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FY 1986 Annual Report

INDOOR ENVIRONMENT PROGRAM

May 1987

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LBL-22153

APPLIED SCIENCE DIVISION ANNUAL REPORT

INDOOR ENVIRONMENT PROGRAM

FY 1986

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

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INDOOR ENVIRONMENT PROGRAM

INTRODUCTION

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

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

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

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

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

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

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

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

Indoor Radon*

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

Radon and its radioactive decay products are ubiquitous contaminants of indoor air, and exposures to radon progeny are estimated to be responsible for several thousand cases of lung cancer per year in the United States. Within the past several years, houses with indoor concentrations two to three orders of magnitude above the average concentration of ca. 60 Bq m^{-3} (1.5 pCi/L)† have been found. These homes (and others like them) have been the focus of increasing concern regarding the health risks associated with occupancy of such homes.

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

ACCOMPLISHMENTS DURING FY 1986

Soil as a Source of Indoor Radon

Soil is now recognized as a significant, if not predominant, source of radon in the indoor environment, particularly in those houses with elevated indoor concentrations. Several factors influence the flow of radon-bearing soil gas into buildings, including the intrinsic properties of the soil, the characteristics of the building substructure, and changes in environmental conditions both outside and inside the structure.

Current investigations of soil focus on the problem from two distinct, but complementary perspectives[1]. The first of these approaches is to assemble data at a geographical scale, appropriate for understanding the general characteristics of soils. In this way, values of important soil parameters are obtained which may be useful in developing a predictive method for geographical estimates of where high indoor radon concentrations are likely to occur. The second approach is to investigate the influence of soils at the level of a specific house. Since the details of radon production and transport depend upon local soil conditions, such investigations should assist in illuminating the basic physical processes involved and will, in turn, aid in the systematic development of mitigation techniques to prevent or reduce radon entry into dwellings.

Ranges and nominal values of the parameters influencing radon production and transport are presented in Table 1. Radium, the progenitor of radon gas in soils, is widely distributed in crustal materials. As indicated in the table, the typical radium content of surface soils varies by slightly more than an order of magnitude. The emanating fraction, the ratio of mobile radon to the total radon produced by the decay of the radium, varies by approximately an order of magnitude as well. This parameter is governed by the physical characteristics of the soil particles and by the moisture content of the soil. Observed soil gas concentrations vary by almost two orders of magnitude.

The radon may then migrate through the soil and into buildings by both diffusion and pressure-driven flow. Typical pressure differentials between the outside and inside of the building are in the region of 3 Pa. An important parameter in defining the flow rate through the soil is the air permeability,

Table 1. General soil characteristics.

Parameter	Range	Typical Value
Radium in surface soils	10 - 200 Bq kg^{-1}	40 Bq kg^{-1}
Emanating fraction	0.05 - 0.7	0.25
Porosity	0.35 - 0.65	0.5
Radon in soil gas	(0.7 - 22) $\times 10^4$ Bq m^{-3}	2.7×10^4 Bq m^{-3}
Diffusion coefficient	(0.7 - 7) $\times 10^{-6}$ m^2s^{-1}	2×10^{-6} m^2s^{-1}
Permeability	10^{-16} - 10^{-7} m^2	—
Differential pressure	0 - ca. 10 Pa	3 Pa

Source: See reference 1.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division and by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098; by the U.S. Environmental Protection Agency through Interagency Agreements DW89931876-01-0 and DW89930801-01-0 with DOE; and by the Bonneville Power Administration, Portland, Oregon through Interagency Agreement DE-A179-83BP12921.

†The SI units for airborne concentrations of radionuclides are Bq m^{-3}, where 37 Bq m^{-3}= 1 pCi/L.

which can, in principle, range over 9 orders of magnitude. More typical soils have permeabilities that appear to range over 4 to 5 orders of magnitude.

Information on surface soils is available from a number of sources, although data on air permeabilities have not been compiled. However, reports from the Soil Conservation Service (SCS) of the U.S. Department of Agriculture contain information on most soils on a county-by-county basis. Although no direct air permeability data are available, the data and descriptive materials from the SCS reports may be useful in estimating air permeabilities.

We have used these indicators to estimate permeability values for surface soils in Spokane County, WA, in order to compare with values from air permeability measurements conducted as part of a radon mitigation study conducted in that area. A general soil map of the area is shown in Figure 1, which indicates the spatial extent of various soil associations described by the SCS data. These associations generally consist of one or more major soil series and may include one or more minor soil series. Permeability ranges for the two soil associations shaded in the figure have been estimated, and the results shown in Table 2. Air permeabilities were measured at a number of houses in the Spokane vicinity. All the study homes were located in the Garrison-Marble-Springdale association. The average and range of the eleven measurements are shown in Table 2. Although there are a number of uncertainties and assumptions made in deriving estimates of air permeability from the SCS information, the agreement between these estimates and the measured values is reasonably good. In addition, air permeability measurements have been made in 30 different locations at one house site in the Spokane area. These results show little local spatial variation, approximately a factor of 5, in soil permeability at this one site.

Both tracer gas experiments and investigations of remedial radon measures indicate that air permeability plays a substantial role in the convective flow of radon into structures. At present there are few soil air permeability data available that might provide a correlation with indoor radon concentrations or with permeability estimates based on geographical data. Additional work with the SCS data will improve the confidence in the permeability estimates one can obtain, as will additional comparisons between measured and inferred air permeabilities. In addition, further site-specific studies will help in assessing the nature and influence of local building and soil characteristics.

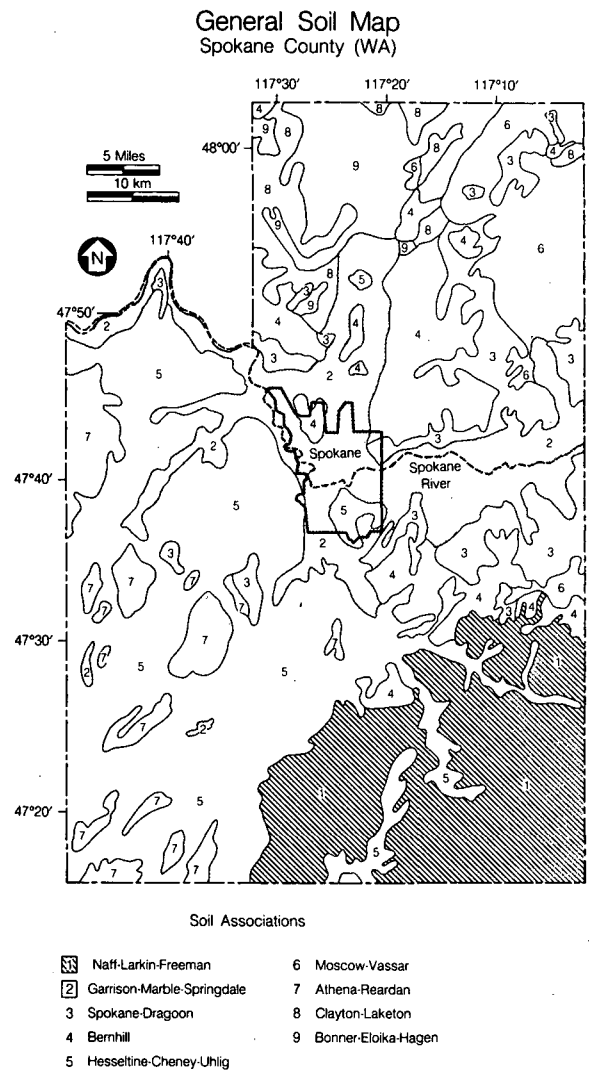

Figure 1. General soil map from the Soil Conservation Service for Spokane County, WA. The two soil associations discussed in the text are shaded. The location of the city of Spokane is shown by the heavy border. (XBL 867-10904)

Perspective on Radon Risks and Control Strategies

Within the past two or three years, the perspective on the seriousness of the indoor radon problem has been altered. In part, this is due to a broader understanding of the distribution of radon concentrations in homes (principally single-family housing) in the U.S., and in part, due to the discovery of houses or groups of houses with concentrations sufficiently elevated that the health risks, even from less-than-lifetime exposures, are excessive. Some of our

Table 2. Permeabilities of selected soils in Spokane County, WA.

Soil Association	Permeability (m^2) Derived from SCS Information	Measured by LBL (Range)
Naff-Larkin-Freeman	10^{-14} to 10^{-12}	—
Garrison-Marble-Springdale	10^{-12} to 10^{-10}	$\sim 2 \times 10^{-11}$
		$(0.3 - 60) \times 10^{-11}$

Source: Reference 1.

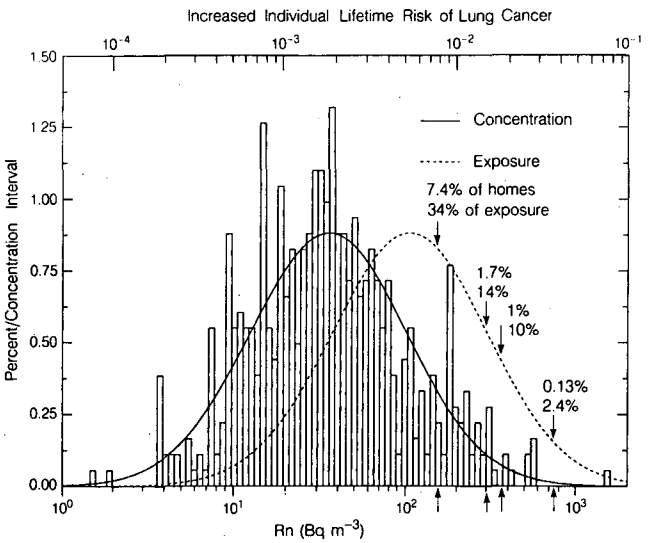

Figure 2. Histogram of the aggregate radon distribution data from samples obtained in 552 houses. The solid curve is the lognormal function with the geometric mean and geometric standard deviation calculated directly from the radon concentration data. The top axis, lifetime risk for individuals, also refers to this solid curve. The dashed curve is the distribution of total population exposures to radon progeny, as a function of indoor radon concentration. The labeled arrows refer to the fraction of homes and the fraction of the total population exposure associated with radon concentrations equal to or greater than the indicated values. (XBL 872-10801)

research effort has been devoted to developing a perspective on these risks and how to effectively attack the problem of locating and remediating houses with elevated radon concentrations[2].

As described in a previous annual report[3], a national distribution of indoor radon concentrations has not been measured, although an aggregate distribution has been assembled from a number of more localized surveys that provides a 'surrogate' national picture[4]. Based on these data, the distribution appears to be lognormal, with a geometric mean of 34 Bq m^{-3}, an arithmetic mean of 55 Bq m^{-3} and a geometric standard deviation of about 2.8. The concentration distribution is illustrated by the histogram and solid curve in Figure 2. These parameters permit one to estimate the number of houses in the U.S. with indoor radon concentrations that exceed chosen values. For example, approximately seven percent of the distribution lies at or above 150 Bq m^{-3}, which translates into approximately 4 to 5 million single-family homes. Similarly, one can estimate with greater uncertainty that there are on the order of 100,000 homes with concentrations above 750 Bq m^{-3}.

The health risks associated with radon exposures are due to the deposition of radon decay products in the lungs and their subsequent alpha decay. Most of the health risk data are based on exposures of underground miners, particularly in the uranium mining industry. While the dose-response estimates are uncertain, the data provide generally consistent health risk estimates (within factors of 2 or 3) which, when applied to the average radon concentration of 55 Bq m^{-3}, yield approximately a 0.3 percent increased lifetime risk of lung cancer. The risks increase in proportion to exposure; thus for a lifetime exposure to radon at a concentration of 750 Bq m^{-3}, the increased lifetime risk of lung cancer is about 4%.

Such risks can be viewed against other risk levels encountered. Risks involved with personal choices, such as driving a car or smoking exceed 10^{-2} to 10^{-1}. These choices are, for the most part, voluntary and may be associated with a perceived benefit. Occupational risks tend to lie in the range of 10^{-3} to 10^{-2}; these are risks over which the worker may have limited control or choice. Again, there may be presumed benefits associated with the choices. The last general category of risks are those associated with environmental exposures. These are often termed involuntary and involve no real choice on the part of the persons exposed. These risk ranges are rarely as high as 10^{-3} and are often typically in the range of 10^{-6} to 10^{-4}. These latter risk levels are the basis of some regulatory actions involving certain categories of exposure to environmental pollutants.

In this context, exposures to radon progeny in the indoor environment, even at average concentrations, provide high risks compared to those associated with other environmental insults, and at concentrations above 750 Bq m^{-3}, risks that are substan-

tial even with respect to risks associated with personal choices. The distribution of individual risks, as indicated by the top axis in Figure 2, can be associated directly with the solid curve in this figure. The dashed curve is the distribution of total population exposure (or, presuming that the risk and dose are linearly related, the risk) as a function of indoor radon concentration. As can be seen by the illustrative examples, while approximately 7% of the single family housing in the U.S. is expected to have indoor radon concentrations $\geqslant$ 150 Bq m^{-3}, almost 34% of the total population risk is associated with these indoor concentrations. Similarly, about 1% of the housing is expected to have indoor concentrations $\geqslant$ 370 Bq m^{-3}, which comprises almost 10% of the total population risk.

A number of organizations, both in the U.S. and elsewhere, have proposed guidelines for radon or radon progeny concentrations in residences. These are summarized in Table 3. The genesis of the earlier guidelines was the discovery of high indoor radon concentrations related to industrial contamination of soils, or in some cases, building materials used in the home. There were three situations in which this problem arose, 1) an association with uranium mining and milling, 2) the use of lands reclaimed from phosphate mining, and 3) radium process residues from various industrial activities.

More recently, several U.S. and international entities have developed guidelines for radon or radon progeny in indoor air for ordinary (*i.e.* unrelated to industrial contamination) homes. The most

Table 3. Recommended guidelines for radon concentrations in buildings[a].

Organization or Country	Existing Buildings: Ordinary (Bq m^{-3})	Existing Buildings: Contaminated (Bq m^{-3})	Future Buildings (Bq m^{-3})
Int'l Commission on Radiation Protection	400 [b]		200
Nat'l Council on Radiation Protection and Measurements	370		
World Health Organization	800 [c]		200
ASHRAE			74
U.S. Surgeon General		370 [d] 74 [e]	
U.S. EPA		148	
U.S. EPA	148		148 (?) [f]
Bonneville Power Admin.	185		
Canada	740 [g]	148	
Sweden	800		200

Source: Adapted from reference 2.

[a] With the exception of the BPA guidelines, which were originally stated in terms of radon concentrations, the guidelines cited here were originally in terms of radon progeny concentrations, and have been converted to equivalent radon concentrations using an equilibrium factor of 0.5.

[b] A higher level is recommended if remedial measures are difficult.

[c] A level of 200 Bq m^{-3} is recommended if the remedial measures are simple.

[d] Remedial action "indicated"

[e] Remedial action "suggested"

[f] Although not explicitly stated, the EPA guidelines appear to apply to new construction as well.

[g] A suggested guideline; specific guidelines for existing houses have not yet been formally established.

recent guidelines, issued by the EPA in August 1986, uses 148 Bq m^{-3} as a basis for action. At the same time, the EPA has adopted a staged approach for the urgency of remedial action. For concentrations between 148 and 740 Bq m^{-3}, action to reduce concentrations below 148 Bq m^{-3} within a few years is recommended; for concentrations in the range of 740 to 7400 Bq m^{-3}, action within a few months is recommended, while for concentrations greater than 7400 Bq m^{-3}, immediate attention, within a few weeks time, is recommended.

