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Author
Grimsrud, David T.

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FIELD STUDY OF EXHAUST FANS FOR MITIGATING INDOOR AIR QUALITY PROBLEMS. Final Report to Bonneville Power Administration

D.T. Grimsrud, R.F. Szydlowski, and B.H. Turk

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FINAL REPORT TO
BONNEVILLE POWER ADMINISTRATION

FIELD STUDY OF EXHAUST FANS FOR MITIGATING INDOOR AIR QUALITY PROBLEMS

DAVID T. GRIMSRUD

RICHARD F. SZYDLOWSKI

BRADLEY H. TURK

INDOOR ENVIRONMENT PROGRAM
APPLIED SCIENCE DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA

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TABLE OF CONTENTS

List of Tables

List of Figures

Executive Summary

Context of Study: The Pacific Northwest Power Planning Act of 1980 authorized the Bonneville Power Administration (BPA) to undertake energy conservation programs to help meet electric load obligations. As a result of a concern about the impact of the programs on air quality in the buildings, BPA initiated several indoor air quality studies to examine this issue. This report describes results form one of the first of a series of field studies undertaken by the Indoor Environment Program of Lawrence Berkeley Laboratory (LBL) for BPA.

Goals of Study: Residential ventilation in the United States housing stock is provided primarily by infiltration, the natural leakage of outdoor air into a building through cracks and holes in the building shell. Since ventilation is the dominant mechanism for control of indoor pollutant concentrations, low infiltration rates caused fluctuations in weather conditions may lead to high indoor pollutant concentrations. Supplemental mechanical ventilation can be used to eliminate these periods of low infiltration. This study examined effects of small continuously-operating exhaust fan on pollutant concentrations and energy use in residences.

Organization of study: Two different exhaust ventilation schemes were investigated. The first was the use of a small exhaust fan operating continuously. The second used a larger exhaust fan that was controlled using a circuit that sensed weather conditions that would lead to low infiltration. The latter scheme was implemented by Honeywell, Inc.; the former by LBL.

Project Results: The report is divided into seven chapters that describe the study's design, measurement protocol, results, and interpretation. Results are summarized in terms of the objectives of the study.

The study addressed all the objectives set out in the original workplan. The first major objective, to determine the ventilation performance of small exhaust fans in typical houses,

was fulfilled in a general way. Quantitative measures of the ventilation supplied by these fans showed the small incremental ventilation that was provided by the fans when operating continuously. This behavior is consistent with their role of supplying "fill ventilation", i.e., a minimum amount of ventilation when the infiltration drops near zero.

The second objective, to determine the effectiveness of exhaust fans for removing indoor air pollutants, was fulfilled in great detail in one sense and remains unfulfilled due to the study design in another, important sense. Except for radon, budget constraints limited the instrumentation used for pollutant measurements to passive samplers, devices that yield average concentrations over the time interval. The passive samplers did demonstrate that air quality was not adversely affected by the exhaust fans. Conversely, the measurements did not demonstrate that a significant improvement in indoor air quality occurred when the exhaust fan was used.

The real-time radon sampler results demonstrated that the source strength of the radon was not increased when the exhaust fans were used. This is a significant result but one that must be interpreted carefully. The exhaust fans used in this project were small, to minimize their cost of operation. This also minimizes the depressurization that occurs in operation. With larger fans and/or tighter houses, the depressurization would be larger and the same result (no impact on radon source strength) may not be true.

The final major objective was to evaluate the energy penalty associated with the use of exhaust fans. Based on the measured increase in ventilation from the exhaust fans, we determined that the daily increase in energy use for the four houses due to the operation of the exhaust fan is 1.5 kWh. This assumes an average indoor-outdoor temperature difference of 10°C. It represents approximately 3% of the daily energy use in these houses.

I. INTRODUCTION

The Pacific Northwest Electric Power Planning Act of 1980 authorized the Bonneville Power Administration (BPA) to undertake cost effective energy conservation programs to help meet electric load obligations. BPA's methods for meeting these objectives include: a) a region-wide house tightening program which includes caulking, weatherstripping and the addition of storm windows, and b) proposed codes for the construction of energy-efficient new homes.

Although house tightening effectively reduces infiltration, it may also lead to an increased concentration of indoor air pollutants, particularly those originating from sources within the building. Acknowledging the potential for adverse health effects, BPA published an Environmental Impact Statement (EIS) [EIS, 1984] that covered the residential conservation programs. However, uncertainties in the information base used to project impacts were identified and studies were approved to quantify the effects of reduced ventilation on indoor air quality and to develop energy conserving strategies to mitigate potential problems that may result.

This report presents results of a study that examined ways that ventilation, particularly that provided by small exhaust fans, can be provided at low energy cost to improve indoor air quality.

Objectives of the Study.

The study had several objectives:

1. To determine the ventilation performance of small exhaust fans in typical houses;
2. To determine the effectiveness of exhaust fans for removing indoor air pollutants;
3. To evaluate a control mechanism for operating the fans;

4. To determine the amount of energy lost or the "energy penalty" associated with operating exhaust fans, and
5. To gain an indication of how various meteorological criteria correlate to air infiltration rate and therefore to air quality.

Study Organization

This research project was a collaborative effort by Lawrence Berkeley Laboratory (LBL) and Honeywell, Inc. to compare three ventilation strategies. One part, designed and conducted by LBL, examined the performance of air-to-air heat exchangers (AAHX) and continuously running exhaust fans on pollutant concentrations in four houses of different design in the Portland, Oregon area. The second, designed by Honeywell and conducted by LBL, examined the performance of AAHX and exhaust fans operated intermittently on a group of four houses matched to the four LBL study houses. This paper discusses the results of the LBL half of the project.

Three separate ventilation modes were investigated:

(A) Balanced ventilation with air-to-air heat recovery (AAHX),

(B) Continuous exhaust ventilation with no heat recovery (LBL),

(B') Intermittent exhaust ventilation with no heat recovery (Honeywell), and

(C) Natural infiltration

The intermittent exhaust ventilation was supplementary ventilation that was switched on by a controller designed for this study by Honeywell. The controller turned the fan on when the indoor-outdoor temperature was small <u>and</u> when the wind speed was low. When these conditions were both true ordinary infiltration would become small; therefore, the exhaust fan was designed to switch on to insure a minimum amount of ventilation at all times.

Ventilation mode (C), natural infiltration, was used as the reference case in each house. It is also present in cases (A) and (B) [or (B')]. Infiltration simply adds linearly to the ventilation provided by an AAHX if the system is truly balanced while it adds in quadrature to the ventilation provided by an exhaust fan [Sherman and Grimsrud, 1982].

The results of this study have been used as inputs to two larger projects that study indoor air quality in Pacific Northwest residences. One, the Existing Home Indoor Air Quality Study, investigated the effects of house tightening infiltration retrofits on the buildup of a variety of indoor pollutants. The second project, the New Energy-Efficient Homes Indoor Air Quality study, investigated indoor pollutant concentrations in newly constructed homes, some built to the Model Conservation Standards code. Mitigation activities in homes in which pollutant concentrations exceed guidelines were a part of both of these studies.

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II. INDOOR AIR QUALITY CONTROL USING MECHANICAL VENTILATION

Residential use of mechanical ventilation is unusual in North American housing. However, as field studies begin to demonstrate the low infiltration rates that are present in much of the new housing stock in Canada and the United States [Grimsrud et al., 1983] concern about the effects of inadequate ventilation grows. In situations in which existing technology is used with care to produce tight housing, mechanical ventilation in residences becomes desirable. It is explicitly mandated in some codes and standards [NKB, 1981] and is implicitly recommended in others [ASHRAE, 1981].

Mechanical ventilation offers several advantages that are particularly attractive to an architect or builder. These include controlled ventilation, the possibility of constant performance characteristics, the ability to match the ventilation to the local pollutant source, and the possibility of energy recovery.

Mechanical ventilation is not a panacea, however. Disadvantages include higher first cost and operating costs, danger of failure, and the need for periodic inspection and maintenance (and consequently an increased responsibility for the homeowner).

Air-to-Air Heat Exchangers

Balanced mechanical ventilation systems, employing heat recovery with an air-to-air heat exchanger, have been studied extensively both in a laboratory and field environment [Fisk and Turiel, 1983]. They appear to be an attractive solution to ventilation problem in some situations [Turiel et al., 1983] depending on building construction, climate, and energy cost. Their major advantages include:

(a) the ability to recover thermal energy from the exhaust air stream;

(b) their modest electrical use;

(c) their lack of effect on house interior pressures. This is important when considering a pollutant, such as radon, whose entry rate may be on affected by indoor-outdoor pressure differences [Nazaroff et al., 1985].

Balanced systems also have disadvantages.

(a) They generally require ductwork for air distribution;

(b) they are subject to freeze-up in cold weather that degrades their performance [Fisk et al., 1985]; and

(c) they simply add ventilation to the existing infiltration of the house since they do not change the pressure difference across the building shell [Sherman and Grimsrud, 1982].

Exhaust Fans

Mechanical exhaust systems for residential application have several configurations. These range from the simple bathroom exhaust fan to the complex humidity-controlled central exhaust fan (marketed by Aldes) used in conjunction with humidity-controlled slot ventilators that are installed in each occupied room of a house [Jardinier, 1984].

There are several advantages to unbalanced mechanical exhaust systems when compared to balanced ventilation systems.

(a) exhaust fan systems require neither whole house ducting nor supply fans and are therefore less expensive to install;

(b) since exhaust fan systems depressurize the house relative to its surroundings, the ventilation rate of the house is less influenced by the environmental pressures that drive infiltration. Therefore, the exhaust fan tends to "decouple" the house from the surrounding environmental pressures. This means that the ventilation rate of a house containing an exhaust fan is relatively constant in time.

Exhaust fan systems may also have disadvantages.

(a) Since the house is depressurized when the exhaust fan is operating, the pollutant entry rate of any pollutant entering the house from the soil through pressure driven flow (such as radon) may increase,

(b) no heat recovery is provided by the exhaust system considered in this project.

Therefore, energy use will increase.

Other disadvantages, such as system noise, drafts during cold weather, and energy requirements for the fan systems may occur in both systems.

Control Strategies

In this project, two separate control strategies were chosen for the exhaust fan systems. One group of four houses used small, continuously operating exhaust fans that ensure that a minimum amount of ventilation was provided during periods of low infiltration but contribute little to the ventilation when infiltration was high. This strategy was employed by Lawrence Berkeley Laboratory. The basis for the control strategy chosen by LBL for the exhaust fan is the following. The ventilation provided by the exhaust fan, Q_U, (U for unbalanced pressures) and the ventilation provided by infiltration, Q_I, adds in quadrature. That is, the total ventilation, Q_T, supplied by the exhaust fan and infiltration is given by

$$Q_T = [Q_U^2 + Q_I^2]^{1/2}.$$

This means that if the exhaust fan supplies 0.20 air changes per hour (ach) to ventilate the house when the infiltration is zero, the total ventilation supplied to the house is also 0.20 ach. The energy cost associated with the exhaust fan is the cost of operating the 22 watt fan continuously plus the energy required to heat or cool the 0.20 ach of ventilation air supplied by the fan.

On the other hand, if the infiltration component of the ventilation is 0.50 ach, the total ventilation supplied by the combination of exhaust fan and infiltration is only 0.54 ach. Therefore, the added ventilation supplied by the exhaust fan is not 0.20 ach (as it would be in the zero ventilation case) but rather 0.04 ach. The total energy use associated with the fan is therefore the 22 watts of fan power operating continuously, plus the energy required to heat or cool the 0.04 ach of ventilation air supplied by the fan.

A second group of four houses used larger exhaust fans that are controlled by a sensor that turns the fans on when both the wind speed and the indoor-outdoor temperature differences are small. When both environmental parameters are small the infiltration contribution to the total ventilation of the house is small [Dick, 1949], so auxiliary ventilation is desirable. This strategy, developed by Honeywell, Inc., is described in a separate report. [Honeywell, 1986].

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III. MEASUREMENT PLAN

Study Design

The basic objective of this project, to study the effects of exhaust fan ventilation strategies on indoor air quality in residences in the Pacific Northwest, was investigated using eight houses located in the Portland, Oregon area. The strategies tested included having the house ventilation supplied by:

a) an exhaust fan

b) an air-to-air heat exchanger

c) infiltration.

In cases(a) and (b) ventilation was supplied by both infiltration and the mechanical systems.

A subsidiary objective of the study was the comparison of two different control strategies for the exhaust fan systems: continuous operation at low fan speeds (LBL design) and intermittent operation -- switching the exhaust ventilation fan on during weather conditions with both low wind speed AND small indoor-outdoor temperature differences (Honeywell design). This was investigated by separating the eight houses into two groups. One group of four houses used the LBL control design, the other, the Honeywell design.

House Selection

Leakage characteristics. The eight houses used in the study were chosen from 26 homeowner-volunteers employed by BPA in the Portland area. Houses were chosen as matched pairs. Similar size, design type, pollutant sources, and predicted seasonal infiltration rate based on leakage area were used as selection criteria.

Based on these measurements, heating season infiltration rates were calculated using the LBL infiltration model. Houses were tested for suitability in the study by obtaining leakage measurements using fan pressurization. The results of this testing are summarized in tabular form in Appendix A.

The features of the houses selected for monitoring are presented in tabular form in Table 3.1.

General house features

The floor plans of the four houses that participated in this study L2, L4, L6, and L8 are presented in Appendix A. The floor plans also indicate the locations of the monitoring instrumentation in each house.

Other details of each house are:

L2 (Identified as house code 07 in Table A.1.) One to three occupants present in the house; no smoking in house; occasional fireplace use; no woodstove use; forced-air gas furnace; electric water heater; electric range and oven.

L4 (Identified as house code 09 in Table A.1.) Zero to two occupants present in the house depending on time of day; no smoking in house; no fireplace; woodstove not used; forced air gas furnace; gas water heater; gas range and oven.

L6 (Identified as house code 18 in Table A.1.) Zero to four occupants normally in house; no smoking in house; gas forced-air furnace; electric range and oven; woodstove.

L8 (Identified as house code 19 in Table A.1.) Two to four occupants normally present in house; no smoking in house; occasional fireplace use; weekend use of woodstove; electric forced air furnace; electric water heater, range, and oven.

Table 3.1

Characteristics of the Eight Houses

House	H1	L2	H3	L4	H5	L6	H7	L8
Floor Area(ft^2)	1120	1190	1750	2000	2410	2980	1440	1760
Volume(ft^3)	9000	9500	14000	18000	18500	23400	11500	15400
Const. Year	1980	1952	1974	1982	1910	1915	1963	1973
Design Type	1 crawl	1 crawl	2 crawl	2 slab	2 half-basement	2 half-basement	1 crawl	1 crawl
Vent Strategies(1)	H	L	H	L	H	L	H	L
Leakage Area (cm^2)	690	750	760	770	790	930	640	720
Infil. Rate (pred-heating season)(2)	0.69	0.68	0.57	0.52	0.49	0.48	0.48	0.42

NOTES:

(1) H refers to Honeywell ventilation strategies (AAHX, Intermittent Exhaust Fans or infiltration).
L refers to LBL ventilation strategies (AAHX, continuous exhaust fans, or infiltration).

(2) Infiltration rate (ach) predicted for each house for average weather in Portland during the heating season following measurements with the blower door. The prediction used the LBL infiltration model (Sherman and Grimsrud, 1980).

Pollutants Monitored

Pollutants representing major pollutant classes were monitored. Each individual pollutant was chosen using criteria of importance as an indoor pollutant and availability of inexpensive monitoring instrumentation. The pollutants selected included:

Combustion Pollutants

1. Nitrogen dioxide (NO_2)
2. Respirable suspended particles (RSP)
3. Carbon monoxide (CO)

Organics

4. Formaldehyde (HCHO)

Radon and Progeny

5. Radon (Rn)

Other Parameters Monitored

Other characteristics of the environment and house conditions that were measured included:

1. Indoor and outdoor dry-bulb temperature.
2. Indoor and outdoor dew point temperature.
3. Wind speed and direction.
4. Average ventilation rate
5. Furnace, water heater and total electrical use.
6. Water vapor concentration.

Activity logs were provided to homeowners and were used to record daily activities within the house that would have an impact on the pollutants monitored. The logs were collected by the field technicians weekly. A sample of the log is presented in Appendix B.

Measurement Protocol

Ventilation System Operation. Each house was equipped with an air-to-air heat exchanger and an exhaust fan. Each separate ventilation strategy (exhaust fan, air-to-air heat exchanger, or infiltration) was used continuously for a week; then switched to a second strategy; then a third. The cycle was repeated five times. The total measurement period in each house was thus approximately 15 weeks. Changes in this design occurred when equipment malfunctioned, weather conditions were inappropriate, or homeowners overruled the plans.

A perfluorocarbon (PFT) tracer gas system was used to monitor the average ventilation rate during each of the one-week periods that a particular ventilation system was used. The sources were mounted permanently throughout the experiment while the samplers were changed weekly when the individual ventilation strategies were changed. (The system is described in more detail in Chapter 4, below.)

Pollutant monitoring. Each pollutant was monitored for weekly intervals that matched particular ventilation strategies. Equipment used for monitoring is described in Chapter 4. Each week the passive samplers (HCHO, H_2O, NO_2, PFT) were retrieved by field technicians and returned to the lab for analysis. New samplers were deployed and a new ventilation strategy was begun. The data from the real-time monitors (Continuous radon monitor, temperature, wind speed and direction, and energy use) that were recorded on an ESM data logger were retrieved by removing the ESM's data module at the site and replacing it with a blank data module. The data stored on the data module were sent to LBL for permanent storage and evaluation. Technicians also retrieved daily activity logs from each homeowner; new supplies of log sheets were left at each house on a weekly basis.

The technicians reported their activities weekly; an example of these activity reports is also included in Appendix C.

IV. MEASUREMENT EQUIPMENT

Instrumentation Package

The following monitoring equipment was installed in each of the houses in the study:

Indoor

Integrating Samplers

1 particulate sampler

3 formaldehyde passive samplers

3 water vapor passive samplers

3 nitrogen dioxide passive samplers

2 perfluorocarbon sources

2-4 perfluorocarbon samplers

Real-time sensors

1 dew point sensor

2-3 temperature sensors

1 continuous radon monitor

1 each furnace, water heater and electrical use sensors

Outdoor

Integrating samplers

1 particulate sampler

1 formaldehyde passive sampler

1 water vapor passive sampler

1 nitrogen dioxide passive sampler

Real-time sensors

1 dew point sensor

2 temperature sensors

1 wind speed and direction sensor

The location of the instrumentation in each house is indicated on the floor plans found in Appendix A.

Data Logger

Data from real-time sensors used in the project were recorded using a data acquisition system developed by the Energy Performance of Buildings Group at LBL. The system, named the Energy Signature Monitor (ESM), is a microprocessor-based data acquisition system designed for long-term unattended operation. The brief description that follows is extracted from the extensive description of the system by Szydlowski (1984).

Data acquisition and communication is controlled by a 6502 CPU microprocessor with 10K bytes of program memory contained in erasable programmable read-only memory (EPROM) and 2K bytes of random-access memory (RAM) for intermediate data storage. The ESM has two pulse-count input channels which count the number of TTL level voltage signals received, and sixteen analog input channels which will accept a sensor output voltage range of -4.095 to +4.095 volts. A 12-bit analog-to-digital converter processes the analog input channels, for an effective resolution of 1 millivolt. Each of the analog channel inputs can be recorded either as an analog millivolt value or as a digital ("on/off") value. The "on" digital signal is defined as a sensor value that is greater than a user-defined threshold millivolt value.

The standard data acquisition program, written in assembly language, monitors the pulse count channels as interrupts and scans all the analog and digital channels either every fifteen seconds or once per record interval, a user option.

Data are stored in 24K bytes of EPROM memory which is contained on a removable 3.5 X 5 inch data module for physical transfer to a central data analysis station (in this case LBL). The data module can store up to 29 days of hourly averages from a typical set of seventeen sensors which consists of one pulse count sensor, eight analog, and eight digital channels.

During normal operation the ESM is line-powered, but battery backup power is supplied for RAM memory, clock, and short-term data acquisition operation. The ESM will continue normal data acquisition operation during a line power failure until the end of the next record interval, at which time the ESM will go into a "sleep" mode. The clock remains operational during the power failure, and the ESM will automatically continue normal operation when line power is restored.

A menu-driven program is used by the ESM to communicate with a terminal through a standard RS-232 interface. Although a computer terminal is used to communicate with the ESM during setup at a test site, it is not required during operation of the experiment.

Pollutant Monitoring

Respirable particulate sampler. The LBL/BPA Constant Flow Air Sampler, designed and built at LBL, is designed to collect respirable suspended particles (RSP) by drawing air through an in-line filter at a constant flow rate independent of filter loading. An in-line cyclone limits the size of the particles collected to those having an aerodynamic diameter less than 3 μm. The constant flow rate is maintained by a differential pressure regulator coupled with a metering valve and a DC vacuum pump. The flow rate is set with the metering valve and built-in rotameter. Pressure drop across the filter and sampling line is indicated on a pressure gauge; the total volume of air sampled is recorded by a dry test meter.

The RSP filter-cassette and cyclone assembly was deployed inside the building near one of the passive sampler locations whenever possible. The sample location was selected to be in a well-mixed part of the room being tested. Care was taken to avoid placing the filter-cassette near supply registers or other sources of heat or strong convective currents. The cassette was not placed within five feet of combustion appliances or smoking locations.

Formaldehyde, nitrogen dioxide and water vapor passive samplers. Three separate passive samplers were used in this project. These measure time-weighted average concentrations of formaldehyde (HCHO), nitrogen dioxide (NO_2), and water vapor (H_2O).

Passive samplers collect samples of air by diffusion. At the closed end of each tube is a chemically treated disc or adsorbent that is specific for the pollutant sampled. The reaction of the pollutant with the disc or adsorber removes it from the air; the concentration gradient in the tube that results from the removal causes diffusion from the open to closed end of the tube. This "pumping" action, at a rate that depends on the diameter and length of the sampling tube, allows continuous collection of the pollutant over long periods of time without the need for sampling pumps. The sampler dimensions are chosen to measure average pollutant concentrations for one-week intervals.

At the conclusion of the sampling period the tubes are returned to LBL for analysis. The HCHO and NO_2 samplers are analyzed using colorimetric development followed by spectrophotometry. The H_2O samplers are weighed to determine their increase in weight.

Sampling locations were chosen to be sites that were expected to provide average pollutant concentrations in the occupied portion of the residences. Locations were chosen in consultation with the homeowner to assure placement in areas normally occupied and to prevent placement close to windows frequently used or other regions of high ventilation.

Typical installation in a house consisted of three interior and one exterior location, i.e., a total of four separate sampling sites per house. One sampling site included the RSP sampler. All occupied levels of multi-story houses were sampled. Sample racks (Fig. 4.1) were mounted at a height of four to six feet above the floor in interior spaces. Care was taken to avoid air that was moving rapidly (close to doors, windows, and fans) or dead air spaces that would lead to stagnation of the sampler [Persoff and Hodgson, 1985].

