ We plan to validate the model in the coming year through multigas tracer measurements both in the laboratory and in the field, as well as through an extensive collaborative international effort with the *Laboratoire d'Energie Solaire (LESO)* at the Ecole Polytechnique Federale de Lausanne in Switzerland.

The bulk of the multizone infiltration modeling work was done in cooperation with the Joint Research Centre of the European Communities in Ispra, Italy. Work included the 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, etc.

Ventilation and Moisture

The MultiTracer Measurement System (MTMS) is a multigas tracer system that allows the simultaneous determination of the air flows between all of the zones within a building, as well as to the outside. The system is built around a quadrupole mass spectrometer which allows fast measurement of the concentration of all the tracer gasses in all zones. Injection of the tracer gas is controlled to keep a nearly constant concentration of the tracer in the zone it is injected. This is done to optimize the measurements and is not required for the analysis, as is the case in a single-gas system. MTMS has been used to measure up to five zones within a building and has the capability to measure eight.

This year MTMS was used in a comparison between multi-zone measurement systems developed by LBL, Princeton University and Brookhaven National Lab.¹² Of the three systems, MTMS gave both the greatest information about air flows and had the most flexibility.

Figure 1 shows a three day segment of one of the trace gases (gas 3) in five zones of the apartment complex. Zone 1 is an upstairs apartment and has no connection to the other zones. Zone 4 is a district heat exchanger room and has a large exhaust fan. At time 75.6 the door between zone 3 and 4 is closed and we see the concentration of gas 3 increase in zone 3 and decrease in zone 4. To obtain the desired target concentration of 10 ppm (of

Figure 1. Tracer gas concentrations in a four-zone configuration. Controlled concentration is in the zone 3.

gas 3 in zone 3) the injection rate is reduced. A similar response is seen at 70.8 when the exhaust fan is turned off, and its opposite at 71.4 when the fan is turned back on.

MTMS was also used in Princeton to measure air flows in conjunction with measurements on radon levels in a residence which used either electric resistance or central forced air heating systems.¹³ The information MTMS provided about inside air flows and flows in combustion devices helped to determine radon entry behavior and flow paths. MTMS was also used in two residences in the Pacific Northwest as part of a study to compare blower-door and passive ventilation measurement techniques.

Our effective ventilation efforts have provided techniques for estimating how much passive ventilation measurement techniques will underestimate the average ventilation rate. For typical housing the underestimates are at the 20% level. Results of the air flow calculations for the data set shown in Figure 1 are given in Figure 2. Note the large drop in flows when the door is closed and when the exhaust fan is turned off. We can also see that the flow direction between zone 3 and 2 changes when the exhaust fan is turned off. Estimated errors for these flows are typically about 10% for flows to/from outside and 20% between zones.

In FY 88, we also initiated a field monitoring project in College Station, Texas to examine the performance of a ventilation strategy for hot, humid climates. The strategy being examined consists of using pressurization ventilation in conjunction with a heat-pump water heater in the cooling season, and exhaust ventilation with the same heat pump during the heating season. This strategy should provide cost-effective ventilation and moisture management, as well as hot water, during the summer, while providing the conventional benefits of exhaust ventilation with heat recovery in the winter. Long-term data acquisition sys-

Figure 2. Air flows calculated from data in Figure 1 showing influence of fan operation and door openings.

tems were installed in both houses this summer, and the ventilation systems installed in both houses in the fall. The systems will be monitored continuously for the next year, including flip-flop tests between the systems and conventional electric resistance heating.

International Energy Agency (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, twenty technical annexes have been formed. As the U.S. representative to Annex V, the Air Infiltration and Ventilation Centre, 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 88 the Air Infiltration and Ventilation Centre responded to over 100 inquiries from the U.S. and delivered over 600 copies of technical papers held in their library of some 2,200 ventilation-related papers.

AIR LEAKAGE

The process of air flowing through unintentional apertures is called air leakage. In buildings, air leakage occurs through apertures in the building envelope, in mechanical systems, and 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. For building envelopes, the technique used for measuring and characterizing their air tightness, the fan pressurization technique has evolved over the past ten years. The air tightness of residential-building mechanical systems (e.g., central furnace ducts) and the air tightness of inter-

nal partitions between zones (e.g., in multifamily buildings) have only recently begun to be examined.

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 alternative techniques for measuring building envelope airtightness, including AC Pressurization and Pulse Pressurization, and are presently developing techniques for measuring the air leakage in residential duct systems and multi-zone buildings. Finally, we are putting our experience to use by assisting the professional societies in the formation of consensus standards.