While the case is compelling that long term exposure to high concentrations of radon progeny presents significant health risks, there are a number of uncertainties that affect the picture for lower exposures. Further examination of the health risks is warranted in an attempt to reduce the uncertainties in the present data and in their application to a different (*e.g.* indoor as opposed to a mining) environment. Additional research on mitigation techniques for use in existing and future housing will provide a better economic and technical basis for their implementation, especially in houses with intermediate concentrations. It is important to note in this connection that addressing these houses will have a larger effect on the total population risk than those fewer individual situations with very high concentrations. The urgency for action in the latter case is clear, the economic and practical aspects in the former are not.

New housing also presents a different and still uncertain picture. The development and use of low cost, durable methods to reduce radon entry in new construction, for example, might effectively eliminate radon-related risks in most future housing. However, it is not clear if a set of standard techniques can be used as a matter of course in all geographical areas, or if specialized techniques will be required in specific areas , or even if certain geographical areas can be eliminated from concern regarding elevated radon entry rates into homes. These are topics requiring additional research effort, along with the need to find and fix the existing houses with high concentrations.

Evaluation of Remedial Measures

As part of a series of surveys of the effects of weatherization on indoor air quality in the Pacific Northwest, radon concentrations were measured in 46 residential buildings in the Spokane River Valley in eastern Washington and northern Idaho. Approximately 57% of these homes exceeded the 185 Bq m^{-3} guideline established by the Bonneville Power Administration (BPA) for remedial action. The average in these 46 residences was 492 Bq m^{-3}. Fifteen of these homes were subsequently selected for research on remedial techniques, with the objectives of evaluating several possible mitigation measures and of reducing the long-term average radon concentration during the heating season to below 185 Bq m^{-3} in each house[5].

The 15 homes represented a variety of ages and substructure combinations. All homes but one had basements; many had combinations of basements and either a crawl space or slab-on-grade. One home was built entirely with slab-on-grade construction. Only two homes used combustion fuel heating; the remainder used electric heating of various types, in some cases supplemented by wood stoves.

A number of diagnostic procedures were utilized to assist in identifying the likely radon entry locations. Because pressure-driven flow of radon-bearing soil gas is generally thought to be the predominant source of radon in houses with elevated indoor concentrations, several procedures were directed toward this source. Scintillation cells (Lucas cell) were used to measure radon-in-air concentrations from a variety of sources, including wall cavities, floor drains and any sealed spaces in contact with the soil. Soil gas samples, obtained from soil depths of up to 1.5 m and between ~0.5 and 5 m from the house, were also analyzed using scintillation cell grab samples. Air permeability measurements were also made with these soil probes. To evaluate the contribution of non-soil sources, radon concentrations were measured in water samples and radon emanation measurements from building materials were made.

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

Several mitigation techniques were evaluated in the course of the study, in some cases, more than one technique was tried in a home in order to provide a comparison. Techniques evaluated included:

- Sealing cracks and holes, in order to reduce the entry rate of soil gas;
- House ventilation with heat recovery, using an air-to-air heat exchanger (AAHX);
- Sub-slab ventilation, used in the depressurization mode to help reverse the natural

pressure differential across the building substructure and to ventilate the soil gas;

- Sub-slab ventilation, used in the pressurization mode to help displace soil gas near the substructure with low-radon-concentration ambient air;
- Basement overpressurization, used to reverse the natural pressure gradient across the building shell; and
- Crawlspace sealing and ventilation, to reduce infiltration flow between the crawlspace and the living space, and to reduce crawlspace radon concentrations.

Results of the diagnostic measurements indicated that soil gas entry into these houses was the most significant source of radon, although the entry locations were generally highly localized, as shown by the variations in radon concentrations observed in the air grab samples taken in various locations in the basement. Only four of the houses obtained domestic water from a private well, and the highest radon concentration in these water samples was $\sim 10^5$ Bq m^{-3}, which would contribute less than 10 Bq m^{-3} to the airborne radon concentrations. Water from municipal supplies had lower radon concentrations, as expected, ranging from (13.5 to 25.5) $\times$ 10^3 Bq m^{-3}, effectively eliminating municipal water as an important source of indoor airborne radon.

Soil gas radon concentrations ranged from (10 to 24.4) $\times$ 10^3 Bq m^{-3}; these observed concentrations are highly dependent upon depth and location with respect to the house. At the same time, soil air permeabilities ranged from (0.3 to 60) $\times$ 10^{-11} m^2. These soil gas radon concentrations, combined with the permeability of the soil, appear to provide the conditions that account for the radon entry rates in the test houses inferred from the observed indoor concentrations. While the typical infiltration flow through the substructure of a building is less than 1% of the total flow, two houses in this study, ESP120 and ESP111, appear to have 20 and 5% of the infiltrating air entering through the substructure, respectively. In the case of ESP120, this appears to be consistent with the fact that the substructure walls are stone-and-mortar.

Results of selected mitigation efforts are summarized in Figures 3, 4, and 5. A brief synopsis of the experiments is presented here; a detailed discussion of each technique can be found in the report.[5] In some cases, more than one mitigation system was tried in a given house. Heat-recovery ventilation (an air-to-air heat exchanger, or AAHX) was employed in three houses; in two of these systems ventilation air was supplied and exhausted from the basement

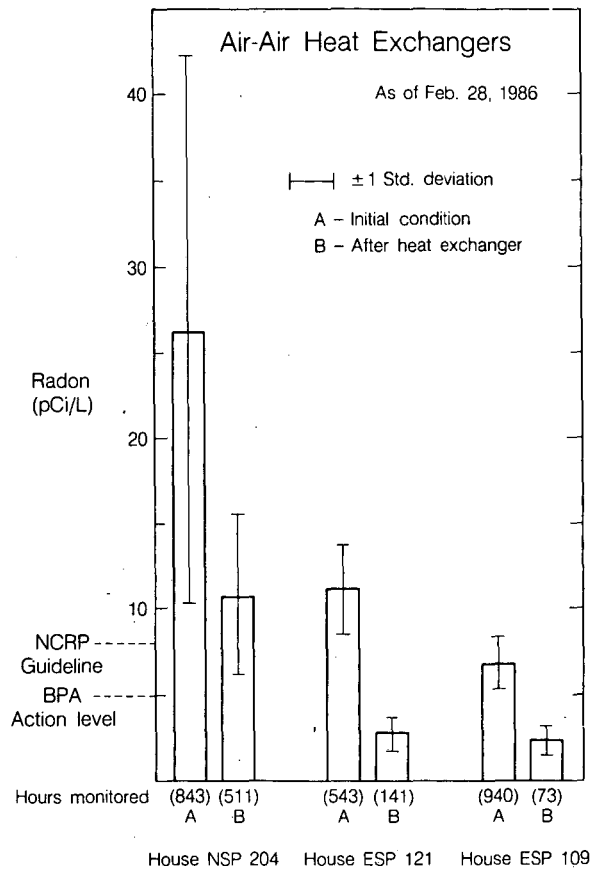

Figure 3. Results from the evaluation of air-to-air heat exchangers in 3 homes. (XBL 863-9157)

respectively. In house NSP204, an existing AAHX system was modified to increase the efficiency of air circulation, and the existing supply and exhaust locations modified. As illustrated in Figure 3, reductions of about 60, 67 and 75% were achieved. In general, the AAHX units were sized to add about 1 ach of ventilation. Since the units, when properly balanced, have a neutral effect on the pressure distribution across the building shell, the radon source strength should not be affected and the radon concentration should therefore be related inversely to the ventilation rate. Use of an AAHX to control radon appears to be best suited for those cases where initial indoor concentrations are not excessive ($<$ 750 to 1500 Bq m^{-3}) and/or where the initial building ventilation rate is low.

Subsurface ventilation (SSV) systems were implemented in five homes, in a variety of configurations. In general, the systems consisted of 7.5 cm diameter PVC pipes inserted in one or more (up to four) locations through the basement floor slab, or in one case, ESP119, along the exterior of the foun-

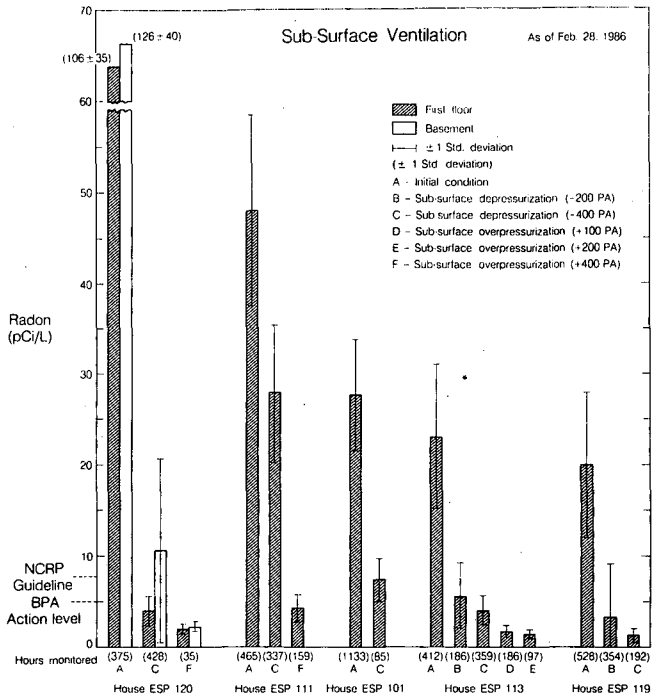

Figure 4. Results of the test of subsurface ventilation systems. Both underpressurization and overpressurization have been evaluated, usually at 2 or 3 operating pressures. (XBL 863-9153)

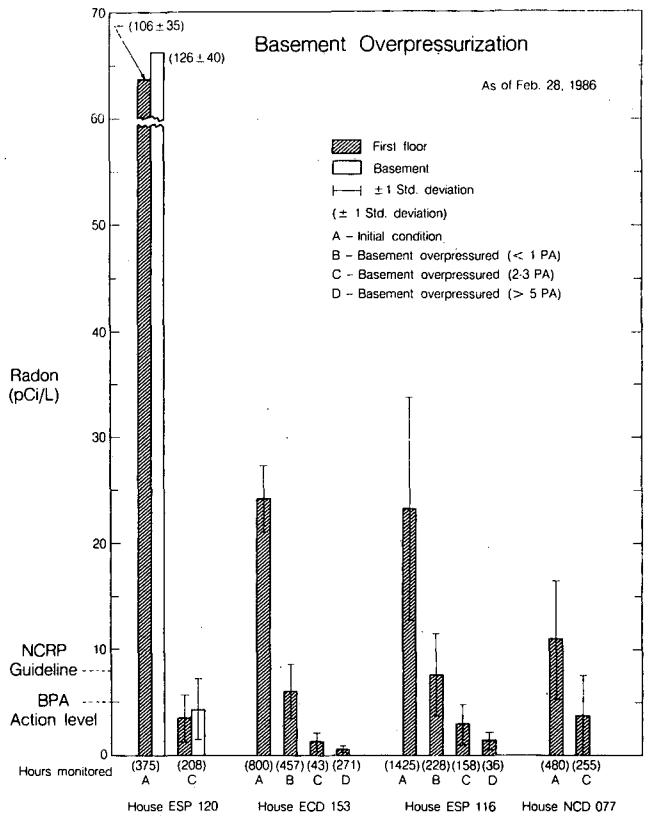

Figure 5. Results from the use of basement overpressurization in four homes. (XBL 866-9199)

dation wall, to a point below the wall footer. The pipes end approximately 30 cm below the floor in a 60 cm diameter dry sump 60 cm deep, backfilled with clean gravel. For the interior systems, the pipes are routed either singly or in a manifold through the top of the basement to the outside of the house. Here, the pipes are connected to a centrifugal blower, sized to develop more than 125 Pa at more than 25 L/s flow.

The results from the use of these SSV systems are illustrated in Figure 4. As can be seen, the effects of SSV operated in a depressurization mode are dramatic for four of the five houses, with almost all configurations leading to concentrations below the 185 Bq m^{-3} guideline adopted by the Bonneville Power Administration, the project sponsor. In three of the five houses, the SSV system was used to pressurize the soil below the slab. In all three cases, the first floor radon concentrations dropped further. In house ESP111, subsurface depressurization resulted in a factor of two reduction in first floor radon concentration, while subsurface depressurization produced a concentration reduction of more than a factor of 10 over baseline conditions. It appears that in highly permeable soils, characteristic of this region, pressurization of the soil below the basement slab dilutes the soil-gas radon concentrations. Thus, even though the pressure differential across the building substructure is increased somewhat by the sub-slab pressurization, the soil gas that enters has a reduced radon concentration. This system requires further study, particularly in situations where the soil permeabilities are lower than in the Spokane River Valley.

Results of basement overpressurization are shown in Figure 5 for four homes. The basements in each home were first sealed, including leakage paths between the basement and first floor. The basements were pressurized with a 100 - 200 L/s fan, using heated air from the first floor. This technique was tried in four homes, resulting in each case with first-floor radon concentrations reduced to below 185 Bq m^{-3}. In two houses, several different overpressurization conditions were investigated, as indicated in the Figure. One disadvantage of this method, encountered in a few situations, is the backdrafting of first floor combustion appliances, such as wood stoves.

Basement pressurization and subslab ventilation were compared in one house, ESP120, and the

results are shown in Table 4. This particular house had stone basement walls and a partially finished basement. The substructure leakage area was large; an estimated 20 percent of the total air infiltration into the house was soil gas, resulting in the relatively high indoor radon concentrations observed. This large substructure leakage may help explain why basement pressurization was somewhat more successful than subsurface ventilation.

Results from the other mitigation techniques, sealing cracks and holes and crawl space sealing and ventilation, are summarized briefly here. Sealing techniques, by themselves, yielded only slight reductions in indoor radon concentrations, due in part, to the difficulty in gaining access to all the wall and floor surfaces in finished or partly finished basements. Sealing the membrane between the crawlspace and the first floor produced modest reductions in first floor radon concentrations. Ventilation of the crawlspace areas also helped reduce radon levels. With the addition of mechanical ventilation to the crawlspace in one house, further radon concentration reductions were observed.

Additional investigations of these and other mitigation measures are needed before one or more of these techniques are generally applicable. Among the important variables to be studied are differences among building substructure design and construction, and soil characteristics, principally air permeability.

Intensive Seven-home Study

During FY1986, a detailed study of radon entry and removal was begun in seven homes in the state of New Jersey. The objectives of this work are to 1) extend our understanding of the fundamentals of soil gas flow and radon entry into buildings and to improve our basic knowledge of factors that influence the entry rate, 2) develop a better basic understanding of why certain mitigation techniques work (or fail) and of the operational ranges of key parameters that affect the utility of these techniques, and 3) provide a diagnostic analysis procedure that can be used in specifying appropriate and effective remedial measures.

Table 4. Comparison of subslab ventilation and basement overpressurization in one house.

		Mitigation Technique	
	Original Concentration ($Bq\ m^{-3}$)	Subsurface Ventilation ($Bq\ m^{-3}$)	Basement Overpressurization $Bq\ m^{-3}$)
Basement	6920	100	27
First floor	5600	85	28

The basic research plan for this project has four components: 1) house and site characterization measurements, 2) baseline and continuous monitoring of radon and parameters thought to have an influence on soil gas flows into homes, 3) diagnostic procedure development, and 4) installation and operation of selected mitigation techniques.

Central to this study are a set of continuous and periodic measurements of radon and other factors thought to influence flow of radon-bearing soil gas into a house. These include:

1) Parameters to be monitored continuously:
   - indoor radon concentrations (various locations within the house), and possibly radon progeny concentrations (smaller subset of houses),
   - outdoor temperature and indoor temperature and relative humidity,
   - meteorological parameters at each site, including windspeed and direction,
   - pressure differentials across the building shell (various locations),
   - soil moisture and temperature, and
   - barometric pressure and precipitation at one central site.