Continuous radon monitor. Passive samplers for measuring time average concentrations of radon in the air exist but lacked the sensitivity required to permit accurate sampling over the one-week period used in this project. Therefore a Continuous Radon Monitor (CRM) was

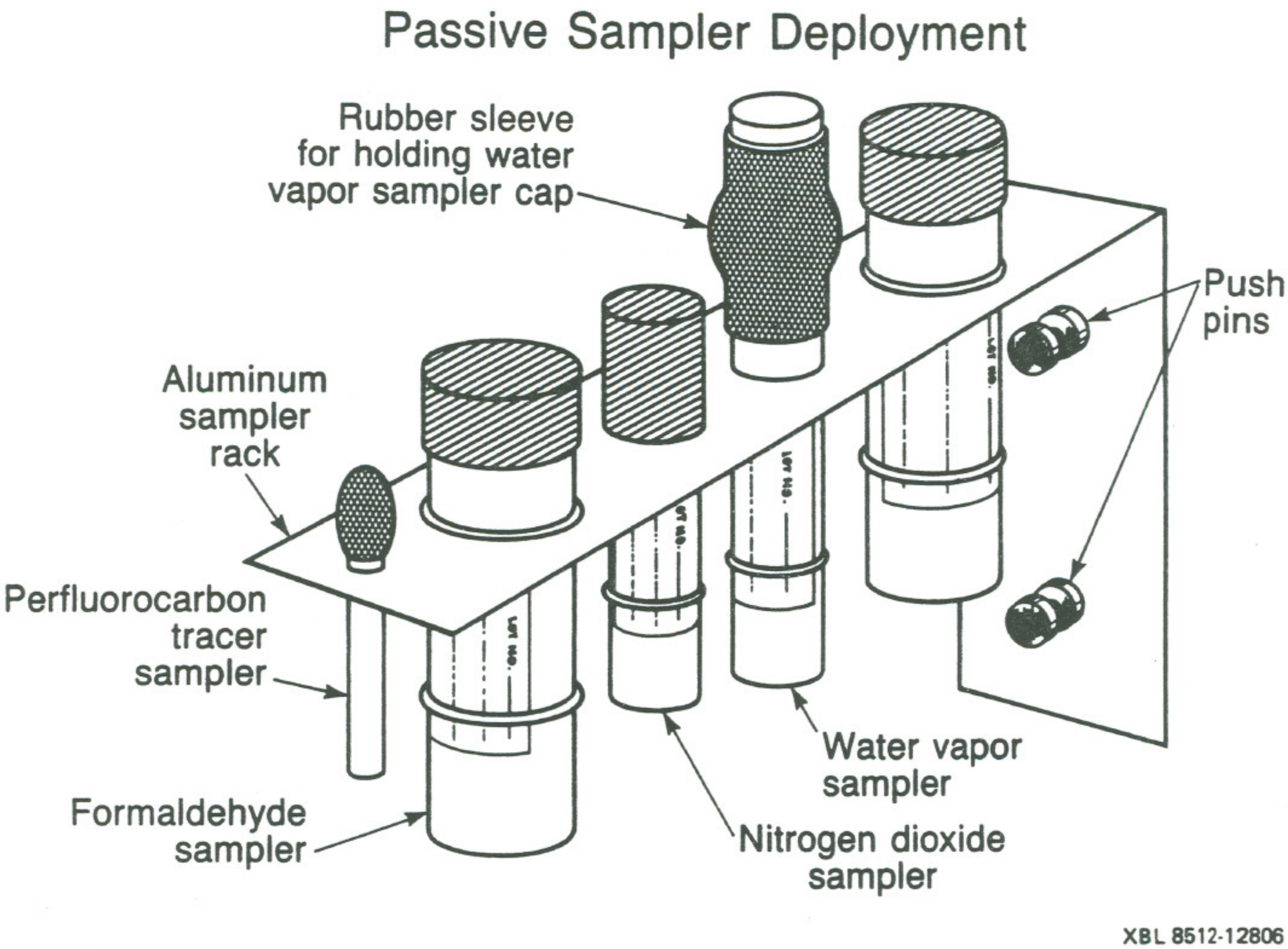

Figure 4.1 A sketch of the sample rack that was used to mount the passive samplers in a house.

designed and constructed at LBL for this application. The design follows the principles described in the papers of Busigin et al. (1979), Lucas (1957), and Thomas and Countess (1979).

The CRM measures environmental radon concentrations as a function of time. It is capable of measuring concentrations in the range from 0.2 to several hundred picocuries per liter (pCi/L), and, depending on the concentration and the mode of data analysis, can resolve the variation of radon with time into intervals as short as thirty minutes.

The diagram for air flow through the instrument is shown in Fig. 4.2. The sampled air passes first through a decay volume of about 900 ml, located under the lid of the CRM case. This volume delays the air flow in order to decrease interference from thoron, an alpha-emitting isotope of radon which is also present in indoor environments. Thoron has a half-life of less than one minute so this 1.5 to 2 minute delay is sufficient to prevent most of the thoron from being counted.

The sample stream is then filtered and drawn into a 100 ml scintillation cell. One end of this cell is a quartz window that is optically coupled to a photomultiplier tube. The inside of the remainder of the cell is coated with a zinc sulfide phosphor (ZnS(Ag)) that produces a flash of light when struck by an alpha particle. These light flashes are detected by the photomultiplier tube and counted by associated electronics.

If radon decays were the only source of counts, the count rate at any time would be proportional to the radon concentration in the cell. Unfortunately there are complications. Radon decays into a series of four, short-lived decay products, two of which also emit alpha particles. These decay products are not chemically inert like radon and those that are created within the cell may become attached to the cell walls. The alpha particles emitted by these decay products also contribute to the count rate, and since their characteristic decay time is about 30 minutes, there is a delay in the response of the CRM to a changing radon concentration that has a comparable time constant.

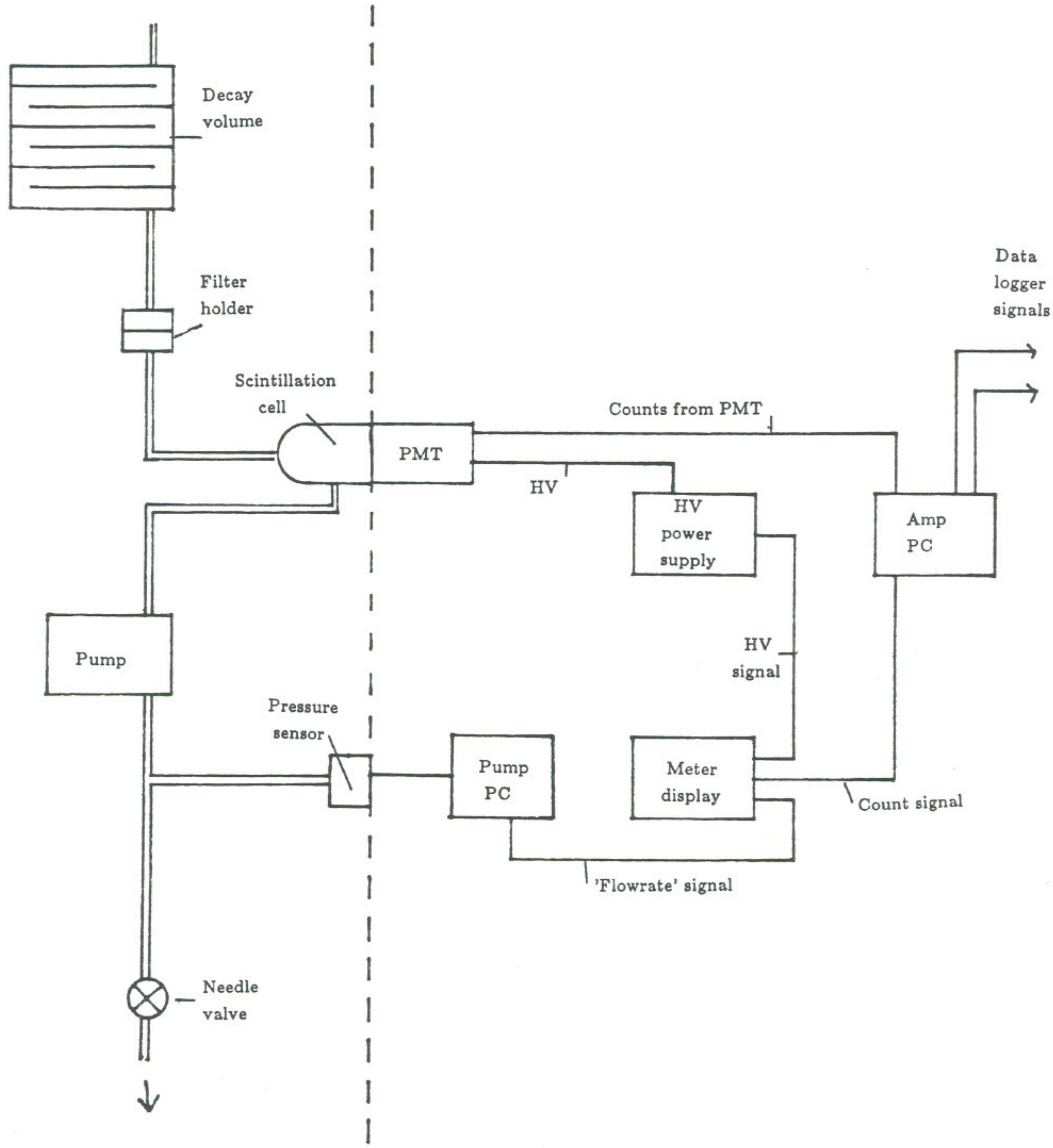

Figure 4.2 The air flow through the CRM follows the path to the left of the dashed line. A block diagram of the signal wiring is shown to the right of the line.

An additional lower limit on the length of the time interval used for analysis is imposed by the random nature of radioactive decay. The uncertainty (one standard deviation) in the observed decay rate is given by the square root of the number of counts observed. At low count rates this limitation becomes more important than the time lag caused by the decay products. For example, at a concentration of one pCi/L, approximately 25 counts per hour will be obtained. Therefore, the count rate will be uncertain by ± 20%.

Carbon monoxide sampler. The real-time carbon monoxide sensor that we had planned to use in the project (Interscan 5140) did not meet specifications in the performance tests that were conducted. Therefore, we substituted an automated grab-sample technique and installed these samplers in the houses during the period from 5 to 8 March, 1984. Thereafter, they collected weekly samples in each house.

Two samplers (one indoor, one outdoor) were installed at each house. The samplers consist of a 0.342-0.352 ml/min peristaltic pump which continuously pumped air into a five-liter Tedlar bag. After sampling the air in the house for a week, the sample was analyzed using a GE Model 15ECS3CO3 carbon monoxide detector (1 ppm sensitivity).

Ventilation Instrumentation

House leakage. The leakage that exists in the external structure of the house is measured using a blower door, a fan mounted in a frame that can be sealed into a doorway of the house. The blower door used in this project was constructed and calibrated at LBL. It consists of a variable-speed motor, a pressure gauge to measure the pressure across the exterior building walls caused by the operation of the fan and a tachometer to determine the fan speed (and therefore the flow rate through the fan).

The relationship between the flow through the fan and the pressure difference across the building shell describes the flow characteristic of the building. From this flow characteristic an "effective leakage area", a quantity roughly equivalent to the sum of the areas of all the openings in the exterior shell of the building through which the air is able to pass [Sherman and Grimsrud, 1980], is determined. The effective leakage area for each of the houses tested in the initial screening of the houses that were potential candidates for monitoring is given in Table A.1 in Appendix A.

Ventilation rates. Ventilation was measured using a perfluorocarbon tracer (PFT) gas system developed at Brookhaven National Laboratory [Dietz and Cote, 1982]. The system consists of a permeation tube source that emits a perfluorocarbon gas into the test space at a constant rate. In steady state, the concentration of tracer in the space is given by the ratio of source tracer gas emission rate and the removal rate, i.e., the ventilation. Since the emission rate is known, a measurement of tracer gas concentration enables a calculation of the ventilation.

The concentration in this system is measured using a technique employing the same physical principle as the pollutant passive samplers described above. In this case the diffusion tube sampler adsorbs air and the other gases it contains on a sorbent called Ampersorb™. The gases adsorbed on the Ampersorb are analyzed quantitatively using a gas chromatograph. While the technique is conceptually simple, in practice it is difficult to maintain high-quality gas chromatography standards when analyzing a large number of samples. Therefore, analysis results were produced very slowly.

Environmental Parameters

Dew point sensor. The dew point sensor used in the project was the General Eastern Model DEW-10 Chilled Mirror Hygrometer. The sensor consists of a light beam that is reflected from a mirror surface onto a phototransistor. The mirror is cooled thermoelectrically until condensation on the surface occurs. When condensation begins, a decrease in the reflected light signal is noted and the temperature of the surface of the mirror, which is measured continuously, is noted. The surface is warmed and then the cycle is repeated.

During use, a fine layer of dust begins to build up on the mirror, changing the calibration of the system. Therefore, the system mounted outdoors required cleaning every 1-2 weeks while the system mounted indoors was cleaned each 3-4 weeks.

Temperature sensors. Temperature sensors used for both indoor and outdoor measurements were Analog Devices AD590 sensors. These are current sources that supply an output current proportional to the absolute temperature. They are trimmed in manufacture to produce an output of 1μamp/K, which translates to 10 mV/°C when the current is driven through a 10 Kohm precision resistor. The sensor uses a +15V voltage source on the ESM; its resolution is 0.1°C in field use.

Wind speed and direction. Wind speed and direction was measured at each house using a Weather Measure W200-SD sensor located on a telescoping weather tower mounted at a 30 ft level adjacent to the test house. The anemometer is a 3-cup generator mounted vertically on a stainless steel shaft rotating on ball bearings and coupled to the permanent magnet of an AC generator. The AC generator produces a voltage proportional to the wind speed at the sensor.

The wind direction sensor is an airfoil vane mounted on an aluminum shaft that rotates to point into the wind direction. Attached to the vane is a wiper connected to a precision potentiometer that forms one leg of a voltage divider network. Application of a fixed DC voltage to the network produces an output voltage that is proportional to the wiper or vane position.

Energy use. Electrical power was measured using a Honeywell microswitch Hall Effect Device 91 SS12-2 that measures current. The device is powered by line voltage stepped down to the appropriate level. The output of the Hall Effect switching device is proportional to the product of the voltage and current and, therefore, to the electrical power.

Furnace operation was sensed using a photoresistor that formed one leg of a voltage divider. When the device was turned on, the output voltage from the voltage divider changed and was sensed by the ESM data logger. Gas water heater operation was sensed using a temperature sensor on the sensor on the domestic hot water flue.

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V. DATA SUMMARY

The results presented below are for the four houses using the LBL ventilation strategies only. A later paper will combine the LBL and Honeywell reports for a final summary.

Ventilation Results

Tables 5.1 - 5.4 present measured ventilation results from the four houses monitored by LBL (labeled L2, L4, L6, and L8). The tables each indicate the measurement interval by date, the ventilation mode used, the average ventilation measured using the PFT samplers (in air changes per hour (ach)), the coefficient of variation of the ventilation measurements*, the average wind speed, (m/s), measured at the site during the interval, and the average indoor-outdoor temperature difference (°C). In the column describing the ventilation mode the abbreviations Hx, Ex, and Infil refer to heat exchanger, exhaust fan, and infiltration respectively. The M or L in parentheses after Ex or Hx refers to the Medium or Low setting of the fans of the respective units. A dash in any entry indicates data collection occurred less than 50% of the hours in the interval.

Figure 5.1 is a composite of the ventilation rates measured in each of the four houses L2, L4, L6, and L8 during the project. The numbers on the abscissa for each of the four figures refer to the mid point of each test interval measured in days. Day one in this scheme is December 1, 1983. The labels on each of the bars refer to the ventilation scheme used in each interval; HX is the air-to-air Heat eXchanger, INF is the INFiltration mode, and EX is the EXhaust fan mode. Note that the ordinates of the four charts have different scales.

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* The coefficient of variation arises from averaging the tracer gas concentrations measured in different samplers present in each house.

Table 5.1

Ventilation Results from House L2

Date	Ventilation Mode(1)	PFT Results Measured Vent (ACH)(2)	PFT Results Coeff. of Variation	Avg. Wind (m/s)	Avg. ΔT(°C)
12.16-12.23.83	Hx(M)	1.86	11	2.8	29.9
12.23-12.30	Infil	1.42	16	3.1	26.8
12.30-1.09.84	Ex(L)	0.70	17	0.8	13.7
1.09-1.17	Infil	1.05	9	1.8	16.6
1.17-1.24	Hx(M)	0.95	9	-(2)	-
1.24-1.31	Ex(L)	1.08	37	-	-
1.31-2.07	Infil	1.20	17	1.5	13.5
2.07-2.14	Hx(M)	1.03	12	2.4	19.8
2.14-2.21	Ex(L)	0.96	14	1.2	13.4
2.21-2.28	Infil	1.00	15	-	-
2.28-3.06	Hx(M)	0.82	10	1.4	12.2
3.06-3.13	Ex(L)	0.99	15	1.3	13.4
3.13-3.20	Infil	1.17	16	2.0	14.2
3.20-3.27	Hx(M)	1.60	3	1.7	12.2
3.27-4.03	Ex(L)	1.92	-	1.1	13.7
4.03-4.10	Infil	1.92	13	1.5	15.1
4.10-4.17	Hx(M)	2.16	1	-	-

Notes: (1) Hx(M): Air to Air Heat Exchanger on Medium setting; infil: infiltration; Ex(L): Exhaust Fan on Low setting.

(2) A dash indicates data collection less than 50% of the hours in the interval.

Table 5.2

Ventilation Results from House L4

Date	Ventilation Mode(1)	PFT Results: Measured Vent (ACH)(2)	PFT Results: Coeff. of Variation	Avg. Wind (m/s)	Avg. ΔT(°C)
12.17-12.23.83	Infil	0.39	27	1.2	21.2
12.23-1.5.84	Infil	0.16	20	-(1)	-
1.5-1.12	Infil	0.21	24	0.4	7.5
1.12-1.19	Hx(L)	0.27	26	0.8	13.1
1.19-1.26	Ex(L)	0.27	26	2.0	2.2
1.26-2.2	Infil	0.23	21	0.6	3.5
2.2-2.9	Hx(L)	0.30	24	1.2	13.0
2.9-2.16	Ex(L)	0.27	28	1.5	11.4
2.16-2.23	Infil	0.24	32	0.8	12.3
2.23-3.1	Hx(L)	0.25	34	0.9	10.5
3.1-3.8	Ex(L)	0.25	31	0.8	9.1
3.8-3.15	Infil	0.21	28	1.0	9.4
3.15-3.22	Hx(L)	0.28	25	1.3	9.8
3.22-3.29	Ex(L)	0.33	26	1.1	9.5
3.29-4.5	Infil	0.29	34	-	-
4.5-4.12	Hx(L)	0.29	25	1.1	11.3
4.12-4.19	Ex(L)	0.30	26	0.8	7.8
4.19-4.26	Infil	0.30	27	1.1	11.2

(1) A dash (-) indicates data collection less than 50% of interval.

Table 5.3

Ventilation Results from House L6

Date	Ventilation Mode(1)	PFT Results: Measured Vent (ACH)(2)	PFT Results: Coeff. of Variation	Avg. Wind (m/s)	Avg. ΔT(°C)
12.17-12.23.83	Hx	0.46	18	3.5	19.7
12.23-12.30	Infil	0.42	22	3.8	18.0
12.30-1.10.84	Ex	0.24	22	-	-(1)
1.10-1.17	Infil	0.37	22	-	-
1.17-1.24	Hx	0.37	22	2.2	8.4
1.24-1.31	Ex	0.33	12	1.4	7.5
1.31-2.7	Infil	0.32	23	-	-
2.7-2.14	Hx	0.29	26	-	-
2.14-2.21	Ex	0.26	31	1.5	10.3
2.21-2.28	Infil	0.39	11	2.1	13.0
2.28-3.06	Hx	0.37	4	-	-
3.06-3.14	Ex	0.33	11	1.3	9.2
3.14-3.20	Infil	0.36	17	2.2	11.6
3.20-3.27	Hx	0.33	15	1.4	8.0
3.27-4.03	Ex	0.46	15	0.9	11.7
4.03-4.10	Infil	0.38	28	-	-
4.10-4.17	Hx	0.46	10	-	-
4.17-4.24	Ex	0.47	20	-	-

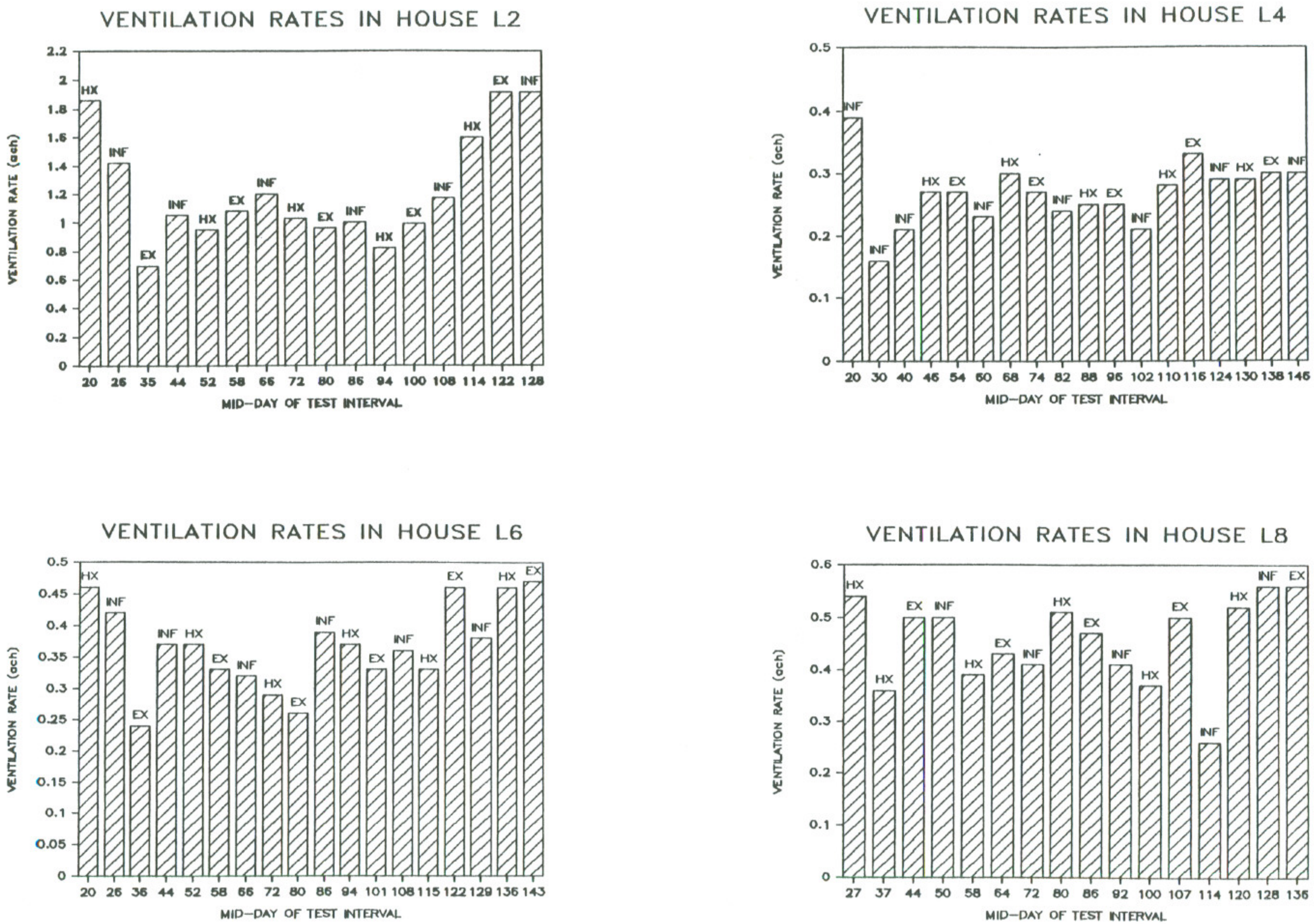
(1) A data dash indicates that data was logged less than 50% of interval