Air leakage research efforts in FY 88 focused on measurement technique development and analysis, specifically on the development of the Pulse Pressurization technique for measuring single-zone leakage, an analysis of the effects of wind on fan pressurization measurements, and on the development and analysis of multi-zone leakage measurement techniques.

The Pulse Pressurization technique determines the leakage characteristics of the envelope of an enclosure (e.g., building) from the decay of the building pressure from an elevated value down to its steady-state value.¹⁴ During FY88, the theoretical work needed to extract the leakage characteristics of the envelope from the pressure decay was performed, as was an experimental examination of the technique in a small test structure.^{15,16} The robustness of the technique was tested using the experimental data obtained, this analysis indicating that although loss mechanisms other than leakage can affect the decay of the oscillating components of the pressure, the technique provides repeatable measurements of envelope air leakage. These results imply that future implementations of the pressure-impulse mechanism will be designed so as not to excite the normal modes of the structure or its contents, which is accomplished by simply increasing the rise-time of the pressure impulse.

As fan pressurization involves the measurement of the fan flows required to maintain measured indoor-outdoor pressure differences, wind-induced pressure variations add uncertainty to the measurement. During FY88 we performed a theoretical analysis of the effects of wind on fan pressurization measurements, as well as an analysis of experimental data taken in at the University of Alberta to explore these effects. The results of these analyses indicate that wind-induced measurement uncertainties can be significantly attenuated using a four wall pressure averaging probe and time-block averaging of pressure and flow data. The analyses also demonstrated a wind-induced bias in leakage area measurements for both single-pressure and four-wall-average pressure techniques.

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 88, including the modification of Standard Test Method E-779, "Determining Air Leakage Rate by Fan Pressurization" and related standards. We are also involved 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. After a five year effort this standard was approved by ASHRAE.

Air leakage research efforts in FY 89 will focus on further development of the Pulse Pressurization technique, further testing of AC-pressurization and fan-pressurization techniques for measuring inter-zonal leakage, and analysis of existing data on residential duct leakage. The multi-zone techniques will be tested under controlled conditions in a multi-zone building. The duct leakage analysis will be based on data in our air-leakage database, data taken over the past several years by our staff, and on data taken as part of a field study performed by a monitoring contractor in Oregon.

The other focus of air leakage research in FY 89 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.¹⁷

WOOD BURNING

Approximately 14% of residential space heating in the U.S. is supplied by wood burning, which when added to industrial burning, adds up to more than 3% of our primary energy needs. More importantly, approximately one third of the primary energy needs of developing countries is provided by combustion of biomass. These factors, along with the fact that wood and other biomass combustion typically occurs at very low efficiencies with high emissions of noxious gasses, particulates and greenhouse gases, have been the impetus behind the wood-burning research in our group. Our work has included the development of techniques to measure the thermal efficiency of wood burning in the laboratory and in the field, as well as studies of emissions from wood burning.

Based upon a single-channel woodstove heat-output monitor we developed several years ago, a study of wood heat delivery to single family residences was conducted in the Pacific Northwest. In FY 88, in collaboration with Pacific Power and Light, we continued our comparison between measured wood stove heat outputs and reported wood use based upon occupant surveys and site visits.¹⁸ The principal finding of this study was that the apparent field efficiencies of wood burning averaged between 20% and 30%, far below the quoted laboratory efficiencies of 40% to 60% for the types of stoves monitored. Based upon these findings, and on the apparent changes in efficiency over the course of the two-year study, it seems clear that the conventional technique for estimating wood energy delivery is both imprecise and biased. This can be

explained either by concluding that field efficiencies are far below laboratory ratings and thus the laboratory procedure should be reexamined, or by concluding that occupant reported wood use, even in conjunction with site visits by trained technicians is both a biased and uncertain estimator of actual wood consumption.

The other accomplishment in wood-burning research in FY 88 was the completion of a study of the effects of wood load and wood surface area on emissions from wood burning.¹⁹ This study provided a simple theoretical explanation for trends in emissions found in experiments performed at the Royal Institute of Technology in Sweden. Based upon the oxygen-controlled nature of enclosed wood burning, it was shown that emissions of CO, CH₄, and soot scaled almost linearly with the amount of wood surface area above some critical value (dependent upon the rate of air supply). The results of this study have implications for wood-burning policy, stove design, and appropriate test methods. In FY 89, we hope to expand our capabilities to include the development of appropriate test methods for the efficiency and emissions from cookstoves in developing countries.

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