2) Parameters to be monitored periodically:
   - soil air permeability,
   - ventilation rate,
   - indoor water vapor,
   - soil gas radon concentrations at selected locations, and
   - occupant effects and activities, including operation of a fireplace or wood stove, forced air furnace systems, exhaust fans, *etc.*

3) Parameters to be measured once or occasionally:
   - effective leakage area,
   - radon progeny concentrations,
   - soil characteristics (in the lab), including permeability, grain size distribution, soil radium concentration, and emanation ratio,
   - frost depth and snow cover,
   - pressure-field mapping to determine coupling between building shell and surrounding soil,
   - tracer gas (SF_6) injection in soil and resulting concentrations within the building shell (if utilized), and

- additional parameters specific to the mitigation technique under investigation, such as the flow rate of air through a block wall or subslab ventilation system, or tracer gas analysis of flow pathways.

By the end of the fiscal year, the seven homes had been chosen for the study. This process began with a list of 130 homes, from which 33 were selected. Detailed selection criteria were then developed, and the final study homes were chosen based on detailed site and house evaluations. At the end of FY86, most of the continuous monitoring systems described above had been deployed in the seven homes and data collection had begun.

PLANNED ACTIVITIES FOR FY 1987

A significant effort in FY87 will be directed toward acquisition and analysis of the data from the field project in New Jersey. The field portion of this project will be completed at the end of the fiscal year. Data on the soil properties will be used as input to physical and statistical models to assist in elucidating important factors in radon migration from the soil into houses. Detailed data on and analysis of several mitigation systems will provide information on their performance and operating characteristics. Analysis of radon progeny data from field and laboratory experiments will continue, and measurement systems for unattached progeny will be improved.

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Volatile Organic Contaminants in Indoor Air

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Reduction of heating and cooling costs in buildings through a reduction in ventilation is increasingly being used as a component of energy conservation strategies and has become an integral part of current building practices. Decreased ventilation in combination with increased uses of synthetic building materials and consumer products in new and renovated buildings has been implicated as the cause of numerous complaints about "sick buiding syndrome" and of work losses. The causes are not currently well understood nor have effective mitigation strategies been developed. There is a need to develop methods to identify and quantify the airborne contaminants that cause these health effects, to identify the sources of the contaminants, and to develop a fundmental understanding of the relationships among building materials, construction practices, and ventilation so that appropriate mitigation strategies can be developed.

The goal of this research is to understand relationships between airborne organic pollutant compounds in large buildings and energy conservation issues. Specific objectives are: (1) to develop appropriate methodology for identifying and quantifying organic contaminants in non-industrial indoor air; (2) to study the relationships among the emissions of organic compounds, building material usage, and building-related factors such as ventilation; (3) to develop a model based upon emission rates and building characteristics to predict organic contaminant concentrations in buildings; and (4) to verify this model with field measurements. This research has targeted one class of organic compounds known

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to include irritants and carcinogens and shown by previous work in the laboratory to be emitted from widely-used building materials, i.e., the volatile organic compounds (VOC).

In FY 1986, the major research objectives were:

1. to install the remaining mechanical components and to construct the electronic controller assembly for temperature and humidity control in the 20-m^3 environmental chamber;
2. to validate the multisorbent sampling technique for quantifying ppb concentrations of a broad range of VOC in ambient and indoor air;
3. to conduct field studies to quantify concentrations of VOC as a function of ventilation rate in non-industrial buildings using the multisorbent sampler;
4. to quantify the effects of a concentration gradient on emission rates of VOC from an assemblage of carpet adhesive and carpet using small-volume (4 L) chambers; and
5. to measure personal exposures to methylene chloride from the use of paint removers in controlled experiments conducted in residential environments.

ACCOMPLISHMENTS DURING FY 1986

Construction of 20-m^3 Environmental Chamber

The design and construction of a 20-m^3 environmental chamber suitable for a wide variety of indoor air quality studies was described in the 1985 Annual Report. Systems to clean, heat and humidify the air supplied to the chamber were installed in 1985.

In 1986, a chiller-loop assembly to control the dew-point temperature of the supply air was designed, constructed and installed. An electronic-controller assembly for regulation of the temperature and humidity of the supply air was also designed and assembled.

Measurement of VOC In Indoor Air

The limited data on indoor/outdoor concentration ratios of VOC in residences, offices and schools show that, for many compounds, these ratios are greater, and in some cases much greater, than one. Considerably more data are needed on indoor concentrations of VOC for anything more than rudimentary assessments of population exposures and chronic health risks. Acute health problems, in some buildings, principally mucous membrane irritation, have also been postulated to result from elevated concentrations of VOC. The present paucity of data can be largely attributed to the difficulty and expense of analysis for a wide range of VOC.

In 1986, we completed the development of an analytical method to quantify ppb concentrations of a broad range of VOC in ambient and indoor air.[1] The method employs a multisorbent sampler in combination with a thermal desorption system for sample concentrating and inleting, a gas chromatograph equipped with an on-column cryogenic focusing attachment, and an electron-impact mass spectrometer. The sampler contains a series of Tenax-TA, Ambersorb XE-340® and, in some cases, activated charcoal. Sampler breakthrough volumes for representative low-boiling compounds are $\geqslant$ 10 L. With a 10-L sample volume, limits of quantitation are $<$ 1 ppb. Overall precision is normally better than 5% at analyte concentrations ranging between one and several tens of ppb. Accuracy for representative low-boiling compounds is typically $\pm$ 5%. With this level of precision and accuracy, it is possible to detect small variations in concentrations of VOC with location and ventilation rate in buildings.

The multisorbent sampling method was used to quantify VOC in a school classroom and in a large office building. Both buildings were relatively new, having first been occupied approximately five months prior to our measurements. In addition, a number of occupants in both buildings had experienced acute health problems, presumably related to poor air quality. Samples were collected indoors and outdoors at the two buildings. Since ventilation is the main removal mechanism for airborne contaminants and ventilation system deficiencies are often implicated in cases of unacceptable air quality, indoor samples were collected at conditions near steady-state at several different ventilation rates. In the classroom, samples were collected at ventilation rates of 1.55 h^{-1} and 0.26 h^{-1}. In the office building, samples were collected with the ventilation system set at 100% outside air (4.52 h^{-1}) and with the ventilation system set at 16% outside air (0.75 h^{-1}).

The identified compounds at both locations were ubiquitous components of urban outdoor and indoor air. Nineteen of the compounds were quantified using multipoint calibration curves. Table 1 compares the indoor concentrations of these compounds to the outdoor concentrations. The measured indoor concentrations were within the ranges reported for 15 Italian homes[2] and for 344 U.S. homes.[3] The trichloroethylene concentration in the office building was twice the median level reported for the U.S.

Table 1. Comparison of indoor VOC concentrations in a classroom and in an office building to outdoor VOC concentrations ($\mu g\ m^{-3}$).

Compound	CLASSROOM Concentration, $\mu g\ m^{-3}$ Outdoor	Indoor $1.55h^{-1}$	Indoor $0.26h^{-1}$	I/O[a]	OFFICE BUILDING Concentration, $\mu g\ m^{-3}$ Outdoor $4.52h^{-1}$	Indoor $0.75h^{-1}$	Indoor	I/O
Isopropyl alcohol	[b]	23.3	73.0	>73	[b]	[b]	[b]	
Acetone	6.5	23.8	36.3	6	5.2	16.9	30.5	6
Methylethylketone	[b]	[b]	[b]		5.0	20.1	63.5	13
1,1,1-Trichloroethane	[b]	[b]	[b]		1.0	5.5	12.6	13
Trichloroethylene	[b]	[b]	[b]		[b]	[b]	7.2	>7
m,p-Dichlorobenzene	[b]	3.1	9.2	>9	[b]	[b]	[b]	
n-Pentane	4.9	5.6	11.7	2	0.9	3.5	1.8	4
n-Hexane	3.1	3.4	4.8	2	[b]	2.1	[b]	>2
3-Methylhexane	2.0	2.1	3.9	2	0.4	1.4	[b]	4
n-Heptane	2.0	1.6	8.0	4	[b]	[b]	[b]	
n-Decane	[b]	[b]	[b]		2.4	2.4	3.6	2
n-Undecane	[b]	[b]	[b]		[b]	5.0	5.5	>6
Methylcyclohexane	1.4	1.4	[b]	1	0.6	[b]	[b]	<1
Benzene	5.8	6.0	12.0	2	6.7	6.9	2.8	1
Toluene	13.2	15.0	27.0	2	4.3	11.4	12.0	3
Ethylbenzene	2.7	3.0	4.2	2	0.9	4.3	10.1	11
m,p-Xylene	10.0	11.2	20.6	2	3.2	17.1	43.0	13
o-Xylene	3.7	4.1	6.6	2	2.4	6.0	15.2	6
α-Pinene	[b]	12.1	33.9	>34	[b]	[b]	[b]	
TOTAL	55	116	251	5	33	103	208	6

[a]Ratio of highest indoor concentration to outdoor concentration.
[b]Not detected or less than ~0.4 $\mu g\ m^{-3}$.

homes while benzene in the classroom was close to the median for the U.S. homes and benzene in the office building was only one-fourth the median value. The indoor/outdoor concentration ratios for both locations were generally greater than one, indicating contributions from indoor sources.

Fig. 1 shows the effect of ventilation on the indoor concentrations of VOC for the office building. Concentrations of VOC in outdoor air are also shown for comparison. When the ventilation rate was increased six-fold, from 0.75 h^{-1} to 4.52 h^{-1}, concentrations of VOC's were generally decreased by only one-half to one-third. This suggests that source strengths (emission rates) were increased as a result of the lowered concentrations from increased ventilation or that ventilation efficiency was low.

A simple mass-balance model was used with these data to calculate apparent source strengths:

$$dC = PaC_o dt + \frac{S}{V} dt - (a + k)Cdt, \qquad (1)$$

where:

C = indoor pollutant concentration (ppm or $\mu g\ m^{-3}$);

C_o = outdoor pollutant concentration (ppm or mL m^{-3});

P = fraction of the outdoor pollutant level that penetrates the enclosed space (unitless);

a = ventilation rate in air changes per hour (h^{-1});

S = indoor pollutant source strength ($\mu g\ h^{-1}$);
V = volume (m^3);
k = net rate of removal processes other than ventilation (h^{-1});
t = time (h).

The apparent source strengths per unit volume (S/V) at the two ventilation rates are compared in Fig. 1. For 10 of the 11 VOC's, these source strengths were higher at the higher ventilation rate when VOC concentrations were lower. This suggests that emission rates of VOC may be dependent upon the concentration gradient between the source and the indoor air as a driving force. This effect has also been observed in small chamber measurements of emission rates of VOC from an assemblage of carpet adhesive and carpet. The consequence of this mass-transfer effect is that increasing the ventilation rate may not reduce indoor VOC concentrations proportionately.

The concentrations of VOC in the two buildings when they were first occupied are unknown. However, if a simple exponential decay with a half-life of one month is assumed, the initial concentrations of total VOC may have approached 6000 $\mu g\ m^{-3}$, which is within the range reported by Molhave *et al.*[4] to cause irritant effects in sensitive but otherwise healthy human subjects.

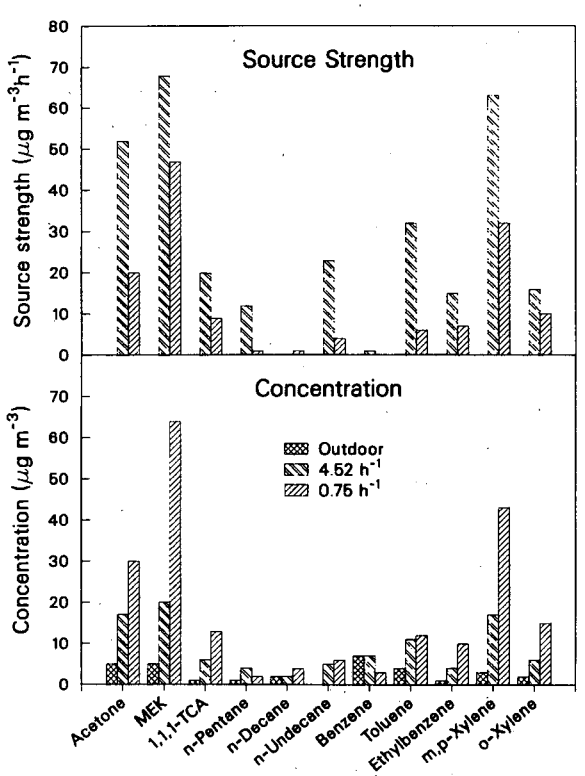

Figure 1. Concentrations of VOC in outdoor air and in indoor air at two ventilation rates at an office building. Apparent source strengths per unit volume were calculated for the two ventilation rate conditions using a mass-balance model.

Emissions of VOC from Building Materials.

Elevated concentrations of VOC in new and newly remodeled office buildings are postulated to be a major contributing factor to the increasing incidence of building related illnesses. The materials used to finish interiors of buildings are the dominant sources of VOC. Therefore, a basic understanding of emission rates from these materials is essential to develop and evaluate strategies to reduce indoor concentrations of VOC.

Previously, emission rates of VOC from 15 adhesives used in buildings were measured in small-volume (4 L) chambers at standardized conditions for material age and chamber temperature, ventilation rate and loading.[5] A simple mass-balance model was then used to estimate indoor VOC concentrations from these sources for a hypothetical office space. The results demonstrated that some water-based carpet adhesives can be a major contributor to VOC in indoor air.

In 1986, experiments were conducted to quantify environmental effects on emission rates of VOC from materials. A model system consisting of a water-based adhesive plus overlying carpet was used for these experiments. Emission rates of VOC from this assemblage were measured at steady-state conditions over a wide range of ventilation rates. Preliminary results indicate that emission rates depend on the difference between chamber and source concentrations.

Exposures to VOC from Use of Consumer Products

Consumer product usage can be a major source of VOC in indoor air. There is particular concern about consumer exposures to methylene chloride (CH_2Cl_2) from products such as paint removers and aerosol finishes since CH_2Cl_2 is metabolized to CO leading to elevated levels of carboxyhemoglobin and possible anoxic stress. In addition, a recently completed bioassay found CH_2Cl_2 to be an animal carcinogen.[6]

To provide information on exposures sufficient to conduct a health risk assessment, CH_2Cl_2 source strengths and personal exposures were characterized in the 20-m^3 environmental chamber at two ventilation rates for typical applications of paint removers

and aerosol finishes.[7] The source strength and environmental data were used in a single-equation mass-balance model, and the resulting theoretical concentration profiles were integrated over the work periods to produce estimates of exposures. The calculated exposures were in good agreement with measured exposures.

In 1986, the investigation was expanded to include the field measurement of personal exposures to CH_2Cl_2 from paint removers in residential environments for a variety of use scenarios. Experiments were conducted outdoors with varying wind speeds and directions and in enclosed spaces with different volumes such as garages, basement workshops, and living quarters. In these spaces, ventilation patterns and rates were varied by opening doors and windows and through the use of fans. Ventilation rates were measured by tracer gas decay. Paint remover was applied to and finishes were stripped from uniformly-prepared panels and pieces of furniture. As was done previously, personal exposures of workers to CH_2Cl_2 were continuously measured by infrared spectroscopic analysis of a pumped breathing-zone sample, and source strengths of CH_2Cl_2 were estimated from product composition and usage rates.