Table 5.4

Ventilation Results from House L8

Date	Ventilation Mode(1)	PFT Results: Measured Vent (ACH)(2)	PFT Results: Coeff. of Variation	Avg. Wind (m/s)	Avg. ΔT(°C)
12.20-1.3.84	Hx(M)	0.54	3	0.0	26.0
1.3-1.9	Hx(L)	0.36	6	0.2	13.3
1.9-1.16	Ex(L)	0.50	6	0.1	20.4
1.16-1.23	Infil	0.50	6	0.1	21.4
1.23-1.30	Hx(L)	0.39	7	0.1	12.9
1.30-2.6	Ex(L)	0.43	7	0.0	15.1
2.6-2.15	Infil	0.41	7	0.1	13.3
2.15-2.21	Hx(L)	0.51	1	0.0	15.4
2.21-2.27	Ex(L)	0.47	4	0.1	13.8
2.27-3.5	Infil	0.41	7	0.0	12.5
3.5-3.13	Hx(L)	0.37	10	1.8	10.6
3.13-3.19	Ex(L)	0.50	10	0.1	13.2
3.19-3.26	Infil	0.26	-	0.1	8.0
3.26-4.2	Hx(L)	0.52	11	0.1	11.0
4.2-4.9	Infil	0.56	-	0.1	12.7
4.9-4.13	Ex(L)	0.56	21	7.0	12.2

Figure 5.1


VENTILATION RATES IN HOUSE L2
VENTILATION RATE (ach)
MID-DAY OF TEST INTERVAL
20 26 35 44 52 58 66 72 80 86 94 100 108 114 122 128
VENTILATION RATES IN HOUSE L4
VENTILATION RATE (ach)
MID-DAY OF TEST INTERVAL
20 30 40 46 54 60 68 74 82 88 96 102 110 116 124 130 138 146
VENTILATION RATES IN HOUSE L6
VENTILATION RATE (ach)
MID-DAY OF TEST INTERVAL
20 26 36 44 52 58 66 72 80 86 94 101 108 115 122 129 136 143
VENTILATION RATES IN HOUSE L8
VENTILATION RATE (ach)
MID-DAY OF TEST INTERVAL
27 37 44 50 58 64 72 80 86 92 100 107 114 120 128 136

Pollutant Concentrations

Summaries of measured values of pollutant concentrations are presented in Tables 5.5-5.12. Tables 5.5 through 5.8 present data of measurement, ventilation mode, average indoor and outdoor formaldehyde concentrations (ppb), and average and outdoor nitrogen dioxide concentrations (ppb).

Table 5.9 through 5.12 present date of measurement, ventilation mode, average indoor and outdoor water vapor concentration (g/kg), average indoor and outdoor concentration of respirable suspended particles ($\mu g/m^3$), and average radon concentration (pCi/L).

Figures 5.2 and 5.3 represent composites of the indoor and outdoor formaldehyde and nitrogen dioxide concentrations in the LBL test houses. The numbers on the abscissa for each figure refer tot he mid point of each test interval measured in days. Day one in this scheme is December 1, 1983. Indoor concentrations of formaldehyde are clearly higher than outdoor; the opposite is the case for nitrogen dioxide concentrations. This is discussed further in chapter VI.

Figures 5.4 and 5.5 represent composites of the indoor and outdoor concentrations of water vapor and respirable suspended particles. Water vapor concentration is measured in units of grams H_2 per kilogram dry air using a passive sampler; respirable particle concentrations are given in micrograms per cubic meter of air. In each house, the water vapor concentration tracks the outdoor concentration but is slightly higher indicating the presence of an indoor source; the RSP figures are more complex. These are discussed in detail in chapter VI.

Table 5.5

Pollutant Concentrations in L2

Date	Vent Mode	HCHO (ppb) in	HCHO (ppb) out	NO_2 (ppb) in	NO_2 (ppb) out
12.16-12.23.83	Hx(M)	21	11	2	8
12.23-12.30	Infil	22	6	6	12
12.30-1.9.84	Ex(L)	54	10	6	20
1.9-1.17	Infil	22	0	4	17
1.17-1.24	Hx(M)	30	11	3	10
1.24-1.31	Ex(L)	34	6	3	15
1.31-2.7	Infil	-	-	9	24
2.7-2.14	Hx(M)	32	5	8	15
2.14-2.21	Ex(L)	35	11	8	20
2.21-2.28	Infil	31	11	6	16
2.28-3.6	Hx(M)	45	7	9	21
3.6-3.13	Ex(L)	37	7	8	26
3.13-3.20	Infil	42	4	8	18
3.20-3.27	Hx(M)	36	3	5	15
3.27-4.3	Ex(L)	36	10	6	17
4.3-4.10	Infil	29	7	6	18
4.10-4.17	Hx(M)	34	9	6	14
4.17-4.24	Ex(L)	37	15	7	14

Table 5.6

Pollutant Concentrations in L4

Date	Vent Mode	HCHO (ppb) in	HCHO (ppb) out	NO_2 (ppb) in	NO_2 (ppb) out
12.17-12.23.83	Infil	49	2	3	2
12.23-1.5.84	Infil	59	1	5	5
1.5-1.12	Infil	56	0	6	7
1.12-1.19	Hx(L)	72	1	5	6
1.19-1.26	Ex(L)	87	5	5	4
1.26-2.2	Infil	88	9	4	8
2.2-2.9	Hx(L)	-	-	11	13
2.9-2.16	Ex(L)	102	1	9	7
2.16-2.23	Infil	100	5	8	9
2.23-3.1	Hx(L)	89	5	8	6
3.1-3.8	Ex(L)	92	2	8	13
3.8-3.15	Infil	99	4	6	7
3.15-3.22	Hx(L)	129	9	9	7
3.22-3.29	Ex(L)	110	3	5	7
3.29-4.5	Infil	85	5	6	9
4.5-4.12	Hx(L)	104	2	7	3
4.12-4.19	Ex(L)	100	6	4	2
4.19-4.26	Infil	110	15	6	7

Table 5.7

Pollutant Concentrations in L6

Date	Vent Mode	HCHO (ppb) in	HCHO (ppb) out	NO_2 (ppb) in	NO_2 (ppb) out
12.17-12.23.83	Hx(M)	7	6	2	12
12.23-12.30	Infil	8	1	7	13
12.30-1.10.84	Ex(L)	28	7	6	22
1.10-1.17	Infil	16	1	5	18
1.17-1.24	Hx(M)	17	7	9	12
1.24-1.31	Ex(L)	20	10	6	21
1.31-2.7	Infil	-	-	12	26
2.7-2.14	Hx(M)	19	9	10	17
2.14-2.21	Ex(L)	22	9	8	24
2.21-2.28	Infil	17	5	9	20
2.28-3.6	Hx(M)	18	10	12	24
3.6-3.14	Ex(L)	16	9	11	27
3.14-3.20	Infil	26	6	9	21
3.20-3.27	Hx(M)	21	6	7	19
3.27-4.3	Ex(L)	18	10	8	22
4.3-4.10	Infil	18	1	7	21
4.10-4.17	Hx(M)	32	5	5	17
4.17-4.24	Ex(L)	28	12	6	15

Table 5.8

Pollutant Concentrations in L8

Date	Vent Mode	HCHO (ppb) in	HCHO (ppb) out	NO_2 (ppb) in	NO_2 (ppb) out
12.20-1.3.84	Hx(M)	68	2	1	7
1.3-1.9	Hx(L)	95	5	3	7
1.9-1.16	Ex(L)	73	5	1	8
1.16-1.23	Infil	64	6	1	9
1.23-1.30	Hx(L)	78	0	1	7
1.30-2.6	Ex(L)	-	-	5	12
2.6-2.15	Infil	95	2	4	9
2.15-2.21	Hx(L)	78	7	5	11
2.21-2.27	Ex(L)	68	5	5	8
2.27-3.5	Infil	104	3	4	9
3.5-3.13	Hx(L)	77	3	5	9
3.13-3.19	Ex(L)	103	4	5	8
3.19-3.26	Infil	92	3	1	6
3.26-4.2	Hx(L)	90	1	1	3
4.2-4.9	Infil	87	4	1	4
4.9-4.13	Ex(L)	110	29	1	3

Figure 5.2

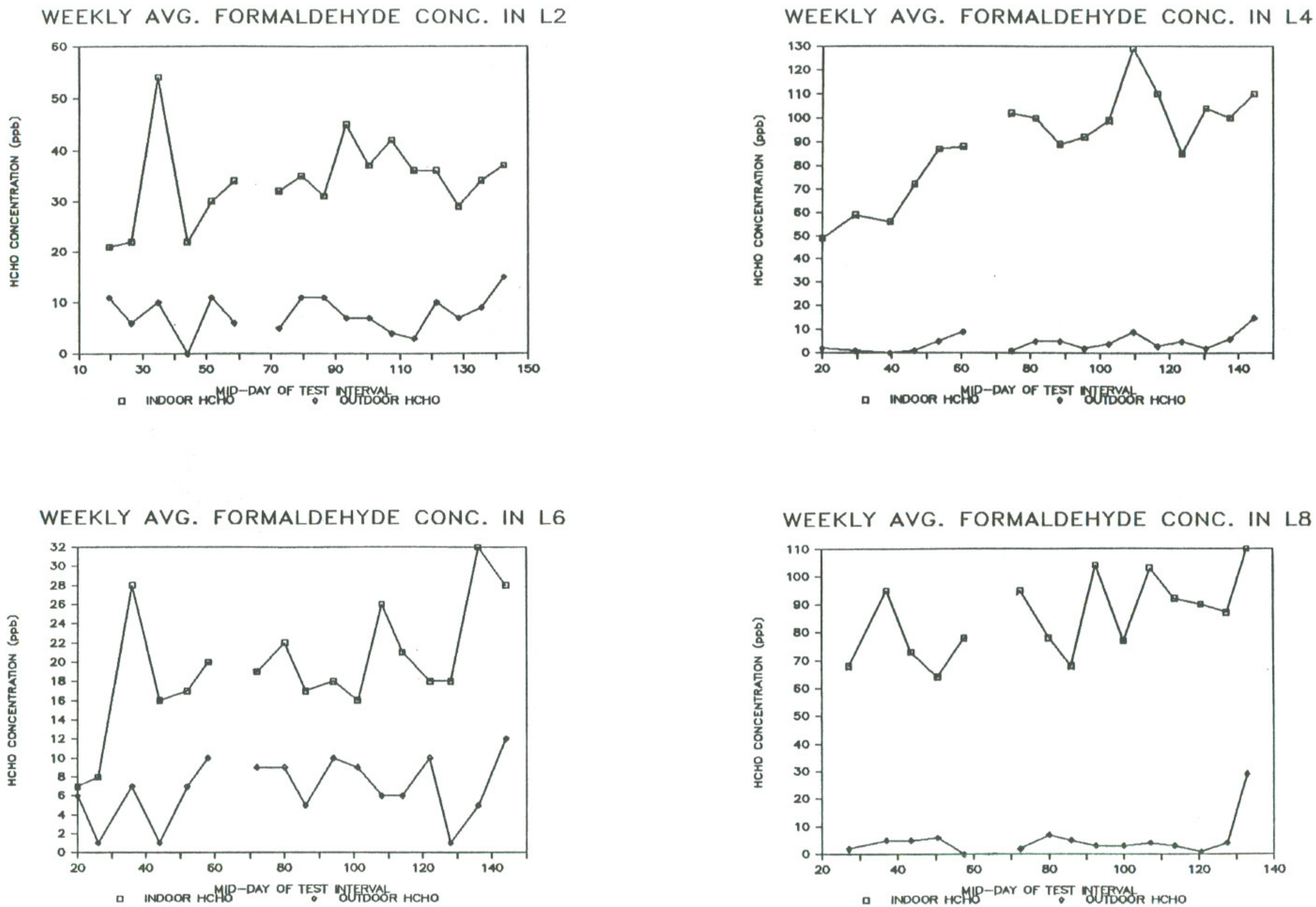

WEEKLY AVG. FORMALDEHYDE CONC. IN L2
WEEKLY AVG. FORMALDEHYDE CONC. IN L4
WEEKLY AVG. FORMALDEHYDE CONC. IN L6
WEEKLY AVG. FORMALDEHYDE CONC. IN L8
HCHO CONCENTRATION (ppb)
MID-DAY OF TEST INTERVAL
INDOOR HCHO
OUTDOOR HCHO

Figure 5.3

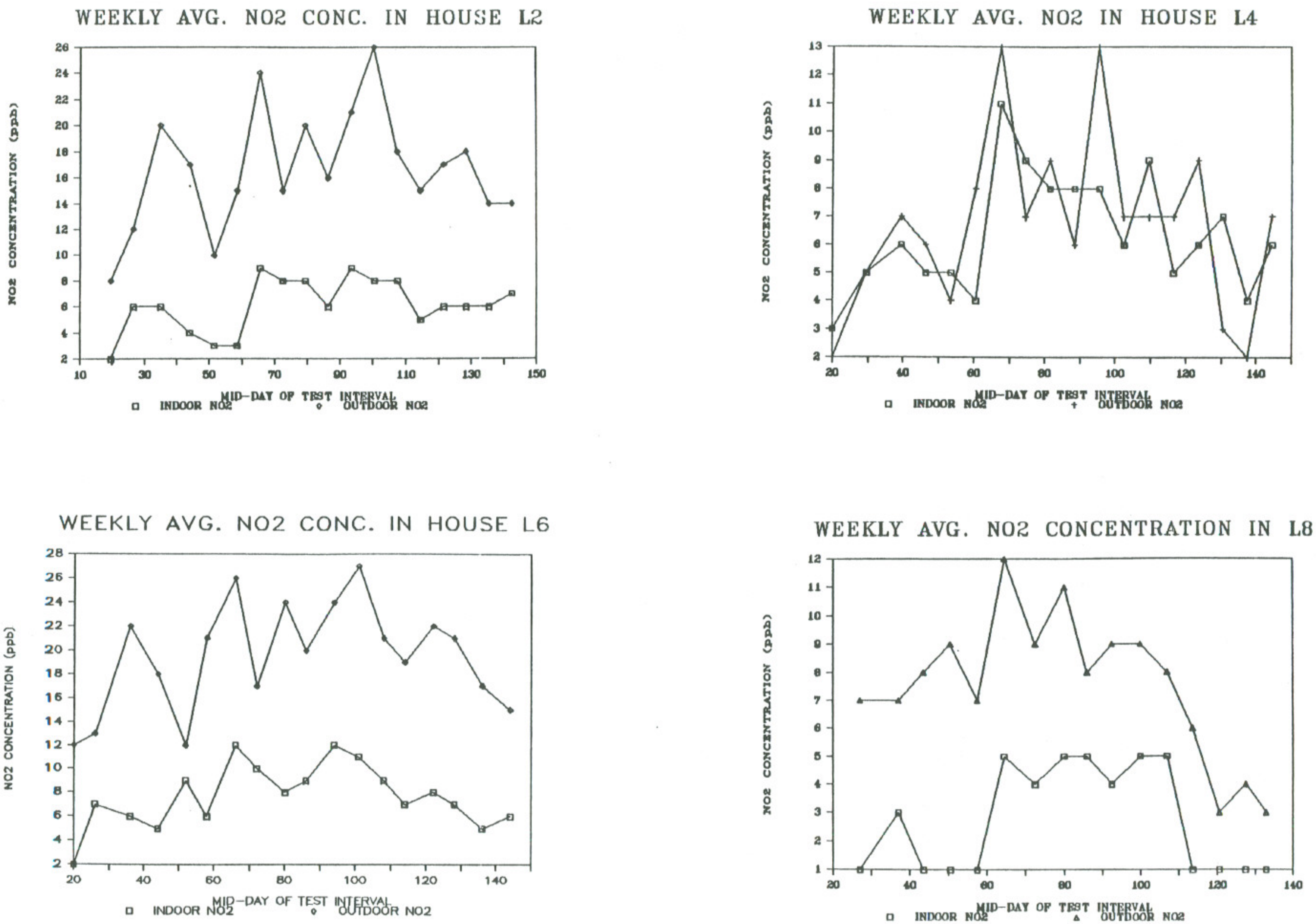

WEEKLY AVG. NO2 CONC. IN HOUSE L2
NO2 CONCENTRATION (ppb)
MID-DAY OF TEST INTERVAL
INDOOR NO2
OUTDOOR NO2
WEEKLY AVG. NO2 IN HOUSE L4
NO2 CONCENTRATION (ppb)
MID-DAY OF TEST INTERVAL
INDOOR NO2
OUTDOOR NO2
WEEKLY AVG. NO2 CONC. IN HOUSE L6
NO2 CONCENTRATION (ppb)
MID-DAY OF TEST INTERVAL
INDOOR NO2
OUTDOOR NO2
WEEKLY AVG. NO2 CONCENTRATION IN L8
NO2 CONCENTRATION (ppb)
MID-DAY OF TEST INTERVAL
INDOOR NO2
OUTDOOR NO2

Table 5.9

Pollutant Concentrations in L2

Date	Vent Mode	H_2O (g/kg) in	H_2O (g/kg) out	Particles $\mu g/m^3$ in	Particles $\mu g/m^3$ out	Radon Concent. (pCi/L)
12.16-12.23.83	Hx(M)	4.43	2.40	34.81	4.89	4.4 ± 1.0
12.23-12.30	Infil	4.65	3.05	29.84	26.60	4.5 ± 1.1
12.30-1.9.84	Ex(L)	6.54	6.26	40.45	22.80	5.6 ± 1.3
1.9-1.17	Infil	5.47	3.76	27.83	25.46	--
1.17-1.24	Hx(M)	4.81	4.55	21.97	26.14	--
1.24-1.31	Ex(L)	6.55	6.13	28.44	25.73	--
1.31-2.7	Infil	5.93	4.66	28.44	43.53	6.3 ± 1.1
2.7-2.14	Hx(M)	6.35	6.05	17.43	13.71	5.2 ± 1.4
2.14-2.21	Ex(L)	6.16	4.91	34.63	31.89	6.5 ± 1.2
2.21-2.28	Infil	6.20	5.01	33.02	19.41	--
2.28-3.6	Hx(M)	6.32	5.11	29.58	28.87	5.5 ± 1.1
3.6-3.13	Ex(L)	7.02	6.33	34.90	34.94	6.4 ± 1.4
3.13-3.20	Infil	7.02	6.92	36.15	13.48	5.6 ± 1.2
3.20-3.27	Hx(M)	6.49	6.34	14.18	18.02	5.4 ± 1.1
3.27-4.3	Ex(L)	6.63	5.46	27.22	21.19	--
4.3-4.10	Infil	6.74	5.92	32.12	16.80	--
4.10-4.17	Hx(M)	6.46	6.05	16.61	12.07	--
4.17-4.24	Ex(L)	6.28	5.92	21.30	13.35	--

Table 5.10

Pollutant Concentrations in L4

Date	Vent Mode	H_2O (g/kg) in	H_2O (g/kg) out	Particles $\mu g/m^3$ in	Particles $\mu g/m^3$ out	Radon Concent. (pCi/L)
12.17-12.23.83	Infil	5.01	2.11	18.34	12.89	0.6 ± 0.5
12.23-1.5.84	Infil	4.85	4.56	16.31	16.37	--
1.5-1.12	Infil	6.96	5.59	17.02	12.53	0.9 ± 0.5
1.12-1.19	Hx(L)	5.20	2.62	15.94	11.07	--
1.19-1.26	Ex(L)	6.00	5.68	14.91	11.69	--
1.26-2.2	Infil	6.95	5.31	17.07	13.53	0.8 ± 0.6
2.2-2.9	Hx(L)	6.31	4.82	17.40	0.17	1.0 ± 0.7
2.9-2.16	Ex(L)	6.78	5.69	21.77	5.05	1.0 ± 0.8
2.16-2.23	Infil	6.76	5.01	11.65	7.55	0.9 ± 0.5
2.23-3.1	Hx(L)	6.69	4.97	10.89	6.49	0.9 ± 0.6
3.1-3.8	Ex(L)	6.66	4.90	14.07	--	0.9 ± 0.5
3.8-3.15	Infil	7.05	6.19	10.86	--	0.8 ± 0.4
3.15-3.22	Hx(L)	7.40	6.31	12.84	4.96	0.8 ± 0.5
3.22-3.29	Ex(L)	7.18	5.50	11.42	8.20	0.9 ± 0.5
3.29-4.5	Infil	7.14	5.56	10.86	12.12	--
4.5-4.12	Hx(L)	7.21	5.52	10.16	6.46	--
4.12-4.19	Ex(L)	7.21	5.72	11.23	7.14	--
4.19-4.26	Infil	7.11	5.28	9.84	--	--

Table 5.11

Pollutant Concentrations in L6

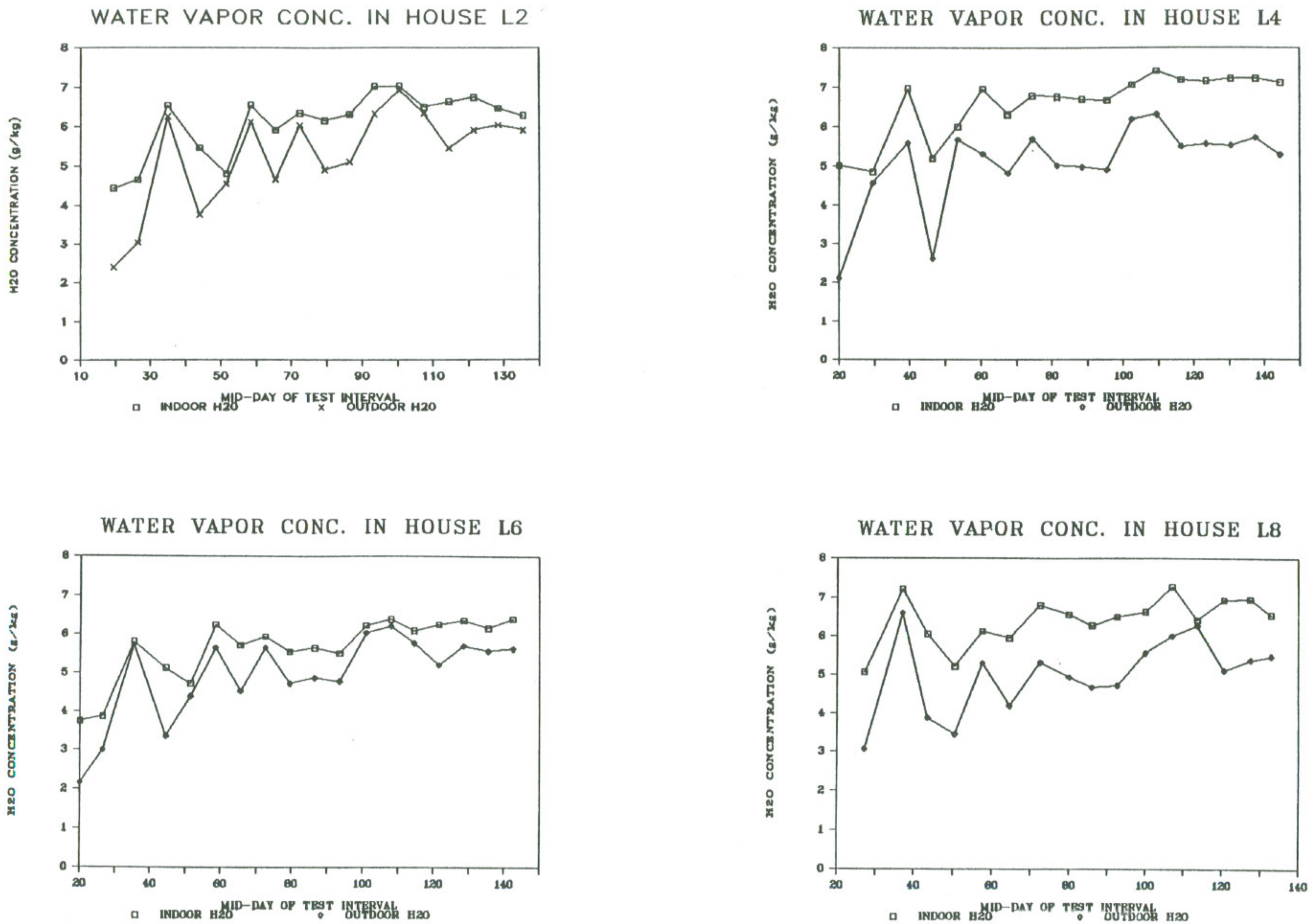
Date	Vent Mode	H_2O (g/kg) in	H_2O (g/kg) out	Particles $\mu g/m^3$ in	Particles $\mu g/m^3$ out	Radon Concent. (pCi/L)
12.17-12.23.83	Hx(M)	3.74	2.16	8.89	16.05	2.2 ± 1.5
12.23-12.30	Infil	3.86	3.01	12.30	18.47	1.9 ± 1.2
12.30-1.10.84	Ex(L)	5.81	5.74	33.23	29.54	--
1.10-1.17	Infil	5.13	3.36	22.58	21.39	--
1.17-1.24	Hx(M)	4.72	4.39	14.00	16.50	--
1.24-1.31	Ex(L)	6.25	5.66	19.11	20.75	2.3 ± 0.7
1.31-2.7	Infil	5.72	4.53	16.46	28.63	--
2.7-2.14	Hx(M)	5.94	5.66	10.01	8.29	--
2.14-2.21	Ex(L)	5.55	4.73	14.07	19.10	2.4 ± 1.0
2.21-2.28	Infil	5.65	4.87	9.70	10.83	2.5 ± 1.3
2.28-3.6	Hx(M)	5.51	4.78	15.00	20.91	--
3.6-3.14	Ex(L)	6.23	6.05	20.30	21.71	1.5 ± 0.7
3.14-3.20	Infil	6.39	6.22	12.12	10.50	1.6 ± 0.8
3.20-3.27	Hx(M)	6.10	5.77	10.21	11.87	1.4 ± 0.8
3.27-4.3	Ex(L)	6.25	5.21	14.65	15.94	1.9 ± 0.9
4.3-4.10	Infil	6.36	5.70	10.96	12.10	--
4.10-4.17	Hx(M)	6.16	5.57	10.22	10.13	--
4.17-4.24	Ex(L)	6.40	5.63	14.19	10.35	--

Table 5.12

Pollutant Concentrations in L8

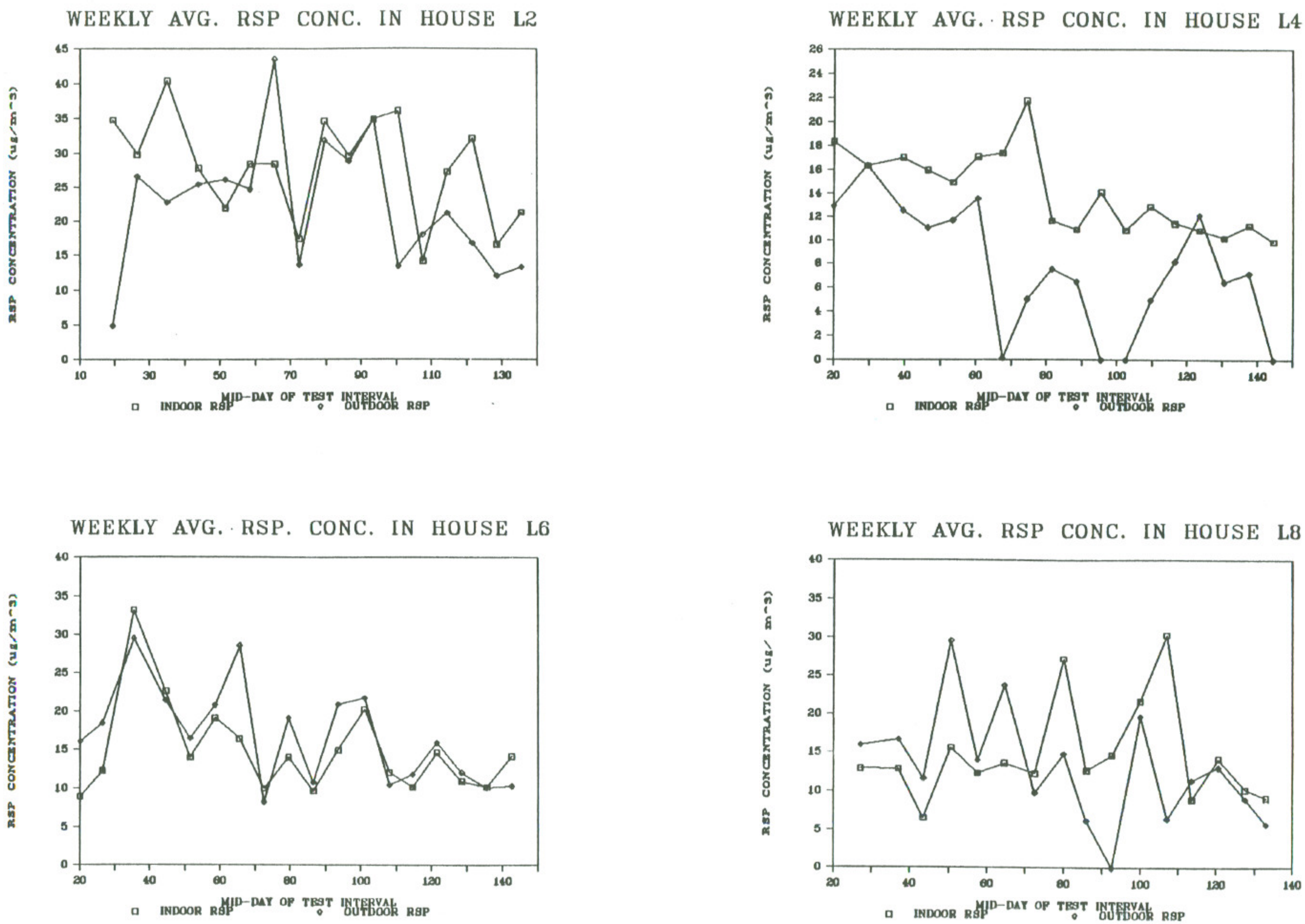
Date	Vent Mode	H_2O (g/kg) in	H_2O (g/kg) out	Particles $\mu g/m^3$ in	Particles $\mu g/m^3$ out	Radon Concent. (pCi/L)
12.20-1.3.84	Hx(L)	5.07	3.08	12.95	15.97	0.2 ± 0.6
1.3-1.9	Hx(L)	7.21	6.60	12.91	16.69	0.4 ± 0.5
1.9-1.16	Ex(L)	6.06	3.88	6.51	11.66	--
1.16-1.23	Infil	5.22	3.45	15.67	29.58	--
1.23-1.30	Hx(L)	6.13	5.31	12.38	13.99	0.2 ± 0.6
1.30-2.6	Ex(L)	5.96	4.19	13.64	23.72	0.7 ± 0.6
2.6-2.15	Infil	6.80	5.32	12.31	9.85	0.6 ± 0.7
2.15-2.21	Hx(L)	6.56	4.94	27.29	14.82	0.7 ± 1.0
2.21-2.27	Ex(L)	6.28	4.67	12.70	6.18	0.6 ± 0.7
2.27-3.5	Infil	6.50	4.72	14.65	--	0.7 ± 0.7
3.5-3.13	Hx(L)	6.63	5.57	21.69	19.61	0.8 ± 0.8
3.13-3.19	Ex(L)	7.27	6.01	30.33	6.45	--
3.19-3.26	Infil	6.42	6.28	8.93	11.38	0.7 ± 0.9
3.26-4.2	Hx(L)	6.93	5.11	14.13	13.05	0.7 ± 0.8
4.2-4.9	Infil	6.95	5.38	10.18	8.99	0.6 ± 0.8
4.9-4.13	Ex(L)	6.55	5.48	9.10	5.68	0.2 ± 0.6

Figure 5.4



WATER VAPOR CONC. IN HOUSE L2
H2O CONCENTRATION (g/kg)
MID-DAY OF TEST INTERVAL
INDOOR H2O
OUTDOOR H2O
WATER VAPOR CONC. IN HOUSE L4
H2O CONCENTRATION (g/kg)
MID-DAY OF TEST INTERVAL
INDOOR H2O
OUTDOOR H2O
WATER VAPOR CONC. IN HOUSE L6
H2O CONCENTRATION (g/kg)
MID-DAY OF TEST INTERVAL
INDOOR H2O
OUTDOOR H2O
WATER VAPOR CONC. IN HOUSE L8
H2O CONCENTRATION (g/kg)
MID-DAY OF TEST INTERVAL
INDOOR H2O
OUTDOOR H2O

Figure 5.5


WEEKLY AVG. RSP CONC. IN HOUSE L2
RSP CONCENTRATION (ug/m^3)
MID-DAY OF TEST INTERVAL
INDOOR RSP
OUTDOOR RSP
WEEKLY AVG. RSP CONC. IN HOUSE L4
RSP CONCENTRATION (ug/m^3)
MID-DAY OF TEST INTERVAL
INDOOR RSP
OUTDOOR RSP
WEEKLY AVG. RSP. CONC. IN HOUSE L6
RSP CONCENTRATION (ug/m^3)
MID-DAY OF TEST INTERVAL
INDOOR RSP
OUTDOOR RSP
WEEKLY AVG. RSP CONC. IN HOUSE L8
RSP CONCENTRATION (ug/ m^3)
MID-DAY OF TEST INTERVAL
INDOOR RSP
OUTDOOR RSP

VI. DATA INTERPRETATION

Ventilation

Tables 5.1 through 5.4 and Figure 5.1 present values of ventilation measured in each house associated with different ventilation modes. In order to determine the effects of the excess ventilation on pollutant concentrations we must assess the amount of ventilation supplied by the heat exchanger and exhaust fan in each house. However, before that is done the infiltration component of the ventilation must be determined.

Determination of Infiltration. The infiltration component of the total ventilation can be computed from information about the house that is under test, and the average weather conditions during the test [Sherman and Grimsrud, 1980].

The infiltration rate calculation procedure was coded by Bruce Dickinson in mBASIC and modified for this application by Brad Turk and Rich Prill. A complete listing of the program is included in Appendix D.

An important feature of this program is its explicit treatment of occupancy effects that contribute to the ventilation of a house. The user is asked by the program to type in general house descriptors and environmental conditions. The program then calculates the baseline infiltration for the house. However, additional information is known about the house that also must be added to improve the calculation. For example, daily homeowner logs (described in Appendix B) give information about kitchen and bathroom exhaust fan use, clothes dryer use, woodstove use, etc., on a daily basis. This information is summarized on a weekly basis and is entered into the program.

Each device that affects the ventilation rate of the house is sorted into one of two categories depending on its effect on the building pressure distribution. The flows associated with unbalanced ventilation systems (exhaust fans, fireplaces, etc.) are added together to form Q_U and are added to the infiltration Q_I in quadrature. The flows from balanced systems are added to the resulting flow from infiltration directly.

That is

$$Q_T = [Q_I^2 + Q_U^2]^{1/2} + Q_B \tag{6.1}$$

where

Q_T = the total ventilation

Q_I = the ventilation supplied by infiltration

Q_U = the ventilation supplied by unbalanced flows

Q_B = the ventilation supplied by balanced flows.

In addition, each device contributes leakage area to the shell of the house. If the device was sealed when the original leakage area of the house was measured, the leakage area associated with the device is added to the measured leakage area of the house to obtain the total leakage area of the house.

There is an uncertainty of approximately 25% in applying the model to any particular house [Sherman et al., 1982]. However, in this set of measurements it is possible to "tune" the model to the house and track changes in ventilation caused by changes in weather conditions.

Every third week the mechanical systems were turned off leaving infiltration as the only source of ventilation for the house. When we calculate the infiltration expected during those periods and compare it to the ventilation measured using the PFT samplers we can determine a correction factor that can be applied to all other calculations of infiltration. This procedure makes the assumption that differences between the measured infiltration (obtained when the mechanical ventilation systems are turned off) and the calculated infiltration is due to errors inherent in the calculation procedure. In fact, there are errors associated with both procedures; this method of adjusting the calculation to the measurement has been chosen to provide a well-defined procedure for interpretation of results.

Table 6.1 presents the values of the measured and calculated infiltration from houses L2-L8, the ratio of measured to predicted infiltration and the mean ratio for each house.

Table 6.1

Predicted and Calculated Infiltration Values for Each House

House L2

Date	Measured Infiltration (ach)	Calculated Infiltration (ach)	Ratio (M/C)	Average M/C
12.23 →	1.42	0.83	1.71	
1.31 →	1.20	0.53	2.26	2.00 ± 0.28
3.13 →	1.17	0.58	2.02	

House L4

Date	Measured Infiltration (ach)	Calculated Infiltration (ach)	Ratio (M/C)	Average M/C
12.17 →	0.39	0.48	0.81	
1.05 →	0.21	0.29	0.72	
1.26 →	0.23	0.20	1.15	
2.16 →	0.24	0.36	0.67	0.80 ± 0.19
3.08 →	0.21	0.33	0.64	
4.19 →	0.30	0.36	0.83	

House L6

Date	Measured Infiltration (ach)	Calculated Infiltration (ach)	Ratio (M/C)	Average M/C
12.23 →	0.42	0.65	0.65	
2.21 →	0.39	0.47	0.83	0.77 ± 0.10
3.14 →	0.36	0.44	0.82	

House L8

Date	Measured Infiltration (ach)	Calculated Infiltration (ach)	Ratio (M/C)	Average M/C
2.06 →	0.41	0.44	0.93	
2.27 →	0.41	0.47	0.87	0.99 ± 0.21
3.19 →	0.26	0.31	0.84	
4.02 →	0.56	0.43	1.30	

Measured and predicted mechanical ventilation. The measured ventilation during times when the exhaust fan or heat exchanger used in this project operation is composed of two terms -- the mechanical ventilation and the infiltration. Therefore, the mechanical ventilation term can only be determined if the infiltration portion of the total ventilation can be subtracted from the total.

In the case of a balanced ventilation system this procedure is straightforward. The ventilation from the heat exchanger simply adds to the ventilation supplied by infiltration. For house L2 having a volume of 9520 ft^3, the heat exchanger operating at its medium setting (50 cfm) is expected to add

$$Q_{hx} = \frac{(50 \times 60)}{9520} = 0.32 \text{ ach} \quad (6.2)$$

to the ventilation of the house. This assumes that the ventilation efficiency of the heat exchanger in supplying air to the house is 100%. Previous laboratory evaluations of these devices suggest that the actual value is likely to be lower than this [Offermann et al., 1983]. We have used an estimate of 0.6 as a ventilation efficiency for these heat exchangers. This lowers the expected added ventilation in house L2 to 0.19 ach.

The contribution to the other houses is given in Table 6.2.

Table 6.2

Ventilation Expected from Heat Exchangers

House	Volume (ft^3)	HX Ventilation (ach)
L2	9520	0.19
L4	18000	0.05
L6	23400	0.08
L8	15400	0.07

In the case of the exhaust fan system, the added ventilation expected is more difficult to predict since an exhaust system provides unbalanced flow. This means that the ventilation supplied by the infiltration and that supplied by the exhaust fan add in quadrature [Sherman and Grimsrud, 1982]. Therefore the net added ventilation supplied by the exhaust fans depends on the amount of infiltration that is present. Using the infiltration model that was described above, the total ventilation predicted during weeks when the exhaust fan was in operation was computed. A second calculation for the same period included all occupant contributions but did not include the exhaust fan. Table 6.3 summarizes the differences in these two calculations in the column labeled "Net Ventilation Supplied".

Table 6.3

Contribution to Ventilation from Exhaust Fan (Expected)

House	Fan Size (cfm)	Gross Ventilation Supplied (ach)	Net Ventilation Supplied (ach)
L2	27	0.17	0.06
L4	27	0.09	0.03
L6	27	0.07	0.01
L8	27	0.11	0.03

The column headed "Gross Ventilation Supplied" refers to the amount that would be supplied if ventilation from the exhaust fan were simply additive. The net ventilation supplied is the result that is obtained when the gross value is combined with the predicted infiltration.

Observed mechanical ventilation. Tables 6.2 and 6.3 present the net ventilation expected from the heat exchanger and the exhaust fan respectively. What was actually observed? To answer this we must separate the infiltration component of the ventilation from the total ventilation measured. This is done by computing the predicted infiltration for the weeks when the mechanical ventilation systems were in operation (including average weather conditions and occupant influences for those particular weeks), adjusting the values of the predictions using the "tuning" factors given in Table 6.1, and subtracting from the measured total ventilation for each house and week. The results for houses L2 through L8 are summarized in Table 6.4.

Table 6.4

Infiltration Contribution to Mechanical Ventilation

Date Test Began	Predicted Infiltration (ach)	Adjusted Infiltration (ach)	Measured Ventilation (ach)	Difference (ach)
		House L2 - Heat Exchanger Mode		
12.16.83	0.85	1.70	1.86	0.16
2.07.84	0.59	1.18	1.03	-0.15
2.28	0.51	1.02	0.82	-0.20
3.20	0.52	1.04	1.60	0.56
		House L2 - Exhaust Fan Mode		
12.30.83	0.51	1.02	0.70	-0.32
2.14.84	0.51	1.02	0.96	-0.06
3.06	0.52	1.04	0.99	-0.05
		House L4 - Heat Exchanger Mode		
2.02.84	0.38	0.30	0.30	0.00
2.23	0.35	0.28	0.25	-0.03
3.15	0.36	0.29	0.28	-0.01
4.05	0.37	0.30	0.29	-0.01
		House L4 - Exhaust Fan Mode		
2.09.84	0.37	0.30	0.27	-0.03
3.01	0.32	0.26	0.25	-0.01
3.22	0.34	0.27	0.33	0.06
4.12	0.30	0.24	0.30	+0.06

Table 6.4 continued

House L6 - Heat Exchanger Mode

Date Test Began	Predicted Infiltration (ach)	Adjusted Infiltration (ach)	Measured Ventilation (ach)	Difference (ach)
12.17.83	0.63	0.49	0.46	-0.03
3.20.84	0.40	0.31	0.33	0.02

House L6 - Exhaust Fan Mode

1.24.84	0.35	0.27	0.33	0.06
2.14	0.38	0.29	0.26	-0.03
3.06	0.37	0.28	0.33	0.05
3.27	0.41	0.32	0.46	0.14

House L8 - Heat Exchanger Mode

12.20.83	0.67	0.66	0.54	-0.12
1.03.84	0.51	0.50	0.36	-0.14
1.23	0.44	0.44	0.39	-0.05
2.15	0.49	0.49	0.51	+0.02
3.05	0.43	0.43	0.37	-0.06
3.26	0.45	0.45	0.52	0.07

House L8 - Exhaust Fan Mode

1.30.84	0.40	0.40	0.43	0.03
2.21	0.44	0.44	0.47	0.03
3.12	0.45	0.45	0.50	0.05
4.09	0.43	0.43	0.56	0.13

Table 6.5 and Figure 6.1 summarize the measured values of additional ventilation supplied by the heat exchanger and exhaust fan from the four houses. The 90% confidence interval for the measurements is obtained assuming a t-distribution for the number of samples in each test.