PLANNED ACTIVITIES FOR FY 1987

- The temperature and humidity controllers for the environmental chamber will be programmed and chamber performance will be evaluated.
- Several theoretical modeling approaches will be used to describe emission rates of VOC from model material systems as functions of material age, chamber temperature, ventilation rate, mixing and loading.
- Additional small-volume chamber experiments will be performed to provide the necessary input data for the models and to validate model results.
- A complementary literature search will be undertaken to determine the major-types of materials used to finish interiors of office buildings and identify VOC used in their manufacture.
- The data from the field experiments on personal exposures to methylene chloride from paint removers will be analyzed to determine exposures for various use scenarios and environments, to evaluate-mitigation strategies and to evaluate the predictive capability of the mass-balance exposure model.
- Experiments will be conducted in the environmental chamber to determine the effectiveness of portable air cleaners in reducing VOC concentrations in indoor environments.
- The concentrations of extractable organic matter and polycyclic aromatic hydrocarbons in respirable particulate matter from seven homes in Wisconsin will be determined and compared for periods with and without wood-burning.

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Indoor Exposure Assessment *

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The Indoor Exposure Assessment Group (IEAG) is part of the Lawrence Berkeley Laboratory's Indoor Environment Program. The research within the IEAG during FY 1986 had four major research themes: 1) to develop a macromodel to characterize indoor exposures to harmful pollutants; 2) to characterize pollutant emissions from indoor combustion sources; 3) to compile a data base of field measurements of indoor pollutants; and 4) to conduct human risk assessments associated with exposure to indoor air pollutants. Conceptually, projects that are part of the first three research themes supply the exposure data needed to assessing health risks from indoor air pollutants.

In FY'86, macromodeling efforts to assess exposures to combustion pollutants were conducted; semivolatile and nonvolatile organic pollutant emissions from unvented kerosene space heaters were characterized; the concentration of indoor pollutants (CIP) data base was expanded; and a preliminary risk assessment of indoor exposures to organic pollutants was conducted.

MACROMODEL TO ASSESS INDOOR EXPOSURES

Accomplishments During FY 1986

With funds from the Department of Energy, the efforts towards developing a macromodel to assess indoors exposures to combustion pollutants was expanded. Brookhaven National Laboratory, Upton, NY, (contact Ken Novak), Mueller Associates, Inc. Baltimore, MD (contact Linda L. Green), and Energetics, Inc., Columbia, MD (contact Ann Smith-Reiser) were all funded separately by DOE's Office of Environmental Analysis (contact: David Moses) to collaborate on the project.

The macromodel combines many input parameters such as combustion appliance market penetration, pollutant emission rates and degree of appliance venting with appliance source usage models and residential building characteristics to develop a distribution of indoor pollutant concentrations of a regional building stock. Results will allow the quantification of indoor exposures to combustion pollutants and will identify high risk groups.

Work in FY 1986 concentrated on these tasks: 1) the theoretical development of a macromodel to assess indoor exposures to combustion-related pollutants, 2) the computerized implementation of the theoretical model, 3) the collection, on a national scale, of data usable as inputs to the macromodel. Tasks 1 and 2 were largely completed in FY 1986 and Task 3 is an on-going project.

Planned Activities For FY 1987

The development of a macromodel for combustion-pollutant exposures will continue in FY1987. Four regions of the United States will be modeled. In addition, extensive sensitivity analyses of the model will be conducted. Finally, field studies will be designed to fill major information gaps.

Table 1. Nitrated-PAH source strengths from a well-tuned-radiant and a maltuned-convective kerosene space heater.

Compounds	RAD-1,2,4,5 (ng/h)	RAD-3 (ng/h)	MCON-1,2 (ng/h)
1-nitronaphthalene			
XAD-2	280	140	260
Filter		3	120
TOTAL	**280**	**140**	**380**
9-nitroanthracene			
XAD-2			53
Filter		3	41
TOTAL		**56**	**41**
3-nitrofluoranthene (filter only)	1.9		
1-nitropyrene (filter only)	44	8.2	

*This work was supported by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division, by the Assistant Secretary for Environment, Safety and Health, Office of Environmental Analysis, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building System Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098; by the U.S. Environmental Protection Agency through Interagency Agreement DW 89930753-01-0,1 with DOE; by the Gas Research Institute, Chicago, IL with DOE; and by the Electric Power Research Institute, Palo Alto, California through contract RP2034-14 with DOE.

Table 2. Selected organic pollutant source strengths from a well-tuned radiant and a maltuned convective kerosene space heater.

COMPOUND CLASS		RAD-1,2,4,5 (μg/h)	RAD-3 (μg/h)	MCON-1,2 (μg/h)
PAH:				
Naphthalene	XAD-2:	56	230	18
	Filter:			140
	TOTAL:	**56**	**230**	**160**
C2, Naphthalene (filter only)				30
C3, Napththalene (filter only)		1.1		4.5
Phenanthrene (XAD only)		1.9	16	5.9
Fluoranthene	XAD-2:		0.84	
	Filter:	0.11	0.07	1.8
	TOTAL:	**0.11**	**0.91**	**1.8**
Anthracene (filter only)				2.3
Chrysene (filter only)		0.05		
Indeno(c,d)pyrene (filter only)			0.12	
Total PAH in XAD-2		58	250	24
Total PAH on filter		1.3	0.2	180
	TOTAL PAH from XAD-2 and filter	**59**	**250**	**200**
Alkyl benzenes:				
	XAD-2:	89	61000	840
	Filter:	1.8		17
	TOTAL:	**91**	**61000**	**860**
Pentachlorophenol:				
	XAD-2:	36	48	
	Filter:	0.34	1.1	920
	TOTAL:	**36**	**49**	**920**
Phthalates:				
	XAD-2:	1200	3300	3500
	Filter:	7.8	13	1500
	TOTAL:	**1200**	**3300**	**5000**

Table 2. (Continued)

COMPOUND CLASS		RAD-1,2,4,5 (μg/h)	RAD-3 (μg/h)	MCON-1,2 (μg/h)
Hydro Napthalenes:				
Decalin (XAD-2 only)		300	1000	20
C2, Decalin (XAD-2 only)		1800	6500	1800
C1, Tetralin				
	XAD-2:	700	1600	1200
	Filter:			160
	TOTAL:	**700**	**1600**	**1400**
Aliphatic Hydrocarbons:				
	XAD-2:	1500		2900
	Filter:	9.4	6.4	1400
	TOTAL:	**1500**	**6.4**	**4300**
Aliphatic Alcohols:				
	XAD-2:	10000	4900	4900
	Filter:	5.5	32	590
	TOTAL:	**10000**	**4900**	**5500**
Aliphatic Ketones:				
	XAD-2:	670		4500
	Filter:		1.1	
	TOTAL:	**670**	**1.1**	**4500**
Benzoic Acids (filter only)		2.3		
Aromatic Acid (XAD-2 only)				630
Fatty Acids (filter onlh)		14	18	220
Esters (filter only)		6.4	15	200

COMBUSTION POLLUTANT CHARACTERIZATION

Accomplishments During FY 1986

In FY 1986, semivolatile and nonvolatile organic pollutant emissions from unvented kerosene space heaters were characterized.[1]

In this exploratory study, measurements were made of organic pollutant emissions (including some PAH and nitrated-PAH emissions) from portable kerosene space heaters that are common in the U.S. Two heater/tuning conditions were chosen for this study based, in part, on previously reported particulate emission data.[2] A radiant heater operating under well-tuned normal conditions was chosen as the first heater/tuning combination to be tested. The other heater/tuning combination chosen for testing was a convective heater operated under maltuned conditions. The convective heater was maltuned by lifting the exterior shell of the heater by approximately one cm, thereby providing excess air to the wick.

Each heater was operated in a 27 -m^3 chamber. The heaters were operated intermittently to avoid unrealistically high chamber temperatures. For the five radiant-heater tests, the heater was operated for one hour on, then one hour off, and the cycle was repeated four times. The fuel consumption rates for the radiant-heater tests averaged 7000 ± 100 kJ/h and for the maltuned-convective-heater tests averaged 6900 ± kJ/h. Two eight-hour control tests were also conducted.

Nitrated PAH and other organic analyses were accomplished with a combined gas chromatograph/mass spectrometer (GC/MS).[3] The sample extracts were quantitatively analyzed using an on-column-injection, negative-chemical-ionization (NCI) technique[4] for the following nitrated PAHs: 1-nitronaphthalene; 2-nitrofluorene; 9-nitroanthracene; 9-nitrophenanthrene; 6-nitrochrysene; 6-nitrobenzo (a)-pyrene; 3-nitrofluoranthene; 1-nitropyrene; 1,3-dinitropyrene; 1,6-dinitropyrene; 1,8-dinitropyrene; 2,7-dinitrofluorene; and 2,7-dinitrofluorenone. The accuracy and precision of this technique were within 20%. The analysis of other organic pollutants was semiquantative and only accurate to within a factor of approximately 3. However, the precision of the results is on the order of 30%.

Teflon-impregnated 100-cm^2 glass-fiber filters were used to collect nonvolatile and particle-bound organic compounds and 100 grams of XAD-2 resin, placed behind the glass filter, was used to collect semivolatile organic compounds. Samples of similar types were combined before organic and nitrated-PAH compound analyses were conducted. XAD samples were analyzed seperately from filter samples. Samples for radiant tests coded RAD-1, RAD-2, RAD-4, and RAD-5 were combined (total chromatographable organic test results for RAD-3 were much higher than for the other radiant tests) and samples from maltuned-convective tests MCON-1 and MCON-2 were combined.

For convenience and ease of reporting, results of the contribution of a kerosene heater to indoor air pollution concentrations will be expressed as pollutant source strengths while the heater is on. Pollutant emission rates (expressed in units of mass of pollutants per kJ of fuel consumed) can be calculated by dividing the source-strength values by 7000 kJ/h.

Table 1 lists the source strengths of several nitrated-PAHs. 1-nitronaphthalene was clearly emitted by the well-tuned-radiant and maltuned-convective kerosene space heaters. Nitronaphthalene was collected almost entirely on the XAD for the radiant-heater tests. For the maltuned-convective-heater tests, thirty percent of the nitronaphthalene was collected on the filter. This is presumably due to collection by the heavy loading of fresh soot on the filter during the maltuned-convective test.

Emissions of 9-nitroanthracene were observed in the XAD fraction of one of the radiant-heater tests and in the filter fraction of the maltuned-convective test. (Again, the heavy soot loading on the filters of the convective tests may have captured the 9-nitroanthracene before it reached the XAD.) Emissions of 1-nitropyrene were also observed in the filter fraction of both radiant rest samples, whereas only trace amounts of 3-nitrofluoranthene were observed in one of the two series of radiant-heater tests in the filter-collected fraction.

Both 3-nitrofluroanthene and 1-nitropyrene have been observed to be somewhat mutagenic,[5,6] but the mutagenicity of 1-nitronaphthalene and 9-nitroanthracene is low.[6] Notably missing from Table 1 are the highly, directly mutagenic dinitropyrenes (DNPs). The 1,3-DNP; 1,6-DNP; and 1,8-DNP combined source strengths were measured by another research team to be approximately 0.2 ng/h.i[5] The estimated limit of detection in terms of source strengths for DNPs or other nitrated-PAHs investigated for this paper was 1.0 ng/h.

Table 2 presents a partial list of pollutant source-strength results for organic pollutants emitted from the well-tuned radiant and maltuned convective heaters a complete listing can be found elsewhere.[1] Although the table contains more information than can be discussed here, two topics are of particular interest: 1) the differences in relative source strengths among the three test/sample categories and 2) the PAH emissions.

There is a striking difference in relative source strengths between the RAD-1,2,4, and 5 tests and the RAD-3 test. The alkyl benzene emissions from the RAD-3 test were much greater than those from the other radiant-heater tests, whereas the aliphatic hydrocarbon and aliphatic ketone emissions from the RAD-1,2,4, and 5 tests were much greater than those from the RAD-3 test. From an experimental point of view, all five radiant-heater tests were identical, yet the organic pollutant emission rates of the RAD-3 test are dramatically different from the other radiant tests.

The PAH, phthalate, and aliphatic-alcohol emissions for the radiant and convective tests are very similar, yet the aliphatic ketone and, particularly, the pentachlorophenol emissions are much greater for the convective heater than for the radiant heater. Since pentachlorophenol was used as a calibration standard for this analysis and some pentachlorophenol was emitted during the radiant-heater tests,

we must conclude that the convective-heater pentachlorophenol source strength presented in Table 2 is valid, although the authors do not understand how such a compound could be produced in a kerosene flame. Also of interest is the observation that many SVOCs were trapped by the soot-laden filter during the convective tests.

Relatively few PAHs were detected using the very broad GC/MS scanning technique employed in the study. It is anticipated that other PAHs would be found if a more compound-specific technique were employed. Our analysis shows napthalene to be the primary PAH emission from kerosene heaters. Emissions of fluoranthene and indeno(c,d)pyrene, two slightly mutagenic compounds,[7,8] were also found. Previous research from a turbulent diffusion continuous-flow kerosene combustor showed that 18 nonvolatile or particle-bound PAHs were emitted [7]; napthalene accounted for only 3% of the particle-bound PAHs. The earlier study also found relatively few PAHs accounted for most of the indirect mutagenic activity of the kerosene-heater soot. Of those compounds, only fluoranthene was also observed in this study. A more specific study of PAH emissions using more sensitive techniques is probably warranted.

Planned Activities For FY 1987

In FY 1987, an analysis will be conducted on the effectiveness of add-on catalytic devices for reducing pollutant emissions from kerosene space heaters. In addition, field studies will be designed to quantify pollutant emission rates and venting rates for residential combustion appliances.

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 experiments being carried out to monitor pollutant concentrations and other relevant parameters in a wide variety of building types and geographic locations.

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

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

Accomplishments During FY 1986

In April the first update to Version 2.0 of the CIP Data Base was distributed to 43 users (there are currently 90 users). It contained over 40 new entries and extensive new summary data, and made the data base current through the Fall of 1985.

In August Version 3.0 of the data base was distributed. There were a number of major improvements over Version 2.0, including conversion from dBase II to dBase III (Ashton-Tate), an extensive on-line help facility, compilation to a stand-alone system using Clipper (Nantucket Software), improved performance, and more search capability. With the release of Version 3.0, the software development phase of the project came to a close, with only minor additions and modifications to the software anticipated in the future.

The CIP Data Base (version 3.0) has been implemented in a microcomputer environment running MS-DOS, using dBase III, and a commercial dBase III compiler, Clipper. Periodic updates to the data base are distributed to users, also on floppy diskettes. The system is shipped to the user on 6 floppy diskettes, together with a 45 page user manual, and a printout of the bibliographic database, in a 3-ring binder. User support is provided both over the phone by project staff, and via a periodic newsletter distributed to all users.

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

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

Planned Activities For FY 1987

An update to the data base will be distributed in February, 1987. This will consist of approximately 40 new entries, making the data base current to October, 1986. In addition there will be some minor additions and modifications to the data base software.

A technical reference manual, designed to provide a journeyman programmer with enough information to modify and extend the data base system will be released for distribution. It will include file specifications, heavily commented source code, a subroutine tree, and other useful information.

RISK ASSESSMENT

The overall purpose of this work is to characterize indoor exposures to air pollutants and to examine their health implications. Exposure characterization and examination of health effects are the dominant part of the project. These efforts include studies of the three major pollutant classes to which other efforts of LBL's Indoor Environment Program have been devoted: combustion products, radon and its decay products, and organic chemicals.

Accomplishments During FY 1986

In FY 1986, progress was made in the area of assessing exposures of and potential risks from organic chemicals in indoor air. Increasing experience with so-called "complaint" or "sick" buildings suggests the occurrence of adverse effects on humans from exposure to organic chemicals in indoor air. However, except for a few cases involving such compounds as formaldehyde, chlordane, and pentachlorophenol, the complaints cannot be attributed with any certainty to individual chemicals. Furthermore, while the experience to data constitutes an important indicator of a potential problem, complaints are generally limited to acute or irritant effects, such as unpleasant odors, upper respiratory or eye irritation, or headaches. Thus complaints rarely serve as effective indicators of more lifethreatening endpoints, such as cancer or reproductive effects, if only because individuals are not likely to be able to associate such toxic effects with the air inside the buildings they occupy.

These limitations on our experience with complaint buildings have so far precluded either: 1) assessment of the overall importance of organic chemicals indoors as a cause of any class of toxic effects or 2) identification of the most important contributors to such effects. Nonetheless, substantial data are available, primarily from other kinds of studies, on the toxic effects of many of the chemicals that occur indoors. Effective utilization of information from animal and human toxicology can help to narrow the focus of future studies by targeting high-risk chemicals and by identifying toxic effects to be examined in epidemiological studies. Such studies may include surveys in complaint (and control) buildings, as well as epidemiological studies designed to detect the association between particular chemicals and the more serious toxic effects, such as cancer and reproductive effects. Considering the many chemicals present in indoor air, at widely varying concentrations, and the limitations in sensitivity of epidemiological studies, success can only occur by targeting groups that are highly exposed to chemicals of particular concern. The full range of toxicological data should be brought to bear as a basis for indicating which chemicals (or chemical classes) are worthy of attention, as well as for indicating before hand the potential importance of various classes of effects.

In this study we have examined the current literature reporting concentrations of organic chemicals in indoor environments and have constructed a nominal list of 144 chemicals found indoors. We have then surveyed the known toxicological properties of these chemicals, relying primarily on results from animal studies. Based on the animal data, we have made rough estimates of the concentrations in air that might be expected to cause equivalent toxic effects in humans. We have compared these to measured concentrations in indoor air as an approximate index of the significance of indoor exposures.

Table 3 lists those 44 compounds, among the 144 examined, for which the ratio of measured airborne concentrations to the lowest estimated concentration observed to elicit an effect in animals is less than one thousand. Twenty seven of these compounds are carcinogens, 17 are reproductive toxins, and 24 are miscellaneous systemic toxins or irritants. Because of the lack of a demonstrated threshold for carcinogenesis, we have listed all carcinogens in the table, regardless of whether the ratio was greater than 1000. However, there is great uncertainty involved in predicting risk from exposure to carcinogens at concentrations many orders of magnitude below those which have elicited observed effects. We have therefore indicated those carcinogens where the ratio was greater than 1000 by parentheses.

A quantitative risk assessment was performed for the 24 carcinogens with data available which were suitable for such an analysis.[9,10] We compared risks from exposure to individual compounds using

Table 3. All carcinogens, and other chemicals causing toxic effects detected in animal experiments at doses less than 1000 times maximum indoor air concentrations.

Compound	Carcinogenesis[1]	Reproductive Effects	Misc. Systemic Toxic Effects or Irritation
Acetaldehyde	[+]	+	+
Acetone			+
Acrolein		+	+
Aldrin	+		
Benzene	+	+	+
Benzo[a]pyrene	(+)		
n-Butanol			+
Carbon tetrachloride	(+)		
Chlordane	+	+	
Chloroform	+	+	
Chlorpyrifos			+
Cyclohexane			+
Diazinon		+	
Dibenz[a,h]anthracene	(+)		
1,2-Dibromoethane	(+)		
Dibutylphthalate			+
1,1-Dichloroethane	(+)		
1,2-Dichloroethane	+		
Dichloromethane	+		+
Dichlorvos	[+]		+
Dieldrin	(+)		
Di(2-ethylhexyl)phthalate	+	+	
Dimethylacetamide		+	+
Dimethylnitrosamine	+	+	
Ethanol	(+)		
Ethylamine			+
Ethyl benzene		+	+
Formaldehyde	+	+	+
Heptachlor	+		+
Hexane			+
Hydrogen cyanide			+
Lindane	+	+	
Malathion	[(+)]		
Methanol			+
N-Nitrosopyrrolidine	(+)		
PCBs (Arochlor 1260)	(+)		
Pentachlorophenol		+	
Styrene	(+)		
Tetrachloroethylene	+	+	+
1,1,1-Trichloroethane	[(+)]		
Trichloroethylene	(+)	+	+
1,2,4- and 1,3,5-Trimethylbenzene			+
1,1,3-Trimethylcyclohexane			+
n-Undecane			+
Venylidene chloride	+	+	+
p-Xylene		+	

[1] Parentheses ( ) indicate that the lowest effective dose administered in the carcinogenisis test used to estimate risk, after adjusting to an 'equivalent' airborne concentration (see Methods), was >1000 times the maximum indoor concentration recorded in Table 1. Brackets [ ] indicate data exist suggesting the compound may be have carcinogenic potential, but the evidence was either equivocal, or the route of administration was either skin painting or subcutaneous, which we chose not to use in estimating risk.

several different estimation procedures, and found that by all of these procedures, individual lifetime risk estimates for seven carcinogens (benzene, chlordane, dichloromethane, formaldehyde, lindane, tetrachloroethylene, and vinylidene chloride) were $>10^{-3}$ at indoor air concentrations not untypical of some residential exposures. At mean or median concentrations, risk for only formaldehyde and dichloromethane were $>10^{-3}$.

Lack of data on concentrations of chemicals in the indoor environment represents a major limitation of our analysis. For virtually no organic compounds (formaldehyde is to some degree an exception) do we have sufficient direct information to state with much certainty what the frequency distribution of concentrations is, nor are we able to cite average exposures with any accuracy.

The importance of knowing the frequency distribution is underlined by a limited analysis using results from one 15-home study[11] that measured indoor concentrations in homes of a number of common indoor pollutants, including 9 carcinogens. For 5 of these carcinogens (benzene, formaldehyde, carbon tetrachloride, tetrachloroethylene, and trichloroethylene) we have calculated the percent of the exposed population in these homes that would be expected to be at greater than 1 in a thousand lifetime risk of cancer. Results of these calculations are in Table 4 (see table legend for the method of calculations). Three risk estimates are shown for each chemical: the maximum likelihood (MLE); the corresponding 95% lower confidence interval estimate (LCL); and an estimate calculated from the standardized value, the TD50[12], assuming linearity. All 3 estimates suggest that 1% or more of the population are at $>10^{-3}$ risk from exposure to benzene. The estimates for formaldehyde vary from an extremely small fraction up to more than 99% of the population, the variability being primarily due to the extreme non-linearity of the formaldehyde carcinogenesis dose-response in rats.

If the geometric standard deviations of indoor concentrations of various carcinogens are similar, the relative risks of chemicals based on the per-cent of the exposed population at high risk will be consistent with estimates of individual risk based only on mean risks.

However, as seen in Table 4, the geometric standard deviations of these compounds are not all the same. Hence, rankings based on mean risk and % at high risk may be very different. For example, using the MLE estimates in Table 4, the ratio of risks from exposure to trichloroethylene and carbon tetrachloride are 1.9 using the maximum concentrations and 0.44 using the mean or median concentrations. These do not differ greatly, varying over a range of only about 4, and both are close to unity. However, a very different picture of the ratio of risks is seen from the % at high risk values in Table 4. The MLE risk from exposure to trichloroethylene is 0.014%; and the z-value of 5.67 for risk from exposure to carbon tetrachloride corresponds to a risk of about

Table 4. Percent of exposed population at greater than 10^{-3} risk.

	Concentration Dist. of Chemical ($\mu g/m^3$)[1]		Concentration for 10^{-3} Risk[2] ($\mu g/m^3$)			Percent of Population at $> 10^{-3}$ Risk[3]		
	GM	GSD	MLE	LCL	TD50	MLE	LCL	TD50
Benzene	37	2.48	305	190	240	1.0	3.6	2.0
Formaldehyde	22.9	1.73	342	79	5.5	z=4.93	1.2	>99.0
Carbon tetrachloride	6.03	1.87	210	146	180	z=5.67	z=5.09	z=5.42
Tetrachloroethylene	16.2	2.28	580	446	120	z=4.34	z=4.02	0.75
Trichloroethylene	12.7	3.47	1170	880	630	0.014	0.03	0.08

[1] Geometric mean (GM) and geometric standard deviation (GSD) were calculated from the data of DeBortoli, et al (1985).

[2] The maximum liklihood estimate (MLE) and 95% lower confidence limit on dose (LCL) were estimated using GLOBAL82; values in the TD50 column were calculated from the TD50, assuming linearity. The unit risk factors derived by EPA were not used in this table because we did not wish to assume linearity would necessarily be a valid assumption up to the 10^{-3} risk level.

[3] To determine this fraction we used Normal Probability Error Function tables. For example, for benzene MLE estimate: (In 305 - In 37)/ln 2.48 = 2.32 = z. This, in the error function table, corresponds to 0.4898. Thus, the fraction of the which population distribution above 305 $\mu g/m^3$ is 0.5 - 0.4898, or about 1%. The value of z has been listed instead of percent for all z > 3.9 (percent < 0.01).

7.1×10^{-7}. The ratio of these is almost 20,000, leading to a very different picture of the relative risks from exposure to these two chemicals. This is because the geometric standard deviation for trichloroethylene (3.47) is much greater than that for carbon tetrachloride (1.87).

Similar observations may be made for other pairs of carcinogens. Formaldehyde and benzene provide another example. Based on analysis of mean individual risk (using 95% upper confidence interval estimates), formaldehyde poses at least 10 times more risk than benzene. However, based on the % at high risk analysis, benzene poses a high risk to 3 times more people than formaldehyde because of the relatively narrow distribution of formaldehyde among the DeBortoli homes,[11] as compared to benzene.

Planned Activities For FY 1987

We plan to refine the carcinogenic risk assessments on compounds of possible significance in the indoor environment identified in this fiscal year, and extend the analysis to include reproductive toxins.

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Ventilation and Indoor Air Quality Control*

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The Ventilation and Indoor Air Quality Control Group conducts research on technologies for limiting indoor pollutant concentrations -- these technologies include methods of: 1) ventilation; 2) air cleaning; and 3) minimizing or reducing pollutant source strengths. The goals of the research are to evaluate existing and proposed technologies and, also, to develop new technologies. To evaluate a control technology we consider primarily its impact on indoor pollutant concentrations, the energy requirements or savings associated with the technology, and the associated costs. The research is performed through a combination of laboratory experiments, field studies, modeling, and reviews of literature.

During FY 1986, computer models were developed and utilized to study a technique of residential exhaust ventilation in which heat is recovered from exhausted air using a small heat pump. These models provided information on system energy and economic performance[1,2], ventilation rate as a function of time[1,2], and on the impact of exhaust ventilation on both the entry rate of radon and the indoor radon concentration.[2,3] Experimental evaluations of this technology were also initiated during the year. Another area of research during FY 1986, involved the use of multiple tracer gases to measure ventilation rates, air-flow patterns, and the pattern of distribution of outside air primarily in commercial buildings.[4] A simple two-tracer system was also developed for measurement of ventilation rates in residences. The third major effort during the year[5], was to update and synthesize a prior review of the state of knowledge regarding control of indoor air quality.

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ACCOMPLISHMENTS DURING FY 1986

Energy and Economic Performance of Residential Exhaust Ventilation With Heat Recovery

In the majority of U.S. houses, ventilation occurs by the uncontrolled leakage of air (infiltration) through penetrations in the building envelope and by air flow through open windows and doors. Through the tightening of building envelopes and the use of mechanical ventilation, one gains a high degree of control over the ventilation rate and recovery of energy from the outgoing air becomes possible. During the past five years, one method of providing controlled ventilation to residences has seen increasing use. In this method, equal amounts of air are mechanically supplied and exhausted using fans and energy is transferred between the incoming and outgoing airstreams in a residential air-to-air heat exchanger. In another technique, that is now being introduced in the U.S., air is exhausted at a controlled rate and makeup air is drawn into the building through unplanned cracks and holes and through adjustable-sized, strategically placed slot ventilators installed in the walls. A small heat pump, referred to as an exhaust-air heat pump, extracts heat from the exhaust airstream and transfers this heat, plus the energy consumed by the heat pump's compressor, to the domestic hot water whenever there is a need for water heating. An optional fan coil unit, provides a portion of the space heat using the hot water as a heat source. By increasing the demand for water heating, the fan coil unit causes an increase in heat pump operation and, thus, an increase in heat recovery from the exhaust airstream.

One component of our FY 1986 effort to study exhaust-air heat pumps was the completion of modifications to a computer model of all-electric residences with this type of ventilation system. Both a "standard" house with a typical amount of thermal insulation and double-pane windows, and a highly insulated "Model Conservation Standard" (MCS) house with triple-pane windows were modeled. For purposes of comparison, we also modeled houses ventilated by infiltration and by a residential air-to-air heat exchanger. Through yearly simulations with a 7.5 minute time step, energy usage and ventilation rate as a function of time were predicted. A second model was used to make economic comparisons between the mechanically-ventilated houses and the less airtight, but otherwise identical, houses ventilated by natural infiltration.

As expected, the computer simulations indicate that ventilation rates are much more stable in the more air tight, mechanically-ventilated houses. Periods of low ventilation during mild weather and periods of high ventilation during severe weather are avoided.

Predicted energy savings for the mechanically-ventilated houses with a median ventilation rate of 0.5 air changes per hour (ach) relative to houses ventilated by infiltration with a median ventilation rate of 0.7 ach are presented in Table 1 for three locations. The 0.5 ach ventilation rate for mechanically-ventilated houses is a typical target value. The 0.7 ach median ventilation rate selected for the naturally-ventilated house is comparable to the estimated average ventilation rate in existing U.S. houses. In addition, to limit periods of very low ventilation rate (e.g., less than 0.25 ach), a higher average ventilation rate is required in houses that depend on natural infiltration. The energy savings range from 1200 to 7000 kilowatt-hours (kwh) per year and depend substantially on climate and the method of mechanical ventilation. The exhaust-air heat pump systems generally save more energy than the air-to-air heat exchangers, particularly in moderate or mild climates. Sensitivity studies[1,2] indicate that the energy savings will depend substantially on total hot water usage, nominal heat pump capacity, and heat pump coefficient of performance—typical values for these parameters were used to generate the results in Table 1.

To perform the economic analysis of the mechanical ventilation strategies, we used: 1) the energy savings summarized in Table 1; 2) estimates of the costs of the mechanical ventilation systems and of the cost for maintenance; 3) current electricity prices and an assumed price escalation rate that equals the rate of inflation; and 4) a real (above inflation) discount rate of 5% as inputs to a computer program. Two standard economic parameters, the cost of conserved energy (CCE) and the net present benefit (NPB) were computed. The predicted values for CCE are presented in Table 1 and range from 3.8 to 7.5 cents per kwh which is comparable to or lower than typical U.S. electricity prices and generally much lower than the cost of generating electricity from new power plants. However, electricity prices in the three cities chosen for the simulations, where electric space and water heating are common, are substantially below the national average. Therefore, the predicted values[1] for NPB, which indicate the present value to the home owner of investing in mechanical ventilation, are always negative for Memphis (the most negative NPB is -$1350), always slightly positive for Minneapolis (maximum NPB is +$800) and slightly positive or negative for Portland.

To summarize the energy and economic results, we predict that the residential mechanical ventilation systems, particularly those which incorporate an exhaust-air heat pump, can save substantial amounts of energy and provide ventilation at a stable rate. The economic benefits or costs of mechanical ventilation relative to natural infiltration depend highly on climate and energy prices.