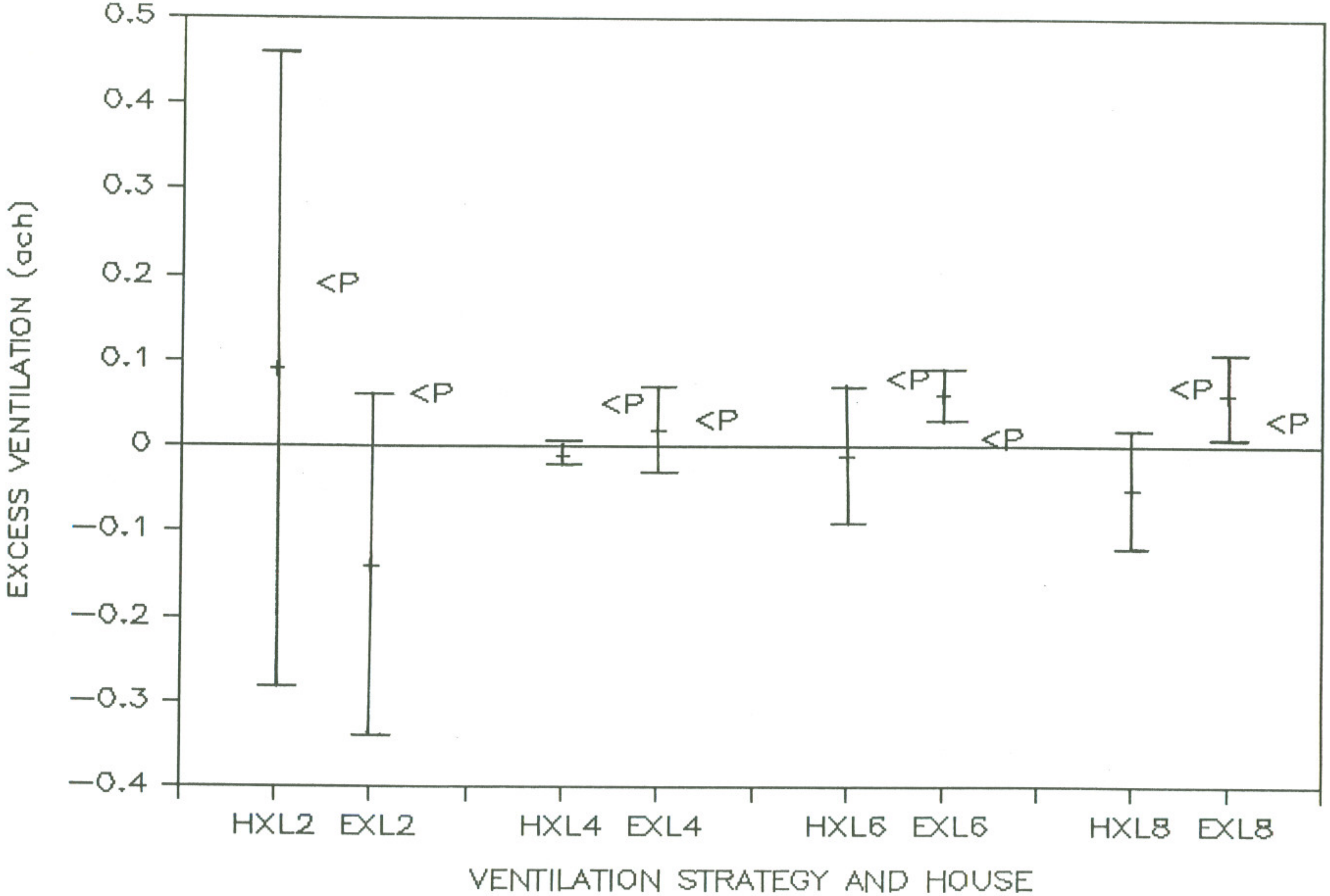
Table 6.5

Measured Additional Ventilation

House	Ventilation Mode	(ach) Difference	Number of Samples	90% Confidence Interval
L2	HX	0.09	4	-0.28, 0.46
L2	EX	-0.14	3	-0.34, 0.06
L4	HX	-0.01	4	-0.02, 0.00
L4	EX	0.02	4	-0.03, 0.07
L6	HX	-0.01	2	-0.09, 0.07
L6	EX	0.06	4	0.03, 0.09
L8	HX	-0.05	6	-0.12, 0.02
L8	EX	0.06	4	0.01, 0.11

Figure 6.1

MEASURED AND PREDICTED VENTILATION



Pollutant Concentrations

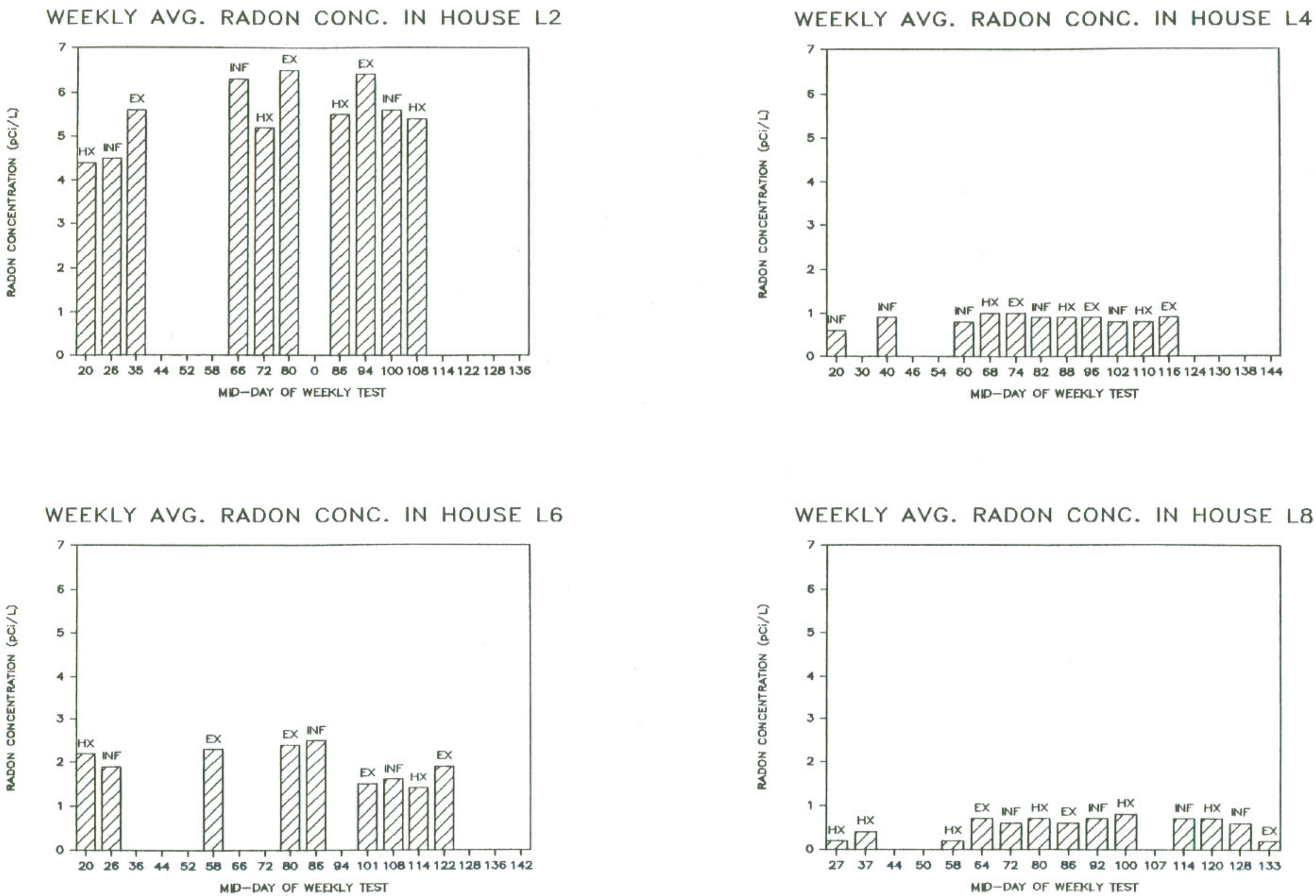
Three different ventilation schemes are under investigation in this project. However, the new system that is being evaluated is the application of a steady, low-flow exhaust ventilation strategy to provide a minimum amount of ventilation at all times that contributes little to the cost of added ventilation. The minimum ventilation eliminates pollutant peaks during times that normal infiltration becomes small and, since it adds in quadrature, adds only a small amount of ventilation during periods when ventilation is sufficient.

Does this strategy have any negative effects on pollutant concentrations? The pressure driven flow hypothesis of radon entry into residences that is gaining acceptance predicts that if the pressure in the structure is reduced (as it will be with an exhaust ventilation system) then the radon entry rate will increase. This is examined for these houses below. Are there other pollutants whose sources are affected by exhaust fan ventilation? We examine this question in the remainder of this chapter.

Radon. The radon data summarized in Tables 5.9 - 5.12 show typical wide variations in concentrations as houses are compared. The concentrations observed in house L8, for example, are of the same order as concentrations normally observed in the outside air while the concentrations observed in house L2 exceed the BPA (although not the NCRP) action guideline for mitigation in houses that have been weatherized [NCRP, 1984]. Figure 6.2 shows the weekly average radon concentrations in the four houses. Also shown are the ventilation modes in operation during these periods.

The effect of exhaust fans on radon concentrations is an issue of serious concern. Evidence that the dominant radon entry mechanism in residences is pressure-driven flow of soil gas into the house is substantial [Nazaroff et al. (1985), Nero and Nazaroff (1984), Turk et al. (1986), Ericson et al. (1984)]. Since the operation of an exhaust fan reduces the pressure

Figure 6.2


WEEKLY AVG. RADON CONC. IN HOUSE L2
RADON CONCENTRATION (pCi/L)
HX INF EX INF HX EX HX EX INF HX
20 26 35 44 52 58 66 72 80 0 86 94 100 108 114 122 128 136
MID-DAY OF WEEKLY TEST
WEEKLY AVG. RADON CONC. IN HOUSE L4
RADON CONCENTRATION (pCi/L)
INF INF INF HX EX INF HX EX INF HX EX
20 30 40 46 54 60 68 74 82 88 96 102 110 116 124 130 138 144
MID-DAY OF WEEKLY TEST
WEEKLY AVG. RADON CONC. IN HOUSE L6
RADON CONCENTRATION (pCi/L)
HX INF EX EX INF EX INF HX EX
20 26 36 44 52 58 66 72 80 86 94 101 108 114 122 128 136 142
MID-DAY OF WEEKLY TEST
WEEKLY AVG. RADON CONC. IN HOUSE L8
RADON CONCENTRATION (pCi/L)
HX HX HX EX INF HX EX INF HX INF HX INF EX
27 37 44 50 58 64 72 80 86 92 100 107 114 120 128 133
MID-DAY OF WEEKLY TEST

within a house, one must be concerned that the operation will increase the radon entry rate or the source strength of radon into the house.

In steady state the concentration of a pollutant in a space is given by

$$C = {}^{S}/_{Q} + C_o$$

where C is the concentration observed

S is the source strength of the pollutant

Q is the ventilation rate in the space

and C_o is the outdoor pollutant concentration.

While the conditions in the houses monitored were never in steady state (the continuous radon monitor measurements shown in Figure 6.3 testify to that), the steady state conditions can be approximated by the weekly average values of C, S, and ${}^{1}/_{Q}$. (The PFT sampler actually measures the average value of ${}^{1}/_{Q}$. The average value of Q for an interval $< Q >$ is estimated from the measured value of $< \frac{1}{Q} >$ to be $1/< \frac{1}{Q} >$. These are not always equal. [Sherman et al. (1980)]). The average source strength, $< S >$, for the weekly measurement period is therefore given by

$$< S > \; = \; < C - C_o > < Q > \qquad (6.3)$$

This assumes that the source strength and ventilation rate are uncorrelated. This issue is discussed further below. The average value of C_o is assumed to be 0.1 pCi/L, a value typical of outdoor air along the west coast of the United States [Nazaroff and Doyle, 1985].

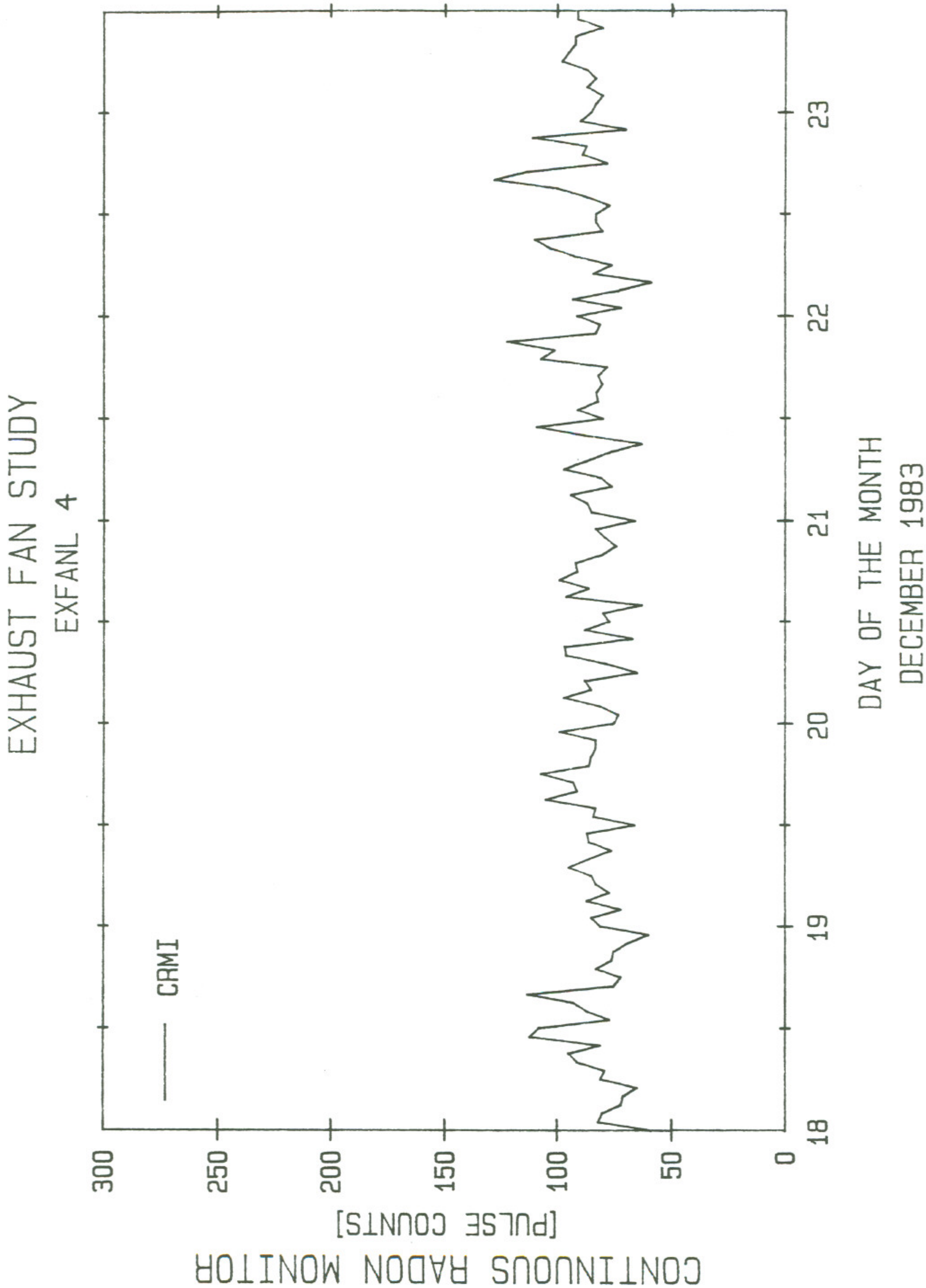
Computing the source strength for the three ventilation modes in house L2 gives

EX: 5.4 ± 1.4 [± 0.8] pCi/L-h

INF: 6.7 ± 0.6 [± 0.4] pCi/L-h

HX: 6.6 ± 2.0 [± 1.0] pCi/L-h.

Figure 6.3


EXHAUST FAN STUDY
EXFANL 4
CRMI
CONTINUOUS RADON MONITOR
[PULSE COUNTS]
0
50
100
150
200
250
300
DAY OF THE MONTH
DECEMBER 1983
18
19
20
21
22
23

The uncertainty listed is the standard deviation of the distribution of weekly averages; the term in square brackets is the standard deviation of the mean. Analysis of variance shows that the means are not significantly different. Thus in house L2, the house that has the largest radon source, the source strength has not been affected by the use of the exhaust fan.

The same is true for the source terms from houses L4, L6, and L8. Although considerably smaller, these source strengths are also from the same statistical distribution; there is no adverse effect on the source strength from the use of the exhaust fan.

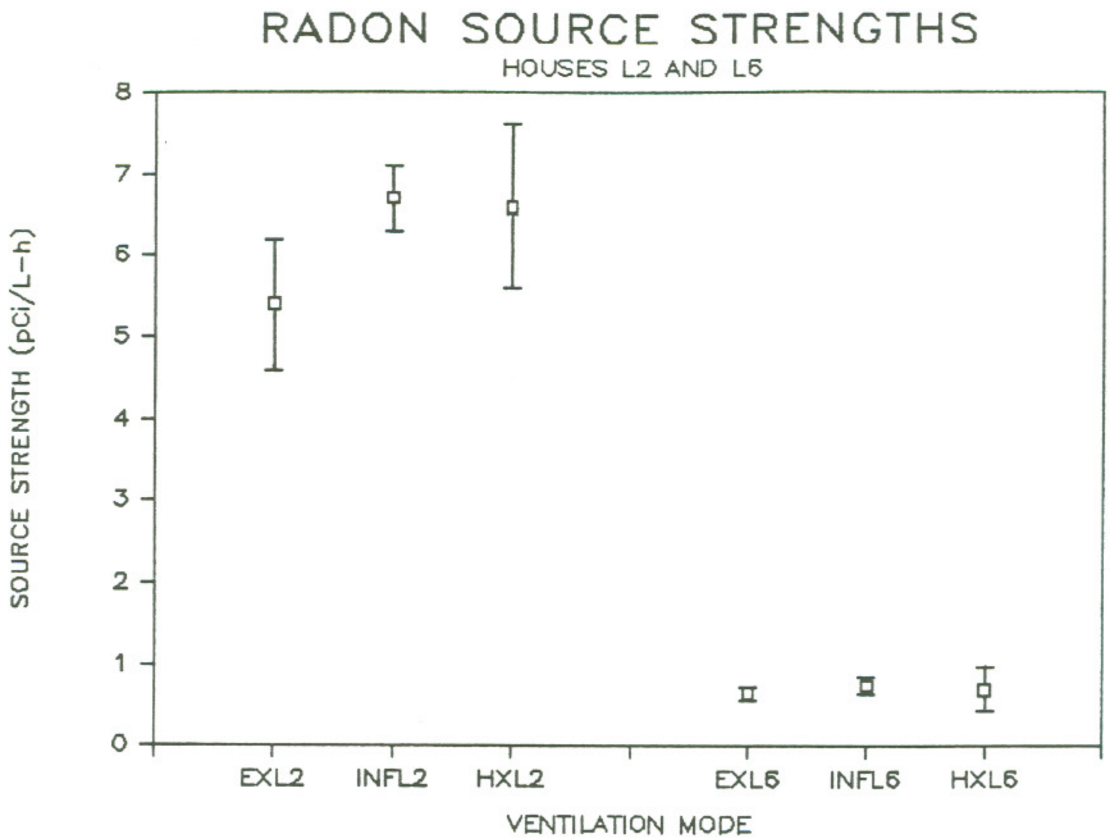
The results from the four houses are collected and plotted in Figure 6.4. The uncertainties plotted for each of the data points are standard deviations of the mean (the terms in square brackets above).

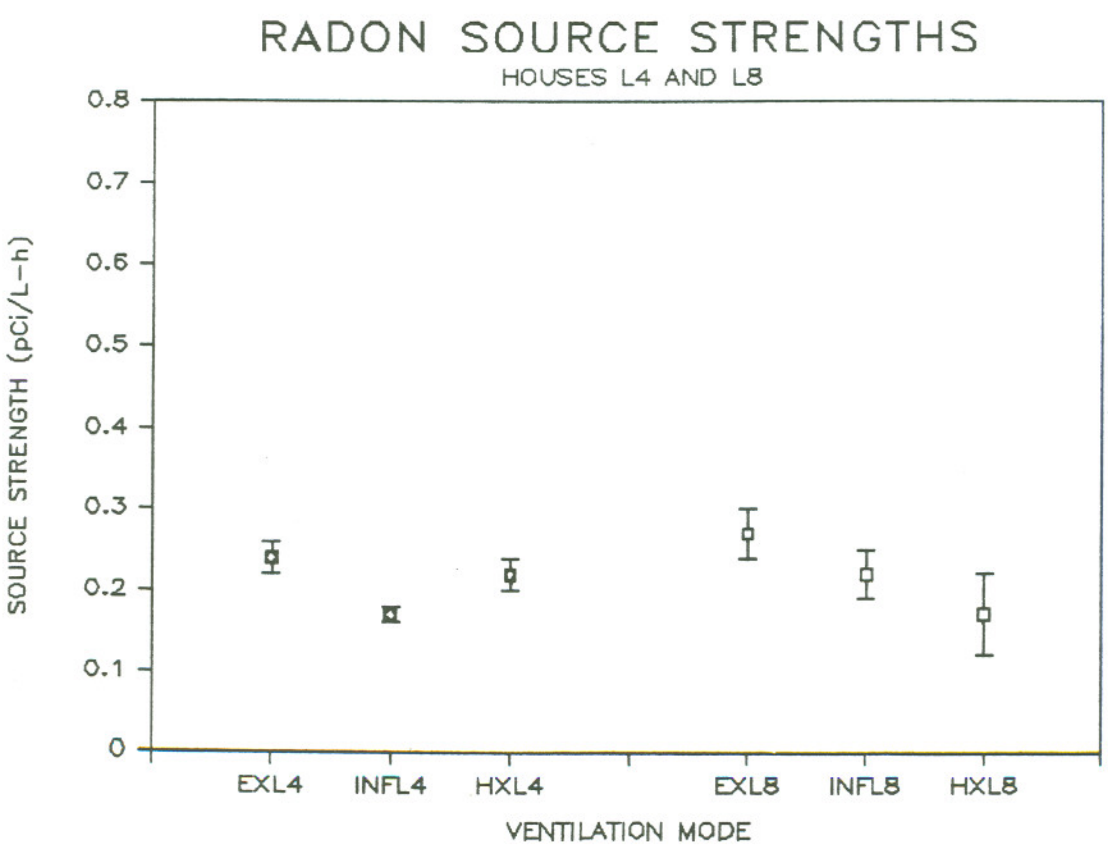
One final comment. The mean values of the source terms from these four houses range in 6.2 pCi/L-h to 0.21 pCi/L-h. This spans the range from the 30th percentile to the 95th percentile of house radon source strengths that have been measured in the United States [Nazaroff and Nero (1984)]. (Note that the ordinates on the two parts of Figure 6.4 vary by a factor of 10.) This is an example of the extreme variability that exists within small geographical areas -- an observation that is one of the reasons that building a predictive model of radon concentrations in houses is so difficult.