Table 1. Predicted yearly energy savings in kilowatt-hours and (in parenthesis) the cost of conserved energy in cents per kilowatt-hour for mechanically-ventilated houses with a median ventilation rate of 0.5 ach relative to naturally ventilated houses with a median ventilation rate of 0.7 ach.

Location/ House Type	Exhaust Vent. & Heat Pump	Exhaust Vent. & Heat Pump & Fan Coil	Air-to-Air Heat Exchanger
Portland/MCS	3900(5.4)	4700(5.7)	2700(5.2)
Minneapolis/MCS	4900(4.3)	6200(4.3)	4700(3.0)
Memphis/MCS	3100(6.8)	3500(7.5)	1200(11.4)
Portland/STD	4200(5.2)	5400(4.9)	3100(4.6)
Minneapolis/STD	5000(4.2)	7000(3.8)	4900(2.8)
Memphis/STD	3200(6.6)	4100(6.5)	1500(9.2)

MCS = highly insulated house with triple-pane windows

STD = typically insulated house with double-pane windows

Residential Exhaust Ventilation and Indoor Radon

Another FY 1986 modeling effort focussed on the impact of mechanical exhaust ventilation on both the rate of radon entry into residences and the indoor radon concentration.[2,3] Exhaust ventilation depressurizes a house slightly and, therefore, can increase the entry rate of radon-laden soil gas through penetrations in a slab floor or basement above that normally caused by wind and the stack effect. (The stack effect results from the lower density of heated indoor air and causes indoor air pressures at floor level to be lower than outdoor pressures at the same level. Wind generally leads to a slight depressurization within the entire house.) Through its impact on the indoor pressure, exhaust ventilation can also increase the draw of crawl-space air, which may contain a substantial amount of radon, into a house through penetrations in the floor located above the crawl space.

Since there are insufficient measured data to relate exhaust ventilation and indoor radon, theoretical models were developed and utilized to examine this relationship. Due to the complexity of the models, only a general description, selected equations, key assumptions, and examples of model outputs are presented here. The models are utilized to estimate the impacts of exhaust ventilation in two hypothetical houses. The first house has a full crawl space and an exhaust ventilation rate (when exhaust ventilation is employed) of 125 m^3/h. We assume that the effective leakage area of this house, which is a standard indicator of the resistance to air flow through the building envelope, is distributed uniformly between walls, ceiling, and floor in proportion to their respective areas and that the crawl space walls contain vents for passive ventilation. The second hypothetical house contains a full basement, has twice the volume of the house with a crawl space, and, when exhaust ventilation is employed, is exhaust ventilated at 250 m^3/h. It is assumed that the only significant penetration between the basement and the soil is a wall-to-floor joint which extends around the entire perimeter of the basement floor. The permeability of the soil surrounding the basement is also assumed to be uniform.

The analysis is performed for an indoor-to-outdoor temperature difference of 20°C and a wind speed of 3 m/s. The first step is a calculation of the ventilation rate of the house using the LBL infiltration model.[6] The magnitude of the pressure difference which drives flow from the crawl space or soil to the building's interior is then estimated, taking into account the impacts of wind, the indoor-to-outdoor temperature difference, and exhaust ventilation. The component of the total pressure difference which results from exhaust ventilation (ΔP_e) is expressed simply by the equation

$$\Delta P_e = \frac{\rho}{2}\left[\frac{Q_e}{ELA}\right]^2 \qquad (1)$$

where ρ is the density of the indoor air, Q_e is the exhaust flow rate, and ELA is the total effective leakage area of the house.

The third step of the analysis is a computation of the flow rates of crawl-space air or soil gas into the house. For a crawl space, this flow rate (Q_{cs}) is easily estimated by using the equation

$$Q_{cs} = ELA_f\left[\frac{2\Delta P_{cs}}{\rho}\right]^{1/2} \qquad (2)$$

where ELA_f is the effective leakage area of the floor and ΔP_{cs} is the total pressure difference across the floor above the crawl space. In the model for a house with a basement, a much more complex procedure, which accounts for the resistance to flow through both the soil and the wall-to-floor gap, is used to estimate the entry rate of soil gas into the basement.

The fourth step, a calculation of the rate of pressure-driven flow of radon into the house, is based on assumed values for radon concentrations in the crawl space or in soil gas. The pressure-driven flow of radon is, therefore, a simple product of the assumed radon concentration and the appropriate flow rate.

The final step is to use a single-zone, steady state, mass balance equation to compute the indoor radon concentration, Rn_i, i.e.,

$$Rn_i = \frac{\sigma_d + \sigma_f + (\lambda_v - Q_{cs}/V)\,Rn_o}{\lambda_v} \qquad (3)$$

where: σ_d is the rate of radon diffusion into the house (which is assumed to equal zero), σ_f is the rate of pressure driven flow of radon into the house, λ_v is the ventilation rate, V is the house volume, and Rn_o is the outdoor radon concentration which is assumed to equal 0.25 pCi/l. For a house with a basement, the "Q_{cs}" term in Equation 3 is replaced by the rate of soil gas entry into the basement.

The results generated with these models are thought to be generally representative, and some favorable comparisons between modeled results and measured data have been presented.[3] However, in instances where the basic assumptions of the model

do not correspond to actual conditions, the trends indicated by the model may deviate substantially from actual trends. Two key assumptions, that may lead to discrepancies, are the physical characteristics of the penetrations between the basement and the soil and the assumption of a uniform soil permeability. In regard to the second assumption, the permeability of the soil immediately adjacent to the basement is clearly a key factor. Also, if the ratio of exhaust flow rate to effective leakage area differs substantially from that assumed for the example calculations presented here, the amount of depressurization caused by exhaust ventilation and the impact on indoor radon will also change substantially.

Examples of results from the analysis of a house with a vented crawl space are presented in Table 2 and indicate that exhaust ventilation plus house tightening, which includes tightening of the floor, will lead to significantly lower indoor radon concentrations and less flow from the crawl space to the house. The tightening of the floor more than counteracts the increased driving force caused by exhaust ventilation. However, if this floor is not tightened exhaust ventilation could, in some situations, lead to an increase in indoor radon concentrations. Our calculations indicate that much of the air that enters a crawl-space house during the heating season, will enter through the floor above the crawl space even if exhaust ventilation is not employed. Therefore, the indoor radon concentration will often be comparable to the concentration of radon in the crawl space and ample ventilation of crawl spaces is recommended for houses with and without exhaust ventilation if radon is a potential problem. A major conclusion of this analysis is that exhaust ventilation is generally suitable (but not optimal) from the perspective of indoor radon, for houses with a full vented crawl space as long as the floor does not have a disproportionate fraction of the total effective leakage area.

The results for a house with a basement are more complex and only the major results are described here. The model indicates that the rate of pressure-driven flow of soil gas into a basement of both exhaust-ventilated and naturally-ventilated houses will be only a few hundred liters per hour if the soil permeability is lower than approximately 10^{-7} cm^2. These low soil gas flow rates will significantly affect the indoor radon concentration only if the soil gas radon concentration is unusually high (e.g., several thousand pCi/l). If the soil permeability is less than approximately 10^{-8} cm^2 (e.g., clay, silt, or silty sand and gravel soils), pressure driven flow of soil gas into a house should not cause problems even when soil gas radon concentrations are unusually high. Therefore, exhaust ventilation appears to be a suitable technology for houses with basements that are surrounded with a low-permeability soil. The presence of a layer of highly permeable aggregate immediately beneath the basement floor, is one factor that might alter this conclusion.

On the other hand, this analysis indicates that exhaust ventilation combined with house tightening could lead to substantial increases in the soil gas entry rate and indoor radon concentration if the basement is surrounded with soil that has a permeability greater than approximately 10^{-6} cm^2. Therefore, exhaust ventilation is not recommended for houses with basements located in highly permeable soils unless some process, such as a major reduction in the size and number of penetrations through the slab, is employed to limit soil gas entry.

Table 2. Examples of predicted indoor radon concentrations, flow rates from the crawl space to the house, and related parameters for a house with a vented crawl space, with and without exhaust ventilation.

Total ELA cm^2	Floor ELA cm^2	Exhaust Flow Rate m^3/h	Air Exchange Rate h^{-1}	Pressure Diff. Across Floor pa	Flow Rate Through Floor m^3/h	Indoor Rn Conc., pCi/l with Rn_{cs}=5	Rn_{cs}=10	Rn_{cs}=50
710	246	0	0.58	1.69	148	4.2	8.4	41.7
460	159	0	0.38	1.69	96	4.2	8.4	41.7
250	86	0	0.20	1.69	52	4.2	8.4	41.7
250	86	125	0.46	2.85	68	2.5	5.0	24.3
|<------Inputs to Model------>|				<------Outputs from Model------>				

*Values for Rn_{cs}, the radon concentration in the crawl space, are inputs to the model.

Tracer-Gas Techniques

A number of experimental techniques, which involve the injection of tracer gases into either the indoor air or the stream of incoming outdoor air, can be used to study building ventilation. Multiple tracer gases are particularly useful if the building has distinct (physically separated) zones or multiple ventilation systems since a different tracer can be used in each zone or with each ventilation system. The tracer gas techniques can provide information on the following aspects of building ventilation: 1) the rate of entry of outdoor air; 2) the overall pattern of air flow between the locations where air is supplied and removed; and 3) the spatial pattern of outside air distribution throughout the building. Each of these factors can significantly affect indoor air quality and building energy consumption.

During FY 1986, we continued development of a multi-tracer experimental system suitable for use in commercial buildings. A two-tracer system for measuring weekly-average ventilation rates in residences was also developed and tested.

For tracer gas studies in commercial buildings, we abandoned plans[4] to use a sampler that automatically collects small samples of indoor air as a function of time (e.g., every 10 minutes) and which stores these samples for analysis at a later time in the laboratory. Tests indicated that a small amount of leakage would occur between different samples after extended use of the sampler. A procedure was adopted which involves the placement of gas chromatographs in the building for real-time measurement of tracer gas concentrations in the airstreams associated with the ventilation system. These real-time measurements will be complemented by time-integrated samples collected in small bags from specific locations in the occupied space. During the past year we acquired enough instrumentation for real-time measurements with three tracer gases, developed an improved system for calibrating the instruments, and developed and tested a technique for collecting time-integrated samples in sample bags.

For studies in residences that have a basement, a two-tracer system was also developed and tested. Typically, one tracer gas is injected at a constant rate into the basement and a second tracer is injected at a constant rate into the remainder of the house. Air samples are collected at a constant rate in sample bags, and at approximately one-week intervals the sample bags are removed from the samplers and replaced. The analysis of tracer gas concentration is performed in the laboratory.

Both the tracer injection units and the samplers are relatively simple devices which contain peristaltic pumps, tubing, and special sample bags as major components. Although a variety of tracer gases could be used, we selected sulfur hexafluoride (SF_6) and bromotrifluoromethane ($CBrF_3$) for an upcoming field study. Two tests of this measurement system were conducted in a well-mixed test space with a known ventilation rate. Multiple samplers and four tracer gases were used during each test. For the two tracer gases selected, measurement precision was approximately 5% and the maximum inaccuracy was approximately 20%.

PLANNED ACTIVITIES FOR FY 1987

During FY 1987, research will continue in the same basic areas. Laboratory evaluations of three exhaust-air heat pumps will be completed and the data obtained will allow us to verify and refine our computer model of exhaust ventilation with heat recovery. Additional data for model verification and refinement will be obtained from a field study conducted by others. In regard to tracer gas studies, we plan to use a three-tracer system to study ventilation in selected commercial buildings. Experiments will also be performed to evaluate the extent to which the tracer gases are thermally decomposed when they are drawn through a lighted cigarette or when a natural gas or electric range is operating. The potential for tracer decomposition into harmful products has not received sufficient study. Additional research may be initiated in other areas if funding is received.

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Energy Performance of Buildings*

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

BUILDING ENERGY RETROFIT RESEARCH (BERR)

While new buildings—both residential and commercial—are responding to higher energy prices and stricter energy codes by becoming more energy efficient, the existing stock represents a large area for energy conservation activity. Of the three buildings sectors (single-family, multifamily, and commercial) multifamily has had the least 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.[1] The reasons for this untapped energy savings are complex, and involve institutional and technological barriers. While we know something about the performance of retrofits in single-family houses, we know very little about retrofits in multifamily buildings. The measured savings from retrofits are typically 25-50% less than the predicted savings, with a large spread around the mean.

The Building Energy Retrofit Research project was initiated to address these problems in all three building sectors. The Department of Energy has designated LBL as the primary lab for carrying out research in the multifamily sector.

Accomplishments During FY 1986

The BERR multifamily work can be broken down into six areas: (1) planning and sector characterization, (2) development of a monitoring protocol, (3) monitoring retrofit performance in multifamily buildings, (4) developing new diagnostic techniques, (5) studying behavior of occupants, owners, and managers, and (6) analysis of utility billing data. In addition to these six areas we have been working on a project in new Swedish multifamily buildings and continuing our investigation of innovative retrofits in single-family housing.

Planning and Sector Characterization

Two planning documents were published this year, one dealing with multifamily retrofit research

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and the other with federally-assisted housing.[2,3] Both characterize the existing building stock, discuss barriers to retrofit activity, outline previous activities and identify research needs. A cost benefit analysis was made for all of the multifamily research projects. The multifamily plan was done in conjunction with similar documents on the single-family and commercial sectors written by Oak Ridge National Laboratory (ORNL). The document has input from over forty organizations, and has had a preliminary review by a dozen organizations. The federally-assisted housing plan has input from several public housing authorities and substantial review and comment from HUD.

Monitoring Protocol

The need for a standardized set of procedures for monitoring buildings led to the development of a monitoring protocol. An early draft was used to specify the procedures used for tests in Chicago and Minneapolis/St. Paul. The experience gained has been incorporated into subsequent drafts.[4] The objective of the protocol is to provide a comprehensive consensus standard for data collection and evaluation of retrofit performance. A compilation of commercially-available monitoring instrumentation has also been prepared.

Retrofit Monitoring

The purpose of monitoring is to evaluate the installation and performance of retrofits in occupied buildings. We are studying the effects of building operation and maintenance and looking at potential health and safety hazards associated with retrofits.

An important aspect of our BERR research is that the work is being done in collaboration with local groups and agencies. Groups we are currently working with include the San Francisco Public Housing Authority, the Center for Neighborhood Technology in Chicago, the Energy Resource Center in St. Paul, the Minneapolis Energy Office, and the Minnesota Department of Energy and Economic Development.

The buildings we have been monitoring range from 7 units to 26 units, and are two or three stories high. The buildings are all heated by natural gas, with gas boilers for hot water. The buildings are between forty and sixty years old, and are representative of a significant fraction of the multifamily building stock in their areas. Figure 1 shows one of the apartment buildings.

The retrofits involve changes to the building shell, the heating system, and the domestic hot water system. Descriptions of these retrofits are given elsewhere.[5] The retrofit selection and installation was determined by the collaborating agencies. Because of their schedules it was not always possible to monitor both before and after the retrofit. In several buildings, different retrofits were added at the same time, so isolating the effect of all the individual retrofits may not be feasible. Diagnostic tests were carried out on certain retrofits to determine if short-term measurements can provide answers validated by the long-term monitoring.

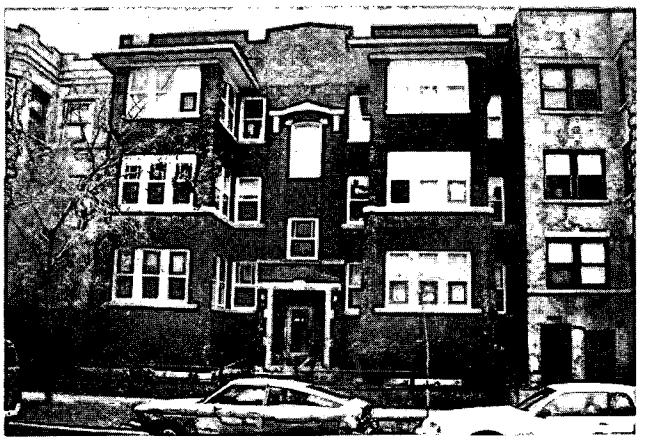

Figure 1. Exterior elevation of an apartment building (Bosworth) where we are investigating the performance of occupant behavior on energy retrofits. (BBC 867-5761)

New Diagnostic Techniques

In addition to the long-term monitoring work there has been development of short-term diagnostic tests. The project focused on a one-week investigation of a 7-unit apartment building in Minneapolis, working in conjunction with the Minneapolis Energy Office. There were measurements of air leakage in the apartments and an evaluation of the building's original steam boiler. A measurement using tracer-gas was made of a vent damper retrofit installed on the boiler.[6]

The air leakage tests have been further tested in buildings in Massachusetts, California, and Illinois. Though the tests have been simplified, the procedure is still complex. A description of this and other air leakage diagnostic techniques was distributed for review.[7]

Behavior Studies of Building Occupants, Owners, and Managers

An important aspect of retrofit performance is understanding the behavioral aspects. Building own-

ers have to make decisions on what retrofits to select, residents modify the retrofits to suit their needs, and building managers take actions that affect the performance of the retrofits.

We have conducted surveys of occupant behavior on retrofit performance in multifamily buildings in California and Illinois. Forty-eight households in low-income apartments in San Francisco were interviewed about their energy and hot water consumption. Data from these surveys were used to predict hot-water consumption that was in close agreement with that measured,[8] as shown in Figure 2.

Residents in two Chicago apartment buildings were surveyed about their behavior relating to ventilation and energy use. Figure 3 shows typical variations in the temperatures in six apartments over a two-day period. Such findings are useful in adjusting the central heating system. [9]

Analysis of Retrofit Performance from Utility Billing Data

Our work in utility data collection and analysis has concentrated on federally-assisted housing, where we have been analyzing the performance of retrofits in public housing. Utility billing data along with information on building characteristics and retrofit strategy have been collected for over forty public housing projects. The study shows the energy savings and cost-effectiveness of the retrofits. [10]

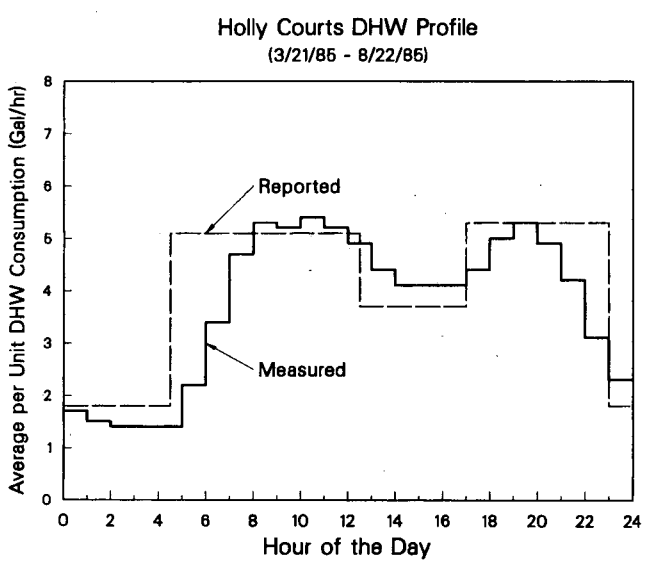

Figure 2. Predicted versus measured domestic hot water consumption, Holly Courts, San Francisco. (XCG 8512-552)

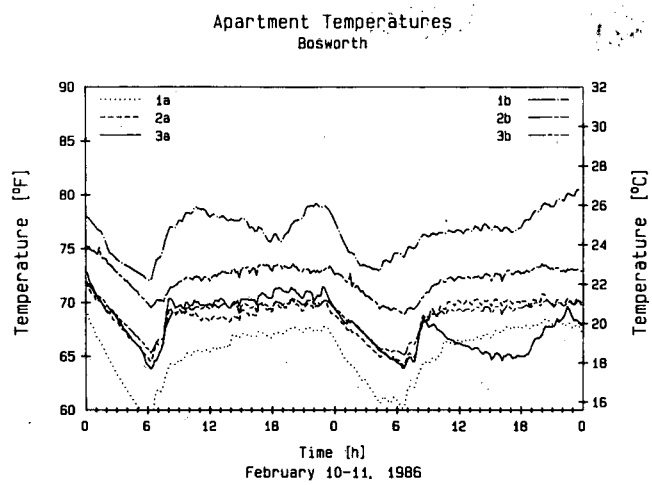

Figure 3. Temperature data for six apartments at Bosworth during February 10-11, 1986. (XBL-867-2749)

Baseline energy use was collected and analyzed from over 40,000 public housing units. Weather-corrected consumption levels were calculated for several years and compared to estimates provided by an earlier study of estimated energy use in public housing.[11]

Swedish Multifamily Housing

Over the last few years the Swedes have developed building technologies that have reduced energy consumption considerably. Buildings there now have triple-glazed windows and high-levels of wall, roof and floor insulation. Work is now proceeding on improving the performance of the heating equipment.

One part of this strategy involves the Stockholm Project, a full-scale demonstration project funded by the Swedish Council for Building Research (BFR). The project includes the construction of six apartment buildings with over 250 apartments. Figure 4 shows the Konsolen building, a 57-unit apartment building that is part of this project. The buildings have built-in sets of sensors for parameters such as temperature, air flow, electricity use and water use. An LBL scientist was invited to Sweden to assist in the data analysis.

While the buildings use very little energy by any standards, the heating and ventilation systems have been experiencing some problems. The analytical and modelling skills developed at LBL proved useful in elucidating the causes of these problems, and then pointing toward solutions.[12] For example, one building with a solar collector was found to be consuming more heat than expected. After a detailed review of

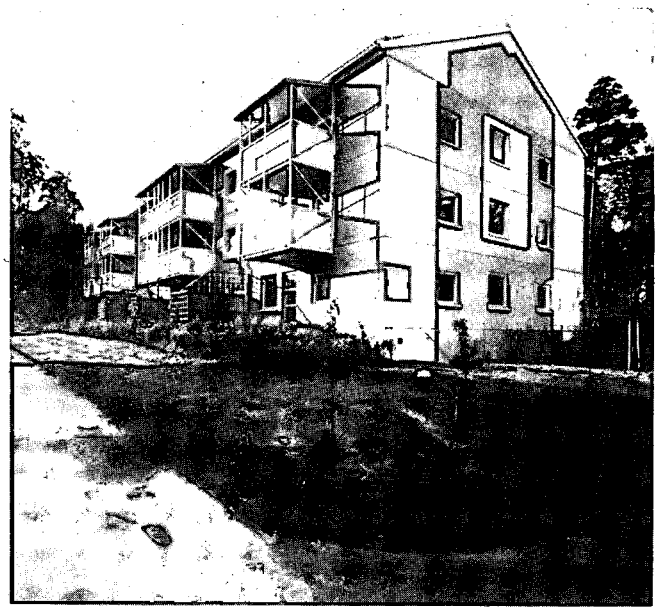

Figure 4. The Konsolen building, a low-energy 57-unit apartment building. This is one of six buildings that are being evaluated in the Stockholm Project, a Swedish Council for Building Research study. (Photograph: Carl Michael Johanesson) (BBC-8612-10410)

the heating and ventilation system, the air flow was re-routed and an extra loop was added to the control system.

Warm Room Evaluation

The warm room retrofit is a response to a common problem: how to stay warm in a large, poorly insulated house during the coldest parts of winter. The problem is especially acute for low-income homeowners who may not have enough money to insulate their whole house. The warm room retrofit has the potential for achieving significant energy savings at costs comparable than costs currently allocated by low-income weatherization programs. The retrofit is a combination of zoning, heating system modification, and insulation which allows the occupant to heat selected areas of the home while leaving the rest of the house cold. In recent years, several groups have pioneered this approach; this study presents the results from a retrofit project in Kansas City, undertaken by the Urban Consortium in 1985-1986.

We selected nine houses for the study, four controls and five houses that received the warm room retrofit. The houses were all single-family detached structures, low-income elderly owner occupied with gas-fired furnaces. The warm zone included the kitchen, bathroom, one bedroom, and one to two additional rooms, depending on family size. Our analysis showed energy savings which averaged 26 percent. An important part of the study was to determine occupant response and the acceptability of the retrofit. The residents participated in the design of the retrofits, and were interviewed after the retrofits were installed to determine improvements in comfort and their satisfaction with the results.[13]

Planned Activities for FY 1987

Our plan for the coming year is to analyze the data that have been collected on the monitored buildings. Before the next cycle of monitoring begins, there is a great deal of information on the performance of the retrofits that needs to be evaluated and disseminated. Tasks will be to analyze the performance of the vent damper retrofits, the air leakage diagnostic tests, occupant behavior, and the hot water retrofits.

New projects may include an investigation of the performance of retrofits on distribution systems, a comparison of techniques for analyzing retrofit data, and the development and testing of new diagnostic techniques. In addition, we hope to secure joint funding (DOE/HUD) for continuing the federally-assisted housing work.

AIR INFILTRATION

With improved insulation of the building shell, heat loss from ventilation — whether controlled or by infiltration — has become an even more important fraction of a building's overall heat loss. Infiltration is the flow of outside air driven by wind pressure and thermal buoyancy into the building. Unlike the equivalent loss for conduction, ventilation heat loss depends upon the inside/outside temperature difference and wind speeds. We carry out research in three main areas: development of a simplified multizone model, multigas tracer measurements, and wind tunnel measurements of wind pressure distribution around buildings.

A number of computer programs have been developed to calculate air flow distribution in buildings. Awareness of the air flow 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 regarding

flow characteristics and pressure distribution inside and outside of a building is essential. To reduce the input data required by detailed infiltration models, simplified models have been developed. Most of these, including the one developed at LBL[14], 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. These models need inordinate amounts of input data .[15] Therefore, a simplified multizone model capable of providing the same accuracy as the established single-cell models is being developed at LBL. A comparison of modelling strategies is shown in Table 1.

Accomplishments During FY 1986

Multizone Modeling

In order to describe the air flow distribution inside a building we introduced five lumped parameters. These parameters reflect the different permeability distributions of a building's envelope and flow resistances inside the building. The *envelope permeability ratio (epr)* describes the ratio of the permeability of the leeward side of a building envelope to the permeability of the whole envelope.[16] For a given permeability of the total envelope, the infiltration rate reaches its maximum at an envelope permeability ratio of 0.5 (typical row house). This is because the value of the resultant permeability is governed by the smallest permeability in a series arrangement. The wind-driven infiltration under steady state conditions will be zero if all air permeability is located on one side.

Table 1. Comparison of modeling strategies.

model	advantage	disadvantage
single-cell	easy to handle few input data reasonable accuracy	only single cell no internal partitions no internal flows
detailed multizone	larger buildings internal flows good accuracy	extensive input mainframe computer
simplified multizone	larger buildings internal flows ease of use reduced input pocket calculators	reduced accuracy

The latest issue of the German standard on heat loss calculation for buildings, DIN 4701[17] introduces another parameter. Based on this parameter we introduced the ratio of the permeabilities from one floor to another, and the overall permeability of the building envelope, which we called the *vertical permeability ratio (vpr).*

With regard to thermal pressure distribution, two extremes exist: *story-type buildings* with no permeability between floors (vpr = 0), and *shaft-type buildings* with no air-flow resistance between the different stories (vpr = 1).

To describe the air-flow distribution for different zones at the story level, two additional lumped parameters were defined.[18,19] The first lumped parameter is the *outside permeability ratio* (opr) of the zone. It describes the influence of cross-ventilation on the zone (cross-ventilation being the portion of the air flow that exfiltrates out of the same zone it infiltrates). The second lumped parameter is the *inside permeability ratio* (ipr) of the zone. It describes the stack influence on the zone. In a previous study, the use of a detailed multizone infiltration model indicated a strong relationship between the two latter ratios and the flow distribution in buildings.[20]

It was determined that the internal air flows of a building due to wind are directly dependent upon the ratios of the resultant permeabilities of the different zones. These are defined as the combination of all flow paths (parallel and series arrangements) from this zone to either the windward or leeward side of a building. The *resultant permeability ratio* (rpr) is the ratio of the resultant permeability of the downstream side to all resultant permeabilities of this particular zone.

Determining the resultant permeabilities is far more complicated than determining the permeabilities used for the other four ratios. An iteration procedure may be necessary.

Multigas Tracer Measurements

To identify air movement into a building and internal flows, we developed a multigas tracer measurement system. By using a gas chromatograph with an electron capture detector, many gases can be detected. The equipment can be used to measure as many as four gases. Unfortunately, the collection cycle is very long, and real-time comparison with the program is impossible.

A more sophisticated multigas tracer measurement system has been designed. It contains a resi-

dual gas analyzer, which will speed up the collection cycle. By the end of the fiscal year, all parts for the new system had been ordered.

Wind Pressure Studies

The first comparison between our simplified multizone infiltration model and tracer gas measurements performed in a building will be made for the office and test building of the *Laboratoire d'Energie Solaire (LESO)* at the Ecole Poytechnique Federale de Lausanne in Switzerland. This test building contains nine zones on three different floors and a central staircase. Tracer gas measurements and weather data have been collected on site by our Swiss colleagues. Pressure coefficient measurements of this multizone building have been carried out using scale models of the building and its surroundings at the boundary-layer wind tunnel at the Architecture Department of the University of California, Berkeley.

Planned Activities for FY 1987

Multizone Modeling

Our task is to validate the detailed and simplified models with data obtained by tracer gas measurements. The first comparison of the results will be performed utilizing data from the LESO building in Switzerland. If the results of comparisons are satisfactory, additional parameter studies using the detailed model will be done in an attempt to further simplify the model.

Multigas Tracer Measurements

The development of the multigas tracer system and its assembling has been planned for the beginning of FY 87. Calibration of the system and its test in the laboratory environment will follow completion of the system. Initial measurements in multizone buildings are scheduled for the second half of FY 87.

Wind Pressure Studies

Pressure coefficient measurements will be performed for all sites and multigas tracer measurements will be taken. Following the testing period of the tracer gas system, buildings in the San Francisco Bay Area will be measured.

IEA SUPPORT

In response to the 1973-74 oil crisis, the OECD countries formed the International Energy Agency. As part of the implementation agreement, technical annexes were created to enable countries to work together on problems of mutual interest. To date, thirteen technical annexes have been formed. Lawrence Berkeley Laboratory has been representing the U.S. on annexes V, IX and XII.

Accomplishments During FY 1986

The U.S. has been one of the most active members of the Air Infiltration and Ventilation Centre (AIVC). LBL provided 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 86 the Air Infiltration and Ventilation Centre responded to approximately 120 inquiries from the U.S. and delivered some 400 copies of technical papers held in their library of some 2,200 ventilation-related papers. AIVC's major accomplishment for FY 86 was the completion of the calculation techniques guide, published in loose-leaf form.