Let us explore further the issue of correlation between ventilation rate and source strength. That is we wish to examine the issue of whether $<\frac{S}{Q}>$ and $\frac{<S>}{<Q>}$ are the same; which will be true if S and Q are uncorrelated. Nazaroff and co-workers examined this issue in studying radon measurements in a house near Chicago [Nazaroff et al. (1985)]. They show that in some situations the source term behaves as though

$$S = A_1 Q + A_2$$

Figure 6.4


RADON SOURCE STRENGTHS
HOUSES L2 AND L6
SOURCE STRENGTH (pCi/L-h)
0
1
2
3
4
5
6
7
8
EXL2
INFL2
HXL2
EXL6
INFL6
HXL6
VENTILATION MODE


RADON SOURCE STRENGTHS
HOUSES L4 AND L8
SOURCE STRENGTH (pCi/L-h)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
EXL4
INFL4
HXL4
EXL8
INFL8
HXL8
VENTILATION MODE

where A_1 and A_2 are constants that are related to pressure-driven flow and diffusive flow respectively. In this case

$$\langle \frac{S}{Q} \rangle = \langle A_1 + \frac{A_2}{Q} \rangle$$

$$= \quad A_1 + A_2 \langle \frac{1}{Q} \rangle \qquad (6.5)$$

However, $\frac{< S >}{< Q >} = \frac{< A_1 Q + A_2 >}{< Q >}$

$$= \quad \frac{A_1 < Q > + A_2}{< Q >} \qquad (6.6)$$

$$= \quad A_1 + \frac{A_2}{< Q >} \qquad (6.7)$$

Therefore, the two situations are equivalent if

$$\langle \frac{1}{Q} \rangle = \frac{1}{< Q >} \qquad (6.8)$$

an assumption implicit in all measurements made with the PFT tracer system. Thus the potential error in assuming that S and Q are uncorrelated when determining source strengths is equivalent to the potential error in determining ventilation rates using a PFT sampling system. As noted above, these are small when the variation in ventilation over time is small.

Nitrogen dioxide. Nitrogen dioxide, NO_2, is a common indoor and outdoor pollutant whose sources are related to combustion processes. Internal combustion engines are a major source of the outdoor concentrations observed while wood, natural gas, and kerosene appliances can be major indoor sources. Tobacco smoking is a minor source of NO_2.

Three of the four houses in this study did not use unvented gas or kerosene combustion devices. House L4 had a gas range and oven which are essentially unvented combustion devices. Vented gas appliances were present in L2, L4, and L6. Wood combustion was present in houses L2, L4, L6, and L8 but in each case it was either a well-sealed wood stove or a well-vented fireplace. In none of these cases did the combustion devices represent a major NO_2 source.

The NO_2 concentrations observed in three of the houses were less than the outdoor concentration and substantially lower than the annual outdoor concentration limit of 100 $\mu g/m^3$ or 50 ppb established in the National Ambient Air Quality Standard (NAAQS) of the EPA under the Clean Air Act. Tables 5.5 through 5.8 and Figure 5.3 summarize the weekly average concentration data obtained in this project. The average indoor/outdoor ratios for the four houses are:

Indoor/Outdoor Ratios

L2 = 0.37 ± 0.09

L4 = 1.09 ± 0.48

L6 = 0.40 ± 0.14

L8 = 0.35 ± 0.18

The indoor-outdoor ratio greater than unity in house L4 is an indication of an indoor source. It is likely the gas range/oven combination since no other combustion devices are unvented.

Respirable suspended particles. The primary indoor sources of respirable suspended particles (RSP) (particles less than $3\mu m$ in diameter) are tobacco smoking and unvented gas combustion devices. Tables 6.6 presents the average concentrations of RSP in each house for the entire project.

Table 6.6

Average Concentrations of Respirable Suspended particles

House	Average Concentration ($\mu g/m^3$)	Standard Deviation ($\mu g/m^3$)	Number of weekly Measurements	Standard Deviation of Mean ($\mu g/m^3$)
L2	28.0	7.5	17	1.8
L4	14.0	3.4	18	0.8
L6	14.9	6.0	18	1.4
L8	14.7	6.5	16	1.6

Indoor-outdoor ratios for the four houses based on weekly averages were:

L2 1.29 ± 0.50 (16) [± 0.13]

L4 1.66 ± 0.86 (14) [± 0.23]

L6 0.91 ± 0.22 (18) [± 0.05]

L8 1.31 ± 1.04 (15) [± 0.27]

The values listed are means and standard deviations for the number of weekly measurements shown in parentheses. The number in square brackets is the standard deviation of the mean.

The average concentrations in house L4, L6, and L8 are low relative to any particle standards or guidelines available. There is no indoor standard for particle concentrations. The only outdoor standard that can be used as a guideline is the 75 $\mu g/m^3$ annual average concentration limit in the NAAQS. However, that guideline applies to total suspended particles (TSP), a class that includes both RSP and larger particles. The EPA is considering a standard for particles less than 10 μ whose annual average would fall in the range 40 to 60 $\mu g/m^3$.

The average concentration of respirable particles in house L2 is somewhat higher than in the other three houses although still considerably below any guideline. The indoor-outdoor ratio exceeding unity indicates the presence of an indoor source. It is difficult to identify such a source from the homeowner activity log. Very little smoking occurred in the house, some modest fireplace use was noted as well as daily clothes dryer use. The latter activity is not known to be a major particle source.

Formaldehyde. The dominant sources of formaldehyde in these houses are plywoods and particle board used both in subfloor underlayment and in furniture. Tables 5.5 through 5.8 and Figure 5.2 indicate that houses L2 and L6 have average concentrations considerably below the most stringent guideline used for indoor formaldehyde, namely 100 ppb. The concentrations in houses L4 and L8, on the other hand, exceed this value during several weeks of the study. It is interesting to note that house L4 is the newest in the study with a construction date of 1982. House L8 was built in 1973 while L2 and L6 were built in 1952 and 1915, respectively.

Examination of the data from house L8 shows no statistically significant differences among the mean concentrations associated with the various ventilation systems employed. Analysis of variance applied to the formaldehyde concentrations in house L4, on the other hand, show that the concentrations associated with the infiltration mode of ventilation are significantly different from the heat exchanger and exhaust fan modes (which are higher) at the 90% level of significance.

Before conclusions are drawn it must be pointed out that the result above comes from an application of analysis of variance to raw average data. Recent results have shown that the emission rate of formaldehyde materials depend on their temperature, the ventilation rate, and the water vapor concentration of the materials in question [Mathews et al. (1984)]. Table 6.6 gives data necessary to adjust measured concentrations to standard conditions so that the effects of ventilation strategies on concentrations can be compared.

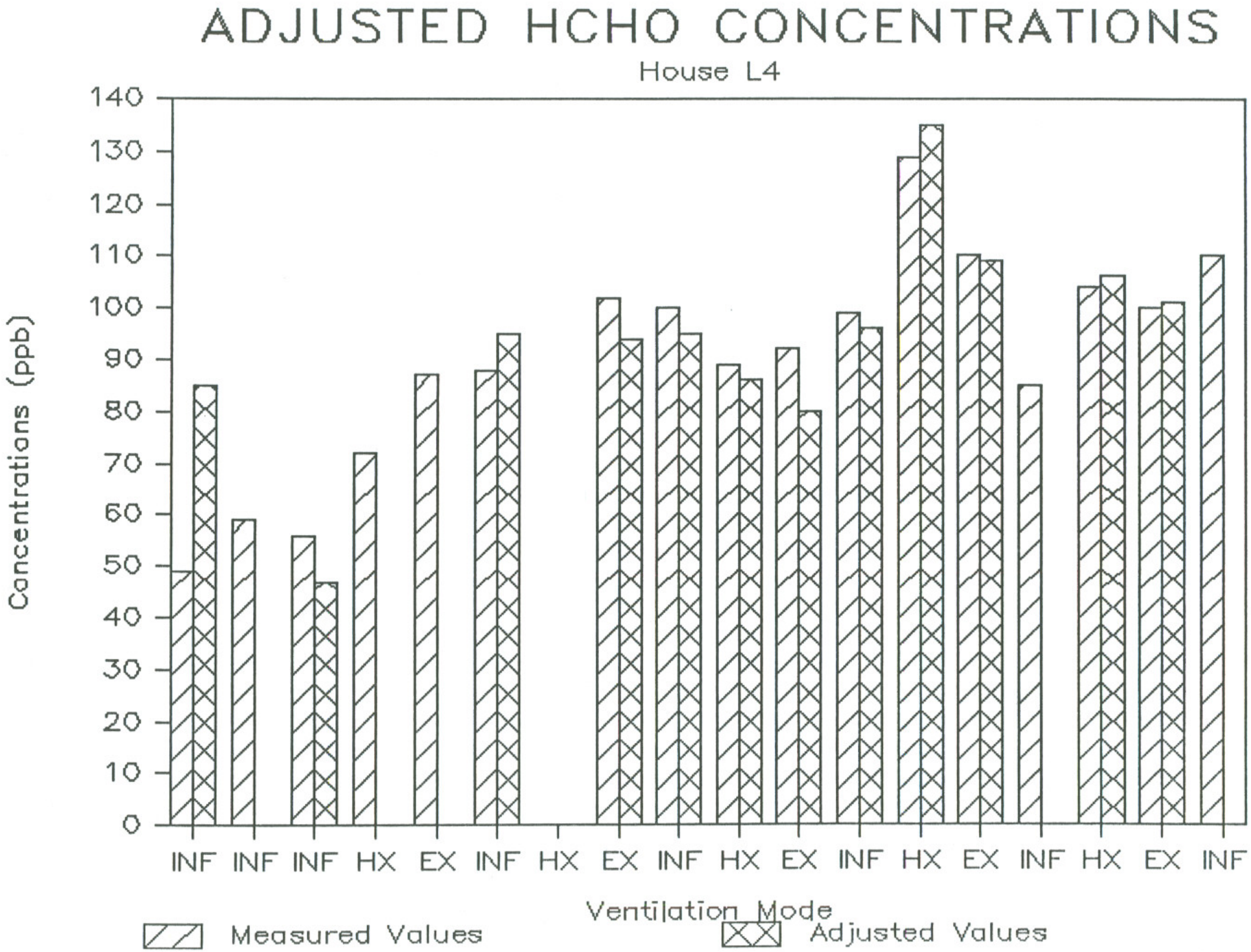
The data contained in Table 6.6 and displayed in Figure 6.5 are each adjusted to a standard condition of 18.6°C, 50% RH and 0.27 ach using relationships described by Mathews et al. (1986) and Meyer and Hermanns (1985). The standard condition is the average of all the weekly average measurements in this house.

Table 6.7

Formaldehyde Concentrations in House L4

Date	Mode	Meas. Vent. (ach)	Indoor Temp. (°C)	Relative Humidity	HCHO (ppb) (measured)	HCHO (ppb) (adjusted)
12.17.83	Infil	0.39	17.2	40	49	85
12.23	Infil	0.16	--	--	59	--
1.05.84	Infil	0.21	18.6	51	56	47
1.12	Hx	0.27	--	--	72	--
1.19	Ex	0.23	--	--	87	--
1.26	Infil	0.30	16.8	58	88	95
2.2	Hx	0.27	19.1	45	--	--
2.9	Ex	0.24	19.2	48	102	94
2.16	Infil	0.25	19.3	47	100	95
2.23	Hx	0.25	18.7	49	89	86
3.1	Ex	0.21	18.5	50	92	80
3.8	Infil	0.28	18.8	52	99	96
3.15	Hx	0.33	19.3	52	129	135
3.22	Ex	0.29	18.9	52	110	109
3.29	Infil	0.29	--	--	85	--
4.5	Hx	0.30	18.6	53	104	106
4.12	Ex	0.30	18.7	53	100	101
4.19	Infil	--	--	--	110	--

Figure 6.5



ADJUSTED HCHO CONCENTRATIONS
House L4
Concentrations (ppb)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
INF INF INF HX EX INF HX EX INF HX EX INF HX EX INF HX EX INF
Ventilation Mode
Measured Values
Adjusted Values

Collecting the measurements that are associated with each of the ventilation strategies yields the following results for the formaldehyde tests:

Infil: 84 ± 21 (5) [± 9] ppb

Hx: 109 ± 25 (3) [± 14] ppb

Ex: 96 ± 12 (4) [± 6] ppb

The notation used for these mean values indicates that the mean formaldehyde concentrations when infiltration was the only mechanism supplying ventilation was 84 ppb. The standard deviation of the five measurements is 21 ppb; the standard deviation of the mean is 9 ppb.

Analysis of variance applied to this corrected data set indicates that the means are different only at the 75% level of significance. Therefore, it is unlikely that the ventilation systems affect formaldehyde sources in any unexplained manner.

Energy Use

The energy use associated with the operation of the exhaust fans is obtained in two ways. The power used for fan operation is 22 watts when the exhaust fans are on. This must be added to the energy required to heat the excess ventilation air supplied by the fan. The latter amount is given by

$$E2 = \rho \, C \, Q \, \overline{(\Delta T)} \, t \qquad (6.9)$$

Where:

E2 is the energy required to condition the air

ρ is the density of the air

C is the specific heat of the air

Q is the ventilation supplied by the exhaust fan

$\overline{(\Delta T)}$ is the average indoor-outdoor temperature difference over the week, and

t is the time interval of operation

The energy required to operate the fan for one day is 0.53 kWh. The range of total energies required to operate the exhaust fans and condition the air supplied for ventilation is given in Table 6.8.

Table 8

Daily Energy Requirements for Exhaust Ventilation

House	Minimum Energy (kWh)	Maximum Energy (kWh)
L2	-9.8	+2.0
L4	-0.6	+3.0
L6	+1.7	+5.1
L8	+0.8	+5.8

The minimum and maximum energies are determined using the measured 90% confidence intervals for the excess ventilation associated with exhaust fans listed in Table 6.5. For comparison, typical daily energy use in these houses during the heating season when the indoor-outdoor temperature difference was 10°C was approximately 57 kWh.

While these energies are not a trivial part of the energy use of each house they are in the noise portion of the measured energy use. Thus as a measurement problem, they are difficult to observe against the background of daily variations in energy use in a house.

On the other hand, they represent a non-trivial part of the daily energy use of a house and provide the reason that the fans chosen were not larger. This point is expanded in the Discussion in Chapter 7.

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VII. DISCUSSION AND SUMMARY

This study had several objectives. Each will be discussed in order followed by general comments and a general summary of the work.

The first objective, to determine the ventilation performance of small exhaust fans in typical houses, was fulfilled in a general way. Quantitative measures of the ventilation supplied by these fans showed the small incremental ventilation that was provided by the fans when operating continuously. These results are shown in Fig. 6.1. This behavior is consistent with their role as essentially "fill ventilation". This term is used simply to indicate that the ventilation fills gaps that exist whenever the natural infiltration ceases to provide adequate ventilation to the house.

Unfortunately, this behavior can only be inferred since continuous, real-time ventilation measurements that would demonstrate the process of "filling in" minima in ventilation rates could not be made within the constraints of this experimental design.

The second objective, to determine the effectiveness of exhaust fans for removing indoor air pollutants, was fulfilled in great detail in one sense and remains unfulfilled due to the study design in another, important sense. Because of budget limitations passive samplers that yield average concentrations of the pollutants that they sample were used to measure most pollutant concentrations. However, in the case of radon, a pollutant of particular concern, real-time instrumentation was deployed.

Passive samplers or, more generally, integrating samplers, will not demonstrate the ability of exhaust fans to prevent large pollutant peaks due to reductions in ventilation rates.

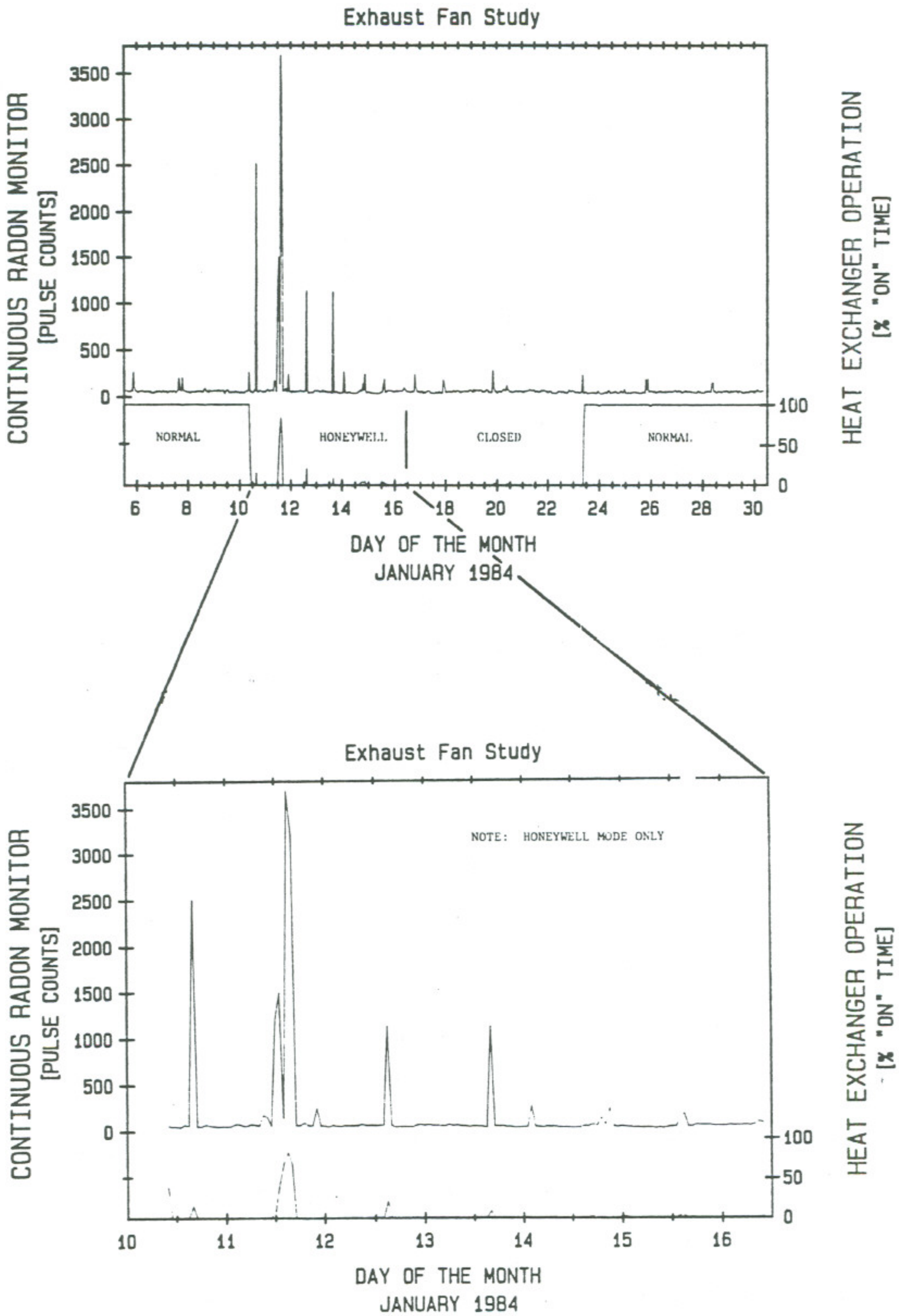
The passive samplers did demonstrate that air quality was not adversely affected because of the presence of the exhaust fans. Conversely, the measurements did not demonstrate that a significant improvement in indoor air quality occurred when the exhaust fan was in operation.

The real-time radon sampler results demonstrated that the source strength of the radon was not increased when the exhaust fans were used. This important result must be qualified lest it be generalized too broadly. The fans used in this project were small, designed to provide incremental ventilation when natural infiltration becomes small. This meant that small, 27 cfm fans were used in the work. This choice minimizes the energy used when the fans are in operation; it also minimizes the depressurization caused by the fans when in operation. For example, in house L2 the depressurization resulting from a 27 cfm fan amounts to approximately 0.02 Pascal. This project demonstrates that changes in source strength resulting from pressures of this magnitude are not observable. (We note that the same fan will cause larger pressure drops in tighter houses. At constant flow the pressure drop is inversely proportional to the square of the leakage area. Thus halving the leakage area of house L2 would increase the pressure drop across the shell to 0.08 Pa.)

The third objective, evaluating a control mechanism for the exhaust fans, was primarily the responsibility of the Honeywell project. The continuous exhaust fan operation provides a baseline performance for that comparison. The comparison must await a final concatination of the two reports.

An observation that was made early that caused us some concern was the presence of a major "spike" in the radon response whenever the exhaust fans were turned on in the Honeywell houses. This is shown in Fig. 7.1. The immediate explanation proposed was an increase in radon due to a depressurization of the house from the exhaust fan. Investigation showed that this explanation was false. A clue comes from the rapid decrease in the concentration following the initial peak. If the space is well-mixed, the time constant for the reduction in the concentration of radon is the reciprocal of the ventilation rate. The result observed and shown in Fig. 7.1 is a much smaller time constant.

Figure 7.1


Exhaust Fan Study
CONTINUOUS RADON MONITOR
[PULSE COUNTS]
3500
3000
2500
2000
1500
1000
500
0
HEAT EXCHANGER OPERATION
[% "ON" TIME]
100
50
0
NORMAL
HONEYWELL
CLOSED
NORMAL
6
8
10
12
14
16
18
20
22
24
26
28
30
DAY OF THE MONTH
JANUARY 1984
Exhaust Fan Study
NOTE: HONEYWELL MODE ONLY
CONTINUOUS RADON MONITOR
[PULSE COUNTS]
3500
3000
2500
2000
1500
1000
500
0
HEAT EXCHANGER OPERATION
[% "ON" TIME]
100
50
0
10
11
12
13
14
15
16
DAY OF THE MONTH
JANUARY 1984

Other tests have shown that the measurement result is spurious; it is the result of noise pickup on the line connecting the continuous radon monitor to the data logger. As a result, all radon data from the project has been filtered to remove these peaks.

The fourth objective, to evaluate the energy penalty associated with the use of exhaust fans has been met through a calculation. Direct measurement can only say that the energy use has not increased beyond 10%. The resolution of the energy monitoring available does not permit a stronger statement to be made. Our calculations, based upon the measured increase in ventilation, indicate a daily increase in energy use for the four houses when the exhaust fan is in operation, of 1.5 kWh. Typical indoor-outdoor temperature differences for the periods when these observations were made were 10°C. Total daily energy use in the houses during these same periods were about 57 kWh (±27).

The fifth objective, to gain an indication of how the various meteorological criteria correlate to air infiltration rate, was examined in an indirect fashion.

Models that have attempted to describe the relationship between wind speeds and temperature differences and infiltration rates in residences can be divided into two categories. The first are essentially statistical. A large amount of data is collected giving the infiltration rate of the structure, the wind speed and the temperature differences between indoors and out. Attempts are then made to develop correlations among these variables using quasi-physical arguments relating the variables. The most exhaustive study of this sort was undertaken at Ohio State University by Reeves et al.(1979). The authors of this report investigated 26 different combinations of functional forms attempting to minimize the rms variation between prediction and measurement in their hourly data sets from six houses in the Columbus area.

Another approach to the problem is to attempt to understand the physical bases for the pressures that drive airflow through buildings. This has been done in several research groups;

the discussion that follows focusses on the LBL effort.

The single-zone residential infiltration model that was developed during the period from 1978 to 1980 was based on a goal of providing a minimal set of physical parameters that would adequately describe the infiltration rate of a house. The model makes physical arguments that lead to a functional dependence between infiltration and meteorological parameters of the form

$$Q = A[\, a_1\, \Delta T + a_2\, v^2]^{1/2} \qquad (7.1)$$

where Q is the ventilation rate

A, a_1, and a_2 are constants that depend on the structure

ΔT is the indoor-outdoor temperature difference

and v is the wind speed.

Evaluations by the International Energy Agency-sponsored Air Infiltration Centre (1983) have shown that this model describes independent data sets measured in different countries as well as, or better than, those obtained from other models tested. Consequently we have only used the LBL model and the functional form of the relationship between infiltration, wind speed, and temperature difference shown in Eq 7.1 to analyze the data from the current set of measurements.

Results from the four houses used in this project show scatter about the ideal value of unity (cf. Table 6.1). When taken together the average of the measured to calculated means of the four houses (summarized on Table 6.1) is 1.14 ± 0.58. The values for houses L4, L6, and L8 are not unusual for predictive capability of the model. The results from house L2 are puzzling. Some feature in the house was apparently changed between the time the air leakage measurements were made and beginning of the infiltration measurements. Results suggest open windows or their equivalent. The homeowner log indicates window opening late in the spring but not earlier. These comments notwithstanding, the average agreement between measurement value and prediction value demonstrates the consistency of the functional form chosen for the infiltration model.

OTHER GENERAL COMMENTS

This project addressed all the objectives set out in the original workplan. In some cases the results were surprising, in others, quite predictable. There are several positive conclusions that can be drawn from the project.

The first is the lack of effect on the radon source strength from the use of the exhaust fans in these houses. One should be careful to note that this conclusion depends on the environment in which the measurements are made. The conclusion may not be true if (1) the houses were tighter than the four investigated here, or (2) the exhaust fans were larger. The energy burden associated with larger fans may be excessive, however. Consequently one should consider their use only if some form of energy recovery is available. This issue requires additional attention.

A second major benefit of the study was the training it provided for future field work and the opportunity it afforded for testing new measurement strategies. Both were important for the major field surveys that BPA began the following winter.

ACKNOWLEDGMENTS

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APPENDIX A

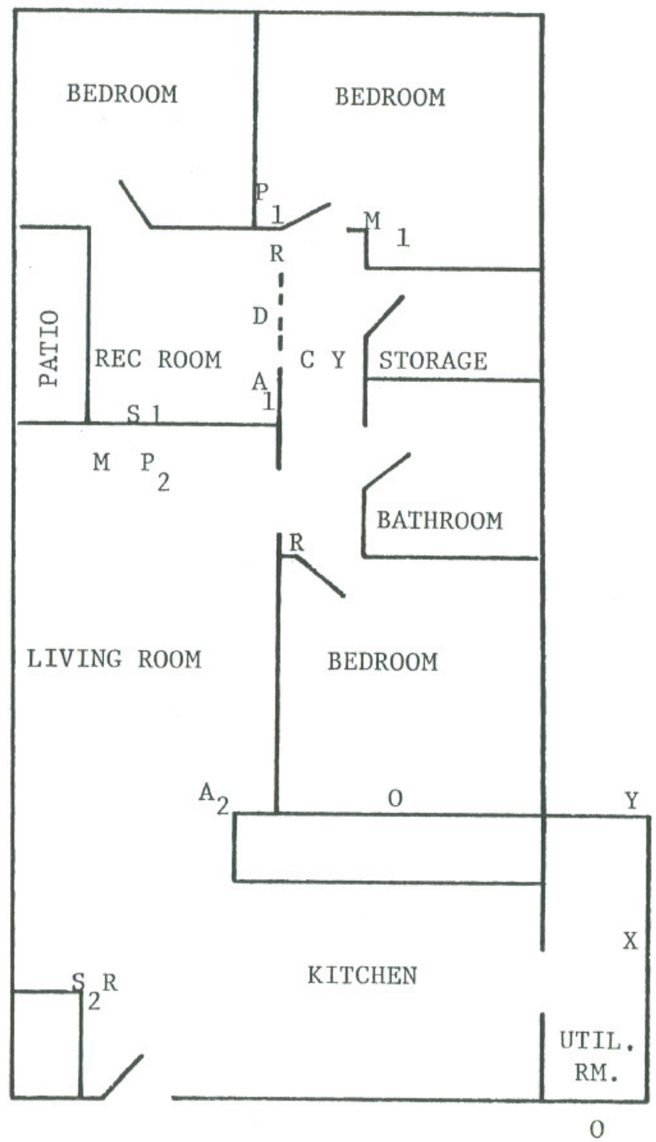
Table A.1

Characteristics of Houses Initially Screened for Study

House Code	House Type (A)	Sub-Structure (B)	Age (yrs.)	Floor Area (ft^2)	Volume (ft^3)	ELA (cm^2)	SLA (cm^2/m^2)	Proj. Heat. Seas. Infil. (ACH)	Proj. Yearly Infil. (ACH)
01	1	C	3	1120	9000	690	6.6	.69	.56
02	1	C	28	930	7400	410	4.7	.48	.39
03	2S	C	10	1750	14000	760	4.7	.57	.44
04	2	HB	42	2160	16650	700	3.5	.47	.38
05	2	C	43	1300	9800	920	7.6	1.06	.85
06	2	B	61	1860	16800	1700	10.0	1.21	.96
07	1	C	31	1190	9500	750	6.8	.68	.56
08	S	S	6	2170	17400	670	3.3	.41	.33
09	2S	S	1	2000	18000	770	4.1	.52	.41
10	2	C	12	2550	23000	1300	5.5	.59	.46
11	2	HB	55	3590	28700	820	2.5	.32	.26
12	1	HB	13	2020	15200	470	2.5	.30	.24
13	2	HB	62	2410	18500	790	3.5	.49	.39
14	2	S	~50	2210	22100	930	4.5	.54	.43
15	1	B	77	870	7700	670	8.3	.90	.72
16	2	HB	67	2610	20900	810	3.3	.46	.37
17	1	C	20	1440	11500	640	4.8	.48	.39
18	2	HB	60	2980	23400	930	3.4	.48	.38
19	1	C	10	1760	15400	720	4.4	.42	.33
20	1	C	50	1140	10200	720	6.8	.70	.57
21	2	HB	67	2250	19700	590	2.8	.36	.28
22	2	B	~50	670	5300	320	5.2	.55	.44
23	1	B	59	780	6600	470	6.5	.70	.57
24	2	HB	99	1740	16600	3240	20.0	2.43	1.92
25	2S	S	7	3000	25500	1310	4.7	.62	.49
26	2	HB	61	2730	22400	1330	5.2	.72	.57

(A) 1, 1-story; 2, 2-story; 2S, 2 story split level

(B) B, basement; C, crawlspace; HB, half-basement; S, slab-on-grade



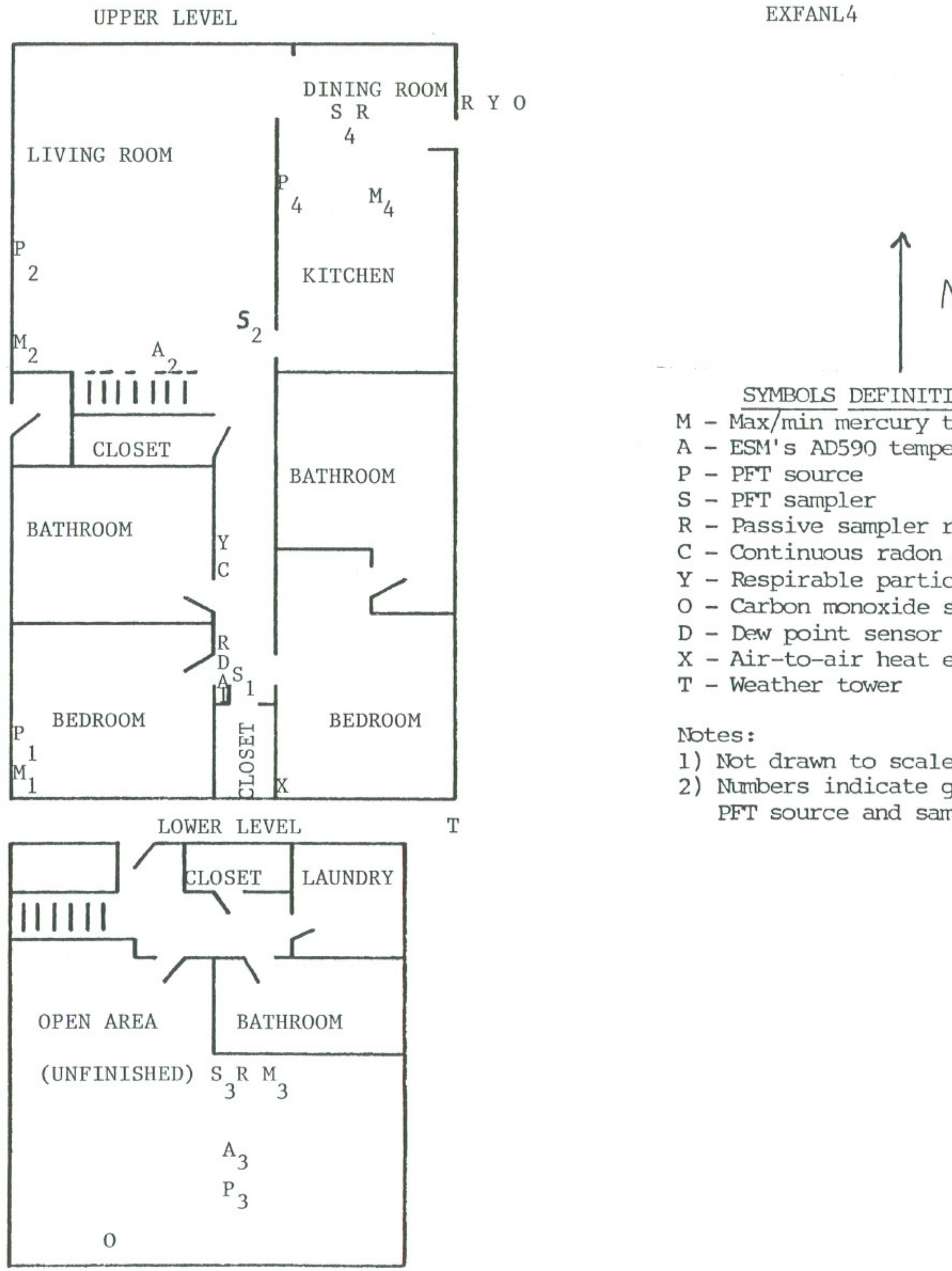
SYMBOLS DEFINITION

M – Max/min mercury thermometer
A – ESM's AD590 temperature sensor
P – PFT source
S – PFT sampler
R – Passive sampler rack
C – Continuous radon monitor
Y – Respirable particule sampler
O – Carbon monoxide sampler
D – Dew point sensor
X – Air-to-air heat exchanger
T – Weather tower

Notes:
1) Not drawn to scale.
2) Numbers indicate groupings used PFT source and samplers.

Figure A.1

EXFANL4



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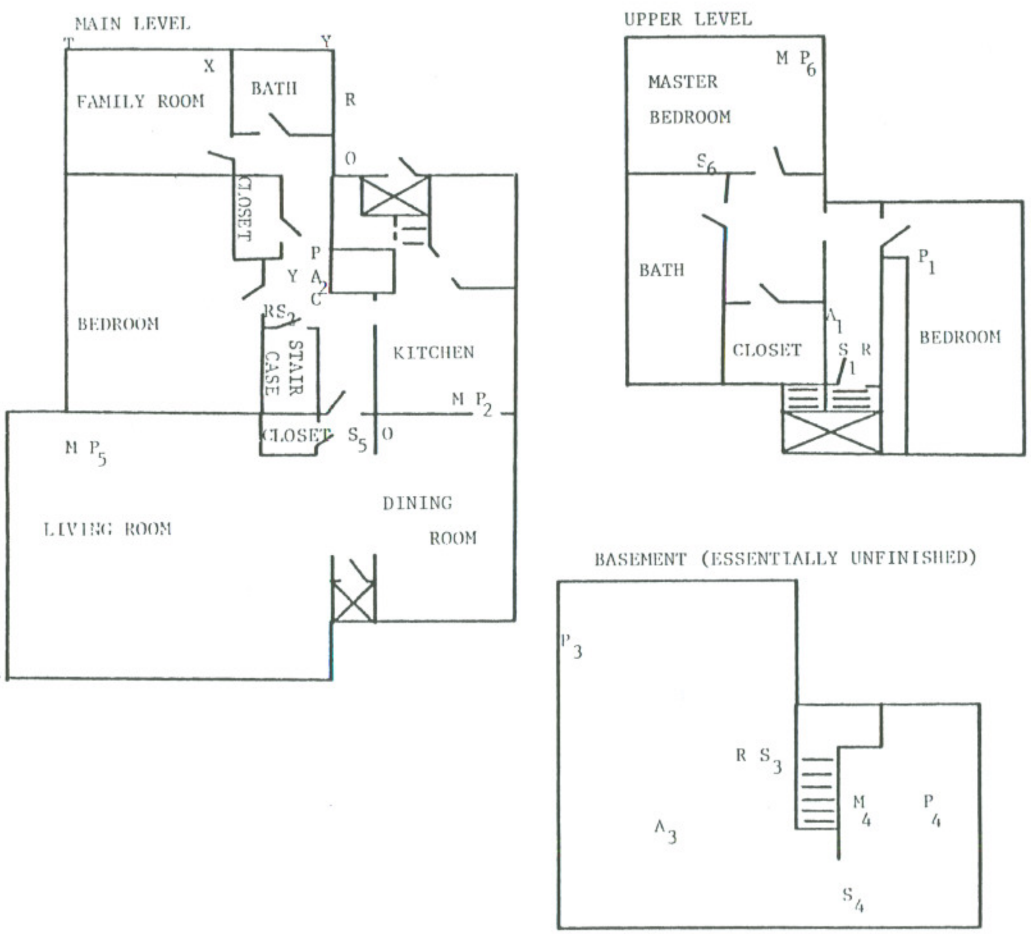
O - Carbon monoxide sampler
D - Dew point sensor
X - Air-to-air heat exchanger
T - Weather tower

Notes:
1) Not drawn to scale.
2) Numbers indicate groupings used PFT source and samplers.

Figure A.2

Figure A.3



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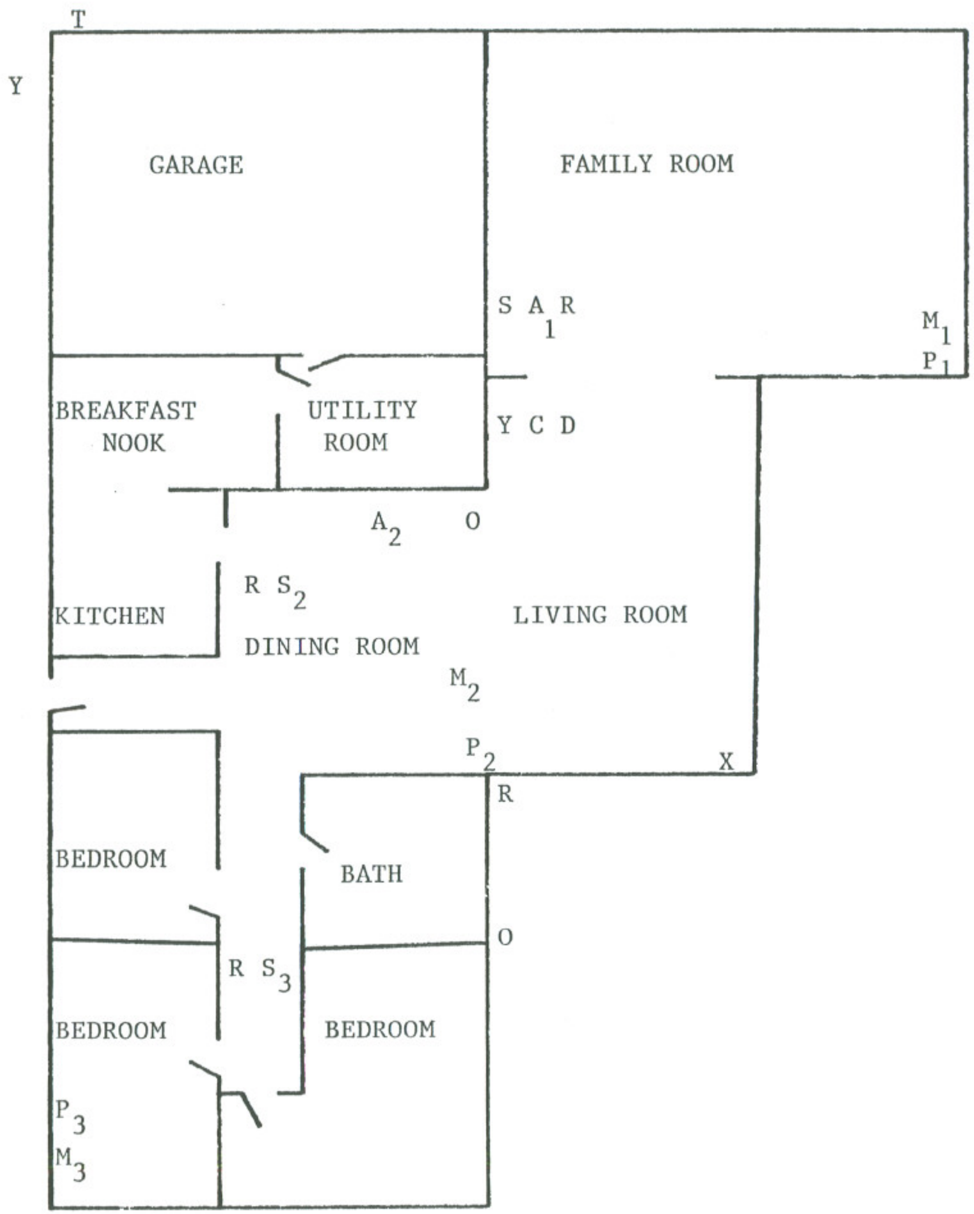

SYMBOLS DEFINITION

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S - PFT sampler
R - Passive sampler rack
C - Continuous radon monitor
Y - Respirable particule sampler
O - Carbon monoxide sampler
D - Dew point sensor
X - Air-to-air heat exchanger
T - Weather tower

Notes:
1) Not drawn to scale.
2) Numbers indicate groupings used PFT source and samplers.

Figure A.4

Appendix B

DAILY ACTIVITIES WITHIN YOUR RESIDENCE

Field Study of Exhaust Fans for Mitigating Indoor Air Quality Problems

DATE: ____________________

ACTIVITY	3AM - 9AM	9AM - 3PM	3PM - 9AM	9PM - 3AM
No. OF PEOPLE AT HOME				
TOBACCO SMOKING[a]				
COOKING PATTERN[b]				
- Stove Top				
- Oven				
EXHAUST FANS VENTED TO OUTDOORS[b]				
- Kitchen				
- Bathroom,				
- Other, specify				
OTHER ACTIVITIES AND UNUSUAL EVENTS[b]				
- Vacuum				
- Clothes Dryer				
- Fireplace				
- Woodstove				
- Kerosene Heater				
- Windows Opening				
- Autos Idling in Attached Garage				
- Other: Could include house painting, decorating, parties burnt food, fumigation				
OUTDOOR ACTIVITIES: - Could include heavy traffic, road repair construction, farm activities				

(Use back of this form to describe any additional activities which may have affected the indoor air quality of your residence.)

Notes:

a) Enter type of smoking (cigarettes, cigars, pipe) and number smoked.
b) Enter estimated time (minutes) of use.

Lawrence Berkeley Laboratory 12/10/83

WEEK 18
REC'D 5/1/84

BLANKS

SEE EXFANH1, EXFANLG, + EXFANH3

HCHO BLANKS - 3, 73, 584, 586, 587

PARTICLE BLANKS - 174, 230, 239

H_2O BLANKS - 321, 331, 341, 347, 348

NO_2 BLANKS - 947, 948, 949

VOID SAMPLERS - 950, 952 (caps were needed for valid house samples)

PFT BLANK 4445

Appendix C

This sample technician log is an example of the weekly reporting of the field technicians. One form was completed for each hose for each week.

FIELD TECHNICIAN WEEKLY CHECK LIST

Field Study of Exhaust Fans for Mitigating Indoor Air Quality Problems

---

EXFANH1		Home: [redacted]
[redacted]		Office: [redacted]
		[redacted]

Fill in each of the following items as they are completed. FINAL

	Deploy	Remove
Technician: JERRY Date:	4.16.84	4.23.84
Arrival Time:	1900	1840
Departure Time:	2130	1950

Continuous Radon Monitor (S/N 1005)

	Deploy	Remove
Replace filter: (Condition: Changed)	[✓]	
Flow rate (ml/min):	0.5 SCFH	METER = 003 / RATE = 0.55 SCFH
High voltage (volt):	1270	1270
CRM operation check. Time: 1913 Count:	552	
Time: 2013 Count:	626	74/hr

4.16 - SEE ALSO SN 1006 CRM DATA. FLOW BY SN 1005 METER = 003.

Respirable suspended particulate sampler

	Inside (S/N 107) Deploy	Remove	Outside (S/N 136) Deploy	Remove
Time:	2025	1940	2030	1945
Cyclone condition:	CLEAN	CLEANED	CLEAN	CLEANED
Max vacuum at flow:	115	115	95	95
Filter cassette No.:	177		183	
Rotometer reading (mm):	9.4(92)	9.4(92)	9.0(92)	9.0(92)
Vacuum reading(in.H2O):	6	6	4	4
Air volume (ft3):	10100	10705	6945	7575
Total air volume (ft3):		605		630

4.16 FLOWS SET BY STD ROTO.

Air-to-air heat exchanger status

	Fan setting	
Heat exchanger openings covered	off	[ ]
Normal heat exchanger operation (Fan med)		[ ]
Heat exchanger inlet covered, (LBL: Fan low). . . .		[ ]
Heat exchanger inlet covered, (Honeywell: Fan high)	HIGH	[✓]
Power cord plugged into Honeywell controller		[✓]
Check heat exchanger filters (clean filter [✓])		[✓]

(Continued on back)

page 2. Weekly Check List: Date: 4.16.84 / 4.23.84 EXFANH1 -

IAQ passive sampler replacement

	Outside	1	2	3	4
Location:	W. SIDE	HALL	LV RM	KIT	BLANK
Deploy Time:	2030	2035	2040	2045	2030
Remove Time:	1920	1925	1930	1935	1920
Sample Number:					
Formaldehyde:	4	5	6	7	8
Nitrogen dioxide:	919	920	921	922	931
Water vapor:	317	318	319	320	322
______:					
______:					

	A	B	C	D	E
Location:		HALL	LV RM		
Deploy Time:		2035	2040		
Remove Time:		1925	1930		
Perfluorocarbon:		4356	4545		
Max/Min Temp (F)	/	~~[illegible]~~/~~[illegible]~~ 75 64	81/63	/	/

Energy Signature Monitor (S/N 101)

	Deploy	Remove
Check weather tower (still standing,etc):	[✓]	[✓]
Dew point mirror test. Weather tower:	[–]	[–]
Inside:	[✓]	[–]
ESM data module. (S/N: 025)	[✓]	[✓]
Check sensor values with terminal:	[✓]	[✓]

4.16 - DM 025 LEFT IN. NO BLANKS. TDPO VALUES NOK.