Planned Activities for FY 1987

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

AIR LEAKAGE

The process of air flowing through a building envelope is called air leakage. Air leakage depends on the air tightness of the building as well as on the pressures driving the air flow. Air tightness is a property of the building alone. Typically, air tightness is quantified by the *Effective Leakage Area* (ELA), which is the amount of open area that would have the same air leakage as all of the leaks in a building under identical conditions. The measurement and study of air leakage allows us to characterize the air tightness of buildings, better understand air flow through building envelopes, evaluate the performance of mechanical ventilation systems, and estimate the effectiveness of air-tightness retrofits.

Our air leakage research can be divided into three areas: leakage characterization, measurement techniques, and consensus standards. Our leakage characterization effort involves collecting and analyzing measured leakage data. The standard method for measuring building airtightness is called fan pressurization. Over the last few years, we have developed a

new method for measuring building airtightness, AC Pressurization, which allows us to determine the effective leakage area at low pressures, independent of wind effects. Finally, we are putting our experience to use by assisting the professional societies in the formation of consensus standards.

Accomplishments During FY 1986

Over the past four years we have been collecting air leakage data. During FY 86 this database, installed in-house on a micro-computer, was extended to 1100 measurements on 750 houses in 110 different zipcodes. These data come from our own research efforts, other researchers, government energy agencies, house doctor companies, and the armed forces. Figure 5 shows the cities for which the database contains leakage measurements.

The leakage database is made up of five separate sections: (1) basic leakage information for quick reference, (2) complete information on the data analysis and the measurement conditions, (3) description of each house, including retrofit history, (4) address, and (5) zipcode and climate information.

The measurement technique work in FY 86 focused mainly on multizone leakage measurements. As part of a larger multifamily retrofit research project, multizone leakage measurements were made in two apartment building in Chicago, Illinois. Unlike earlier measurements, which utilized six blower doors, the technique used in Chicago utilized only two blower doors. It is illustrated in Figure 6, and involved opening the windows in all apartments except the two in which the blower doors were located. The blower doors were then operated so as to obtain data with and without a pressure difference between the two apartments. [21]

Figure 5. Cities in North America for which the database contains measurements of air leakage. (XBL-8612-4955)

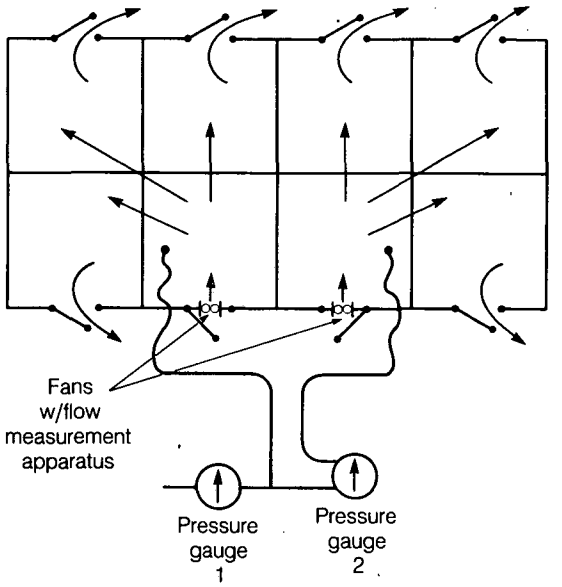

Figure 6. Use of the secondary blower door for the interzonal measurement. (XBL-8612-5991)

The two buildings tested were masonry three-story walk-ups built around the turn of the century. All buildings displayed similar leakage characteristics with 40% of an individual apartment's leakage in its exterior envelope. Using a multizone air flow model, the leakage data were used to examine the air flow patterns under typical conditions.[22] The results, presented in Figure 7, show that upper-story apartments receive very little outside air at windspeeds less than 3 m/s, indicating potential problems with air quality and heating load imbalances.

A number of multizone leakage measurements were also made in the area around Boston, Massachusetts, and in Berkeley, California in FY 86. These measurements were made with the same technique that was used in Chicago. The Boston measurements were part of a collaboration with the Executive Offices of Communities and Development of the Commonwealth of Massachusetts, and are presently being analyzed. The Berkeley measurements, which were made in a wood-frame, three-story walk-up, showed minimal leakage between apartments. This surprising result points out the importance of testing apartment buildings of different construction types, and the need for a larger sample of measurements.

Development of the AC pressurization apparatus was ended in FY 86 due to the issuance of a privately controlled U.S. Patent.

As part of our work with professional committees and organizations, we were involved with two

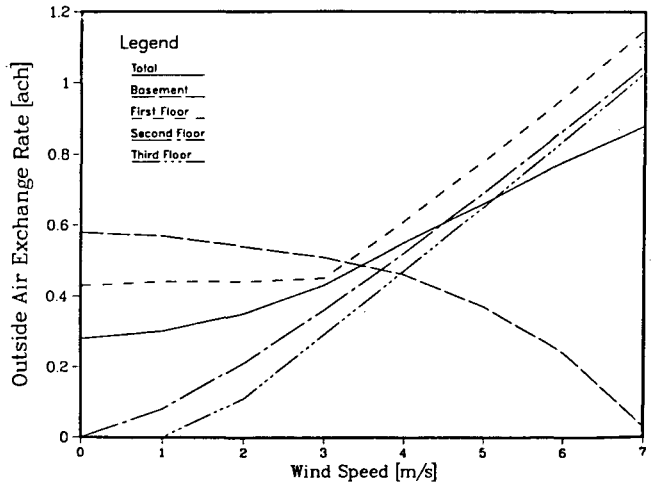

Figure 7. Flow of air from the outside into each apartment at the Bosworth building as a function of windspeed for wind from the west. (XBL-8612-4954)

standard-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 86, including the modification of Standard Test Method E-779, "Determining Air Leakage Rate by Fan Pressurization" to include effective leakage area as part of the standard. During FY 86, Standard E-779 was put out for public review, and is expected to be published by the society in FY 87. We also began participation in four new standards in ASTM.

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. During FY 86 the standard project committee approved the standard to be forwarded for public review. The review draft of the standard is climate-based (introducing the concept of Infiltration Degree Days[23]), uses effective leakage area divided by conditioned floor area as the quantity of interest, and creates a classification method for houses that is independent of the air tightness requirements.

Planned Activities for FY 1987

The leakage characterization work will continue during FY 87, specifically focusing on analyzing the data in the air leakage database, and on characterizing the flow through large apertures under fluctuating pressure conditions. We will first analyze our computerized database to check for important holes in the data. We will also use the database to get a handle on duct leakage in single-family buildings (approximately 100 measurements are presently in the database) as part of our duct leakage measurement effort. The second part of the leakage characterization effort is to develop a workable physical model for air flow through large apertures. This work will include theoretical modelling efforts in collaboration with the Royal Institute of Technology in Sweden, and experimental examination of flow profiles in Berkeley.

In the measurement area, several new projects will begin in FY 87. These include: testing a new single-zone leakage measurement technique based on pulse pressurization; testing a multi-zone leakage measurement technique based upon AC Pressurization; and testing new techniques for measuring and locating duct leakage.

Initial investigation of a new single-zone leakage measurement technique was made in FY 86. The new technique, based upon pulse pressurization, was lab tested in collaboration with Bruel and Kjaer in Denmark. The results indicated that leakage area and flow exponent could be determined by Fourier analysis of pulse response. We will test this technique in buildings in FY 87.

An additional project for FY 87 will be to perform detailed error analyses for both DC pressurization and AC pressurization. These error analyses will be based upon a large number of field measurements, examining the effects of wind and stack effect on both DC and AC pressurization. The DC pressurization analysis will examine different outdoor pressure probes, including the general practice of using a single probe, the four-sided Canadian averaging box technique, and a static pressure probe.

The multi-zone blower door measurements made in FY 86 showed the uncertainties associated with these measurements. In FY 87 we will test a multi-zone AC pressurization technique. This technique will involve exciting a single zone, and measuring the pressure response in that zone and the surrounding zones.

The standards work will also continue during FY 87. We expect that in FY 87 the revised ASTM E779 and ASHRAE standard 119 will become official.

APPLIANCE PERFORMANCE TESTING

Gas and electric utilities use a large array of information for forecasting future energy demands. This project is concerned with the projection of energy demand due to major appliance operation in single family residences. These are gas and electric

domestic hot water heaters, refrigerators, central air conditioners, and central gas furnaces. Although some data is available for residential end-use energy consumption there is no data base available on major appliance field performance. Future energy demand is dependent on knowledge of actual appliance efficiencies changes due to factors such as long-term degradation.

The only appliance efficiency information currently available to energy forecasters is the manufacturer's efficiency rating, which is based on laboratory test procedures. But, the laboratory tests are performed on new appliances under assumed field conditions. Operating conditions for installed appliances may involve different physical configurations and more adverse ambient conditions, which potentially cause both efficiency reductions and increased long-term performance degradation rates.

Accomplishments During FY 1986

We are conducting a project in conjunction with Pacific Gas and Electric, the California Energy Commission, and DOE to develop and test procedures that are applicable for field appliance performance testing. A major goal of the study is to compare the measured and the rated efficiencies of the target appliances. Diagnostic data which will be used to explain differences between the measured and rated efficiencies were also collected. Another goal of the study is the development of simple techniques for a large-scale survey of appliance efficiencies.

Methods development, conducted in early 1986, investigated several techniques for duplicating laboratory appliance efficiency indicator measurements in the field. A total of 31 single-family residences located in north-central California were monitored during the summer of 1986.

Domestic Hot Water Heaters

The short-term field test procedure for determining recovery efficiency, which is a measure of how much of the fuel energy goes into the water while the burner is operating, requires that a tank of cold water be heated to the water heater's maximum aquastat setting. The tank of cold water is created by turning off the burner and drawing hot water from a faucet until the hot water is cold. The tank of cold water is then heated. The long-term field test procedure for standby-loss determination involves monitoring the heat energy input and hot water use.

Figure 8 is a plot of recovery efficiency versus age. It shows some scatter (standard deviation = 8%)

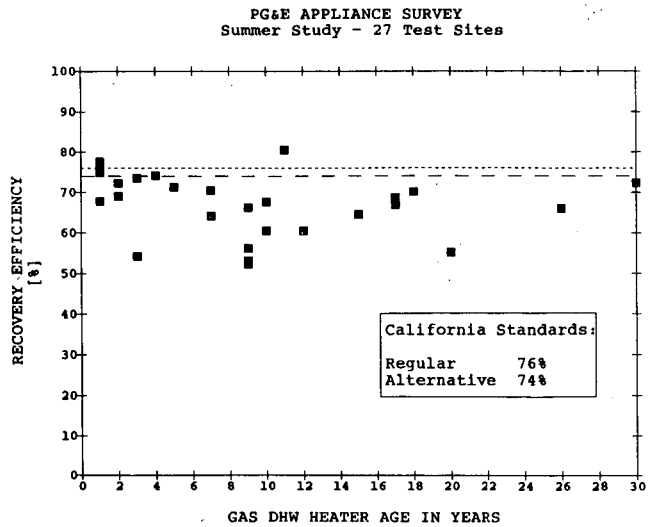

Figure 8. Variation of measured gas DHW heater recovery efficiency with age of unit. (XBL-8612-4952)

around the average efficiency of 67%, but does not show any clear trend of efficiency with age. Most of the units have a measured recovery efficiency between 65 and 76%, as compared to the California standards of 74% and 76%.

The standby loss could not be determined directly for most of the water heaters due to a lack of main heater operation during time periods with no hot-water use.

Central Air Conditioners

The short-term field test procedure involves measurement of both Energy Efficiency Ratio (EER), and Seasonal EER (SEER). Both indicators are ratios of heat removed to electrical energy consumed. EER is a steady-state value, whereas SEER is a steady-state value corrected for cycling of the air conditioner. The energy efficiency calculations are based on condenser coil air flow, condenser coil air temperature difference, and electric energy consumption of both inside and outside units of the air conditioner. EER is calculated based on readings recorded at the end of at least 30 minutes of continuous air conditioner operation. SEER is calculated based on readings recorded during a forced air conditioner cycling pattern of two successive 24-minutes-off and 6-minutes-on cycles.

This study attempts to determine the EER and SEER indirectly by measuring the heat rejection at the outside condenser coil. This technique was chosen due to the difficulties associated with field measurement of latent heat removal. The outside

coil is more accessible for sensor installation and does not have latent heat loads. Three different methods of measuring condenser unit air flow rate were used. The high turbulence and pressure sensitivity of the the fans used resulted in condenser-coil air flow measurement uncertainties on the order of 10%.

A plot of SEER versus age shows a large amount of scatter (standard deviation = 2.3 Btu/Wh) around the average SEER of 5.1 Btu/Wh. The California standards require an EER of 7.0 Btu/Wh for 1977, an EER of 8.0 Btu/Wh for 1979, and SEER of 8.0 Btu/Wh starting in 1980.

Refrigerators

For refrigerators the only efficiency indicator is the monthly energy consumption. Figure 9 is a plot of daily consumption versus age, which although it has a fair amount of scatter, indicates a trend of increasing consumption with age. The mean value is 4.5 kWh/day, with a standard deviation of 1.7 kWh/day.) It should be noted, however, that the plotted values have not been corrected for temperature or door openings, and that a trend in refrigerator size with age may be affecting the results. The California efficiency standards for a 20 ft^3 refrigerator were set at 5.9 kWh/day in 1977 and 4.6 kWh/day in 1979.

A potential problem in the field-monitored energy use is occupant effects. Whereas the laboratory procedure is conducted under controlled refrigerator conditions the field study is not. These effects must therefore be accounted for; the compartment temperatures and ambient temperatures were monitored, and a door-openings sensor has been developed for use during the winter study.

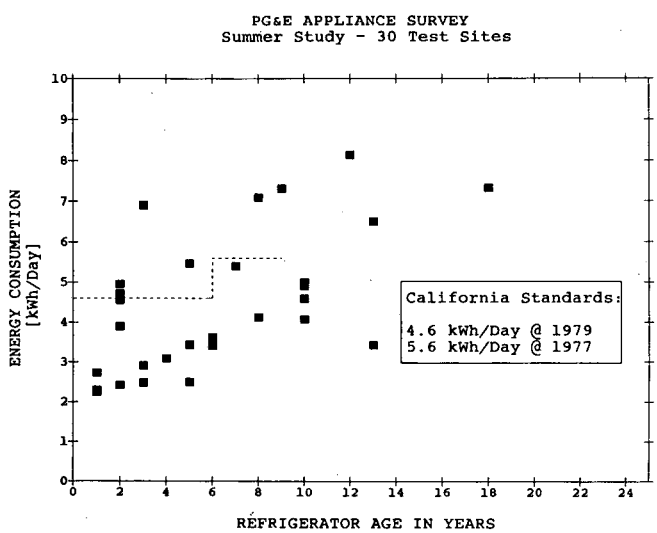

Figure 9. Variation of measured refrigerator energy consumption with age of unit. (XBL-8612-4951)

Planned Activities for FY 1987

The appliance performance survey pilot study involves both summer (FY 86) and winter (FY 87) field monitoring. The winter study involves monitoring of 30 additional test sites in which we will test the furnaces, along with additional refrigerators and water heaters. The furnace field test procedure that was developed during FY 86 will be tested on a variety of actual furnace configurations.

Although preliminary summer data analysis was performed during the summer study field monitoring, complete data analysis and a final report writing is planned for during the coming year. A preliminary report on the summer measurements is due to be delivered in November, 1986. Based on the data collected during the pilot study, procedure and equipment simplifications will be investigated. Within the limitations of the small data set produced by this pilot study, factors such as improper installation, long term appliance performance degradation, and geographic performance influences will be analyzed. This information is important for planning of a proposed large-scale appliance performance testing project. We hope to secure funding for a follow-on large-scale appliance performance survey planning project.

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