4.23 - TDPO & TDPI VALUES LOOK REASONABLE.

Energy use information

Electric meter reading:	10321	10422
Gas meter reading:	1506	1518
Estimated oil used: (units: ______)		
Estimated wood used: (units: ______)		

Homeowner interaction

Homeowner log:	[✓]	[✓]
Interact with homeowner (questions, etc.):	[✓]	[✓]
Schedule next visit:	[✓] MON 7PM	[✓]

Comments (sensor location changes, occupant behavior changes, etc.):

4.16 - SEE CO INFO.

FIELD TECHNICIAN WEEKLY CHECK LIST

Field Study of Exhaust Fans for Mitigating Indoor Air Quality Problems

EXFANH1		Home: [redacted]
[redacted]		Office: [redacted]
		[redacted]

Fill in each of the following items as they are completed. FINAL

		Deploy	Remove
Technician: JERRY	Date:	4.16.84	4.23.84
	Arrival Time:	1900	1840
	Departure Time:	2130	1950

This checklist only provides info for CRM SN 1006 and ESM SN 103.

Continuous Radon Monitor (S/N 1006)

	Deploy	Remove
Replace filter: (Condition: Changed)	[✓]	
Flow rate (ml/min):	147	METER 2003 | ROTO = 0.85 x FH
High voltage (volt):	1295	1295
CRM operation check. Time: 1915 Count:	705	} meter 84/hr display variable
Time: 2015 Count:	992	

4.16 – This unit samples the EXFANH1 Crawl Space. CRM data from SN 1006 is recorded on strip chart and on data module 022 in ESM SN 103. CRM SN 1006 data is not recorded on EXFANH1's ESM SN 101. STRIP CHART MARKED/CHECKED AT 1900.

Respirable suspended particulate sampler

	Inside (S/N ____) Deploy	Inside Remove	Outside (S/N ____) Deploy	Outside Remove
Time:				
Cyclone condition:				
Max vacuum at flow:				
Filter cassette No.:				
Rotometer reading (mm):				
Vacuum reading(in.H20):				
Air volume (ft3):				
Total air volume (ft3):				

Air-to-air heat exchanger status

	Fan setting	
Heat exchanger openings covered	off	[ ]
Normal heat exchanger operation (Fan med)		[ ]
Heat exchanger inlet covered, (LBL: Fan low). . . .		[ ]
Heat exchanger inlet covered, (Honeywell: Fan high)		[ ]
Power cord plugged into Honeywell controller		[ ]
Check heat exchanger filters (clean filter [ ])		[ ]

(Continued on back)

IAQ passive sampler replacement

Location:	Outside ____	1 ____	2 ____	3 ____	4 ____
Deploy Time:					
Remove Time:					
Sample Number:					
Formaldehyde:					
Nitrogen dioxide:					
Water vapor:					
____:					
____:					

Location:	A ____	B ____	C ____	D ____	E ____
Deploy Time:					
Remove Time:					
Perfluorocarbon:					
Max/Min Temp (F)	/	/	/	/	/

Energy Signature Monitor (S/N 103)

	Deploy	Remove
Check weather tower (still standing,etc):	[ ] NA	[ ] NA
Dew point mirror test. Weather tower:	[ ]	[ ]
Inside:	[ ]	[ ]
ESM data module. (S/N: 022)	[✓]	[✓]
Check sensor values with terminal:	[✓]	[✓]

4.16 - ESM SN 103 records only the pulse count data from CRM SN 1066.
ESM SN 103 COLLECTING DATA @ ~1915.

Energy use information

Electric meter reading: ________ ________

Gas meter reading: ________ ________

Estimated oil used: (units: ________) ________

Estimated wood used: (units: ________) ________

Homeowner interaction

Homeowner log:	[ ]	[ ]
Interact with homeowner (questions, etc.):	[ ]	[ ]
Schedule next visit:	[ ]	[ ]

Comments (sensor location changes, occupant behavior changes, etc.):

BPH EXHAUST FAN MITIGATION STUDY

BUILDING ID CODE EXFANH1

TECHNICIAN JERRY

	INSIDE SAMPLER SUITCASE # 701		OUTSIDE SAMPLER SUITCASE # 707	
	DEPLOY	REMOVE	DEPLOY	REMOVE
DATE	4.16.84	4.23.84	4.16.84	4.23.84
ATION:				
CO MONITOR UNIT #		55		55
ZERO/SPAN CALIBRATION (✓)		☑		☑
CO SPAN GAS VALUE (PPM)		21.51		21.51
TIME	2000	1859	2004	1846
TIMER READING	60470	70485	60470	70469
ELAPSED TIME		10015		10001
CO READINGS: #1		Ø PPM		Ø PPM
#2		Ø PPM		Ø PPM

APPENDIX D

```
110 REM ************************** INFNEW.BAS ******************************
120 REM **** This program predicts infiltation rates using the LBL model ****
125 REM **** INPUT: Average windspeed and temperatures for any period.  ****
128 REM ****                           (7/8/85) BPA-IAQ Project         ****
130 REM ********************************************************************
135 REM
138 DEF FNU$(X$)=CHR$(ASC(X$) AND 127+32*(X$>="a")) 'CONVERT to Upper case.
140 DIM TC(2,15)
142 FOR I=1 TO 5
144     READ TC(1,I): READ TC(2,I)              'Read terrain class parameters.
146     NEXT I
148 DATA 1.3,.1,1,.15,.85,.2,.67,.25,.47,.35
149 '
150 A1=10:A2=3:A3=36:A4=15:A5=25:A6=30          'Component leakages...
155 REM                 BEGIN INPUT SEQUENCE
157 PRINT CHR$(26)
160 REM
170 INPUT "City (3 letter code)";CITY$
175 INPUT "House ID (3 numbers)";HOUSE$
180 INPUT "House volume (FT^3)";VOL             'Input house volume (cu. ft.).
181 VOL=VOL*.0283                               'Convert volume to cu. meters.
182 INPUT "House floor area (FT^2)";AREA        'Floor area...
183 AREA=AREA*.0929                             'Convert area to square meters.
185 INPUT "HEIGHT OF CEILING ABOVE GRADE (FT) [dflt=10]";H
187 IF H=0 THEN H=10                            'Default is 10 feet.
190 H=H*.3048                                   'Convert ceil. hght. to meters.
200 INPUT "What is the R value";R
205 REM
210 INPUT "What is the X value";X
220 REM
260 INPUT "What is the tower height at the wind sensor (dflt=32.8 FT)";HP
270                                             'Input tower hght at wind site.
280 IF HP=0 THEN HP=32.8                        'Default is 10 m or 32.8 feet.
290 HP=HP*.3048                                 'Convert tower hght to meters.
300 INPUT "What is the local terrain class (1-5)[dflt=3]";TCL
302                                             'Input terrain class at site.
305 IF TCL=0 THEN TCL=3
306 INPUT "Are you going to use wind data from the airport (Y/N)";AIR$
307 IF AIR$="Y" OR AIR$="y" THEN TCP=2:GOTO 320
310 INPUT "What is the terrain class at wind sensor (1-5)";TCP
312                                       'Input terrain class at wind site.
320 INPUT "What is the local shielding class (1-5)";SC
325 IF SC=0 THEN SC=3                           'Default shielding class = 3.
330                                             'Input shielding class at site.
340 AL=TC(1,TCL):GA=TC(2,TCL)                   'Local terrain parameters.
350 ALP=TC(1,TCP):GAP=TC(2,TCP)                 'Terr. parameters for airport.
360 FOR I=1 TO 5
370     READ SCL(I)                             'Read shielding classes (1-5).
380     NEXT I
390 DATA .324,.285,.240,.185,.102
```

```
391 RESTORE
395 CP=SCL(SC)                                      'Shielding class for site.
400 '****************************************************************
404 '************** Begin Inputs for each test *********************
410 '****************************************************************
420 INPUT "Test phase (3 letter code)";TEST$
430 INPUT "Test Date";DATE$                         'Input date of measurement.
440 INPUT "Effective leakage area (IN^2)";ELA   'Input leakage area (sq.in).
445 ELA=ELA*6.4516                                  'Convert to sq.cm.
450 INPUT "Number of exhaust vents sealed";VENTS
455 INPUT "Number of dryer vents sealed";DRYER
460 INPUT "Number of fireplaces sealed";FIR
470 INPUT "Number of woodstoves sealed";WOD
472 INPUT "Number of heat exchangers sealed";HX
474 INPUT "Number of furnace flues sealed";FURN
475 INPUT "Other sealed leakage sites (sq.in.)";OTHER
477 GOSUB 5510          'Occupancy Tests
478 ADDELA=(VENTS*A1)+(DRYER*A2)+(FIR*A3)+(WOD*A4)+(HX*A5)+(FURN*A6)+(OTHER*6.45
479 AO=ELA+ADDELA                                   'Sum of sealed & meas. ELA.
480 PRINT:PRINT "      ELA (Sq. in.):  Total = ";AO/6.4516;"  Sealed for fan tes
482 PRINT
483 ADDELAOC=ADDELA+OCCELA
484 AOOCC=ELA+ADDELAOC
485 INPUT "Average windspeed during this phase (m/s)";WIND
490 INPUT "Average inside temperature during this phase (C)";TINS
500 INPUT "Average outside temperature during this phase (C)";TOUT
510 TI=TINS+273.16:TOU=TOUT+273.16                  'Convert to Kelvin.
520 REM
540 REM                 END INPUT SEQUENCE
560 REM
1000 REM
1050 REM                CALCULATE INFILTRATION RATES
1080 FT=(AL*(H/10)^GA)/(ALP*(HP/10)^GAP)           'Terrain factor, FT.
1090 FW=FT*CP*(1-R)^.33                            'Reduced wind parameter, FW.
1100 FSP=((1+R/2)/3)*(1-X^2/(2-R)^2)^1.5*SQR(9.8*H/TI)
1220    QS=FSP*AO*.0001*SQR(ABS(TOU-TI))           'Qstack, QS (m^3/sec).
1240    QW=FW*AO*WIND*.0001                        'Qwind, QW (m^3/sec).
1250 QSOCC=FSP*AOOCC*.0001*SQR(ABS(TOU-TI))
1255 QWOCC=FW*AOOCC*WIND*.0001
1260    Q=SQR(QS^2+QW^2)                   'Qtotal, Q (m^3/sec).
1280    ACH=(Q/VOL)*3600                           'Air changes per hour, ACH.
1290    QOCC=SQR(QSOCC^2+QWOCC^2+UNBAL^2)+AAHXBAL
1295    ACHOCC=(QOCC/VOL)*3600
1500 REM *****************************************************************
1510 REM                  PRINT RESULTS ON SCREEN
1520 REM *****************************************************************
1540 PRINT CHR$(26)                                         'Clear screen.
1550 PRINT:PRINT:PRINT
1560 PRINT " City: ";CITY$;"     House ID: ";HOUSE$;"   Test Phase: ";TEST$
1570 PRINT
1571 VOL$="VOLUME (FT^3) = ":AREA$="AREA (FT^2) = "
1575 PRINT "DATE OF FAN TEST: ";DATE$
1577 PRINT USING "& #####   & #### ";VOL$,VOL/.0283,AREA$,AREA*10.7639
```

```
1580 PRINT
1590 PRINT " Leakage Area (Sq.in.):  Total = ";A0/6.4516;" meas. = ";ELA/6.4516;
1595 PRINT"                  Occupied Total = ";A0OCC/6.4516
1600 PRINT
1605 PRINT " Specific Leakage Area (cm^2/m^2):  Total = ";A0/AREA;"  meas. = ";E
1610 PRINT
1620 PRINT "   Terrain Class = ";TCL" Shielding Class = ";SC
1625 IF AIR$="Y" THEN AIRMSG$="  (Airport)" ELSE AIRMSG$=""
1630 PRINT "   Terrain @ wind sensor = ";TCP;AIRMSG$
1640 PRINT
1700 REM
1720 REM NOW PRINT THE RESULTS...
1740 REM
1760 PRINT " ---------------------------------------------------------------"
1780 PRINT " Wind   Indoor Temp.  Outdoor Temp.    Infil:  ACH    FLOW
1790 PRINT " (m/s)      (C)            (C)                (hr-1) (m^3/hr)
1800 PRINT " ---------------------------------------------------------------"
1820 PRINT
1840 PRINT USING "  ##.#     ##.#          +##.# W/Out Occupants #.##   ####.#";
1850 PRINT USING "                               W/Occupants     #.##   ####.#";
1860 PRINT
2080 PRINT
2120 PRINT TAB(27);"<Hit ANY Key to Continue>";:JUNK$=INPUT$(1)
2130 PRINT
2140 PRINT:PRINT TAB(27);"Send output to printer";:INPUT ANS$
2150 IF ANS$="Y" OR ANS$="y"
      THEN GOSUB 3000:GOTO 2200
      ELSE IF ANS$="N" OR ANS$="n"
              THEN GOTO 2200
2160 GOTO 2140
2200 PRINT CHR$(26):PRINT:PRINT:PRINT:PRINT
2220 PRINT TAB(24);"Choose one of the following..."
2225 PRINT TAB(24);"------------------------------"
2230 PRINT TAB(20);"C> CALCULATE Ach for New House"
2232 PRINT TAB(20);"R> RE-calculate Ach for Same House"
2234 PRINT TAB(20);"S> SAVE current data on disk"
2236 PRINT TAB(20);"Q> QUIT"
2238 PRINT
2240 PRINT TAB(24); "Enter Your Choice ---> ";:INPUT ANS$
2320 IF ANS$="C" OR ANS$="c" THEN GOTO 155
2340 IF ANS$="R" OR ANS$="r" THEN GOTO 400
2360 IF ANS$="S" OR ANS$="s" THEN GOTO 4000
2380 IF ANS$="Q" THEN PRINT:PRINT:PRINT TAB(20);"EXECUTION TERMINATED"
2385 ELSE GOTO 2200
2700 END
3000 REM ***************************************************************
3010 REM                    PRINT RESULTS AT LINE PRINTER
3020 REM ***************************************************************
3021 LPRINT:LPRINT:LPRINT
3023 LPRINT "CITY:  ";CITY$;"     HOUSE ID: ";HOUSE$;"    TEST PHASE: ";TEST$
3025 LPRINT
3030 LPRINT "DATE OF FAN TEST: ";DATE$
3035 LPRINT USING "& #####    & #### ";VOL$,VOL/.0283,AREA$,AREA*10.7639
3040 LPRINT
```

```
3045 LPRINT  "LEAKAGE AREA  (SQ. IN.):  TOTAL = ";AO/6.4516;"  MEAS. =";ELA/6.45
3047 LPRINT "                    OCCUPIED TOTAL = ";AOOCC/6.4516
3050 LPRINT
3055 LPRINT  "SPECIFIC LEAKAGE AREA (CM^2/M^2):  TOTAL = ";AO/AREA;"  MEAS. = ";
3065 LPRINT
3070 LPRINT "   TERRAIN CLASS = ";TCL" SHIELDING CLASS = ";SC
3075 IF AIR$="Y" THEN AIRMSG$="  (AIRPORT)" ELSE AIRMSG$=""
3080 LPRINT  "   TERRAIN @ WIND SENSOR = ";TCP;AIRMSG$
3085 LPRINT
3089 GOSUB 8000
3090 REM
3095 REM NOW LPRINT THE RESULTS. . .
3100 REM
3105 LPRINT  "-------------------------------------------------------------------
3110 LPRINT  "WIND   INDOOR TEMP.   OUTDOOR TEMP.    INFIL:  ACH     FLOW
3115 LPRINT  "(M/S)     (C)             (C)                (HR-1) (M^3/HR)
3120 LPRINT  "-------------------------------------------------------------------
3125 LPRINT
3130 LPRINT USING  "##.#      ##.#            +##.# W/Out Occupants #.##   ####.#
3135 LPRINT USING  "                                W/Occupants     #.##   ####.#
3140 LPRINT
3145 LPRINT
3150 LPRINT CHR$(12)
3300 RETURN     'End subroutine...
4000 REM SAVE DATA ON FILE...
4020 PRINT CHR$(26):PRINT:PRINT:PRINT
4030 PRINT TAB(22);"THIS ROUTINE IS NOT READY YET!!!"
4040 GOTO 2200
5500 REM OCCUPANCY TEST
5510 INPUT "Ave. Number of Occupants at Home";OCCUP
5520 INPUT "Is there detail on occupant activities (Y/N)";OCC$
5530 IF OCC$="Y" OR OCC$="y" THEN GOSUB 6000 ELSE UNBAL=0:OCCELA=0:AAHXBAL=0:RET
5550 RETURN
5999 END
6000 REM OCCUPANCY INPUTS
6010 INPUT "Number of days in the test period (##.#)";TPDAY
6020 INPUT "Kitchen fan use";KITCH
6030 INPUT "Bath fan use (min)";BATH
6040 INPUT "Clothes Dryer use (min)";DRY
6050 INPUT "Fireplace use (min)";FIRE
6060 IF FIRE>0 THEN GOSUB 7000
6070 INPUT "Woodstove use (min)";WOOD
6080 INPUT "Number of Windows Open";WINNUM
6090 IF WINNUM>0 THEN GOSUB 7200 ELSE WINMIN=0
6110 INPUT "Minutes door open";DOOR
6120 INPUT "Any Other Unbalanced Flows";UNANS$
6130 IF UNANS$="Y" OR UNANS$="y" THEN GOSUB 7300 ELSE DEV=0
6150 INPUT "Is there an Air-Air Heat Exchanger"; HXANS$
6160 IF HXANS$="Y" OR HXANS$="y" THEN GOSUB 7100 ELSE AAHX=0
6180 REM CONVERSIONS
6190 OCCUPELA=1.9*OCCUP
6200 KITCHCFM=.139*KITCH/TPDAY
6210 BATHCFM=.052*BATH/TPDAY
```

```
6220 DRYCFM=.083*DRY/TPDAY
6230 FIRECFM=FIRECOF*FIRE/TPDAY
6240 WOODCFM=.042*WOOD/TPDAY
6250 DEVCFM=DEVCOF*DEV/TPDAY
6260 UNBAL=(KITCHCFM+BATHCFM+DRYCFM+FIRECFM+WOODCFM+DEVCFM)/2119.1
6270 WINELA=.15*WINMIN*WINNUM/TPDAY
6280 DOORELA=1.12*DOOR/TPDAY
6290 OCCELA=(OCCUPELA+WINELA+DOORELA)*6.4516
6300 AAHXCFM=.069*AAHX/TPDAY
6310 AAHXBAL=AAHXCFM/2119.1
6320 RETURN
7000 REM FIREPLACES
7010 INPUT "Does it have Glass Doors";PEN$
7020 IF PEN$="Y" OR PEN$="y" THEN FIRECOF=.031 ELSE FIRECOF=.101
7040 RETURN
7100 REM AAHX
7110 INPUT "Was AAHX operation time recorded";AAANS$
7120 IF AAANS$="Y" OR AAANS$="y" THEN INPUT "Minutes operated";AAHX ELSE AAHX=0
7130 RETURN
7200 REM WINDOWS
7210 INPUT "Minutes windows open";WINMIN
7220 RETURN
7300 REM OTHER DEVICES
7310 INPUT "Device time-flow coefficient";DEVCOF
7320 INPUT "Minutes device operated";DEV
7330 RETURN
8000 REM PRINT OCCUPANCY EFFECTS
8010 LPRINT "  OCCUPANCY EFFECTS:'
8020 LPRINT "  Number of occupants: ";OCCUP
8030 IF OCC$<>"Y" AND OCC$<>"y" THEN LPRINT "No Occupant Activities Data Was Rec
N
8040 LPRINT "                ITEM            MIN.      ELA/CFM
8045 LPRINT
8050 LPRINT USING"          Kitch. Fan        ####        ##.##";KITCH,KITCHCFM
8060 LPRINT USING"          Bath Fan          ####        ##.##";BATH,BATHCFM
8070 LPRINT USING"          Dryer             ####        ##.##";DRY,DRYCFM
8080 LPRINT USING"          Fireplace        #####        ##.##";FIRE,FIRECFM
8090 LPRINT USING"          Woodstove        #####        ##.##";WOOD,WOODCFM
8100 LPRINT USING"          Other Device     #####        ##.##";DEV,DEVCFM
8110 LPRINT USING"          UNBALANCE TOTAL              ###.##";UNBAL*2119.1
8120 LPRINT
8130 LPRINT USING"          Windows           ####        ##.##";WINMIN,WINELA
8140 LPRINT USING"          Doors             ####        ##.##";DOOR,DOORELA
8150 LPRINT USING"          Occupants                    ###.##";OCCUPELA
8160 LPRINT USING"          OCCUPANCY ELA TOTAL          ###.##";OCCELA/6.4516
8161 LPRINT
8162 LPRINT USING"          A-A HEAT EXCH.   #####       ###.##";AAHX,AAHXCFM
8163 LPRINT USING"                                 ACHR - #.##";(AAHXBAL/VOL)*3600
8165 LPRINT
8170 RETURN
```

APPENDIX E

BPA Ventilation Fan Study

Training Course Agenda

November 15, 1983

Tuesday 15 November — **Hollander Conf. Room 90/3026C**

Time	Topics	Responsible
9 AM	- Introduction to Indoor Air Quality Problem.	Grimsrud
	- BPA Ventilation Fan Study	Grimsrud
	- Air Quality Sampling Strategies	Grimsrud
	- Passive Sampler Design	Grimsrud
	- Sampler Deployment	Grimsrud
	Visit labs in Building 70:	
	- Passive Sampler Fabrications	Girman/Allen
	- Passive Sampler Analysis	Girman/Allen

Wednesday 16 November — **Test house (221 San Carlos)**

Time	Topics	Responsible
9 AM	- Deploy Samplers in Test house	Koonce/Turk
1 PM	Return to 90/3026C	

Wednesday 16 November — **90/3026C**

Time	Topics	Responsible
	- Description of Energy Signatures Monitor (ESM)	Szydlowski
	- Operation of Energy Signature Monitor	Szydlowski

BPA Ventilation Fan Study

Training Course Agenda (Version 11-9-83)

November 1983

Thursday 17 November		90/3026C
Time	Topics	Responsible
	- Operation of ESM with sensors	Szydlowski
	- Interfacing ESM with weather monitoring equipment	Szydlowski
1 PM	Active IAQ Monitoring Equipment	70/3377
	- The LBL Continuous Radon Monitor	Doyle/Grimsrud
	- The Interscan CO Monitor	Turk
	- The LBL Particulate Sampler	Grimsrud

Friday 18 November		Test house (221 San Carlos)
Time	Topics	Responsible
	- Demonstration Deployment of Active Instrumentation	Koonce/Turk
	- Summary Wrap-Up	Everyone

file memo