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April 1983

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I. INTRODUCTION

Increasing energy costs have created a demand for increased energy efficiency in buildings. This demand is potentially in conflict with the need to maintain adequate air quality. A major strategy to increase energy efficiency is to lower the amount of infiltration (or ventilation) in a building since infiltration typically accounts for 25 to 40% of the building's energy loss [1]. However, this action also reduces the effectiveness of the primary removal mechanism (ventilation) for pollutants that are generated within the building. Therefore, the increase in energy efficiency may be obtained at the cost of an increase in the concentration of indoor pollutants.

This chapter reviews measurements of indoor air quality in energy-efficient residences in the United States to determine if patterns of high pollutant concentrations are associated with the construction practices that lead to energy-efficient structures. Additional measurements are reviewed in houses of conventional design having low ventilation rates.

It is important to note that this sample is comprised of houses measured during field investigations by researchers at Lawrence Berkeley Laboratory (LBL). It is neither a statistically valid representation of the entire stock of energy-efficient houses in the United States nor does it represent the indoor air quality measurements made by other researchers who have examined this class of houses. It is a summary of work from the Energy Efficient Buildings Program at LBL.

II. CONSTRUCTION TECHNIQUES FOR RESIDENTIAL ENERGY EFFICIENCY

A. New Construction

Construction techniques in energy-efficient houses vary widely. While we do not presume to define this class of structures, we shall describe the houses in some detail and focus attention on features that may have significant impact on indoor air quality. Where possible, we shall describe the measured thermal performance of the houses.

While details differ, most energy-efficient construction has several features in common: extensive use of vapor barriers, double-glazed windows, extensive use of weatherstripping and high levels of insulation. The houses located in Eugene, Oregon described in this study are a good example of this type of construction. They are built in a modified "Arkansas" style, originally developed by the Arkansas Power and Light Company [2]. The houses are one story buildings with post and beam floor construction and ventilated crawlspaces with plastic groundcovers. Insulation levels include R-38 fiber-glass batts in the ceiling and R-19 in the walls and floor. Windows are double-glazed and limited to no more than 15% of the floor area. Exterior doors are of the insulated type with magnetic weatherstripping. Furnace ducts are placed within the heated part of the building.

A critical feature of these structures is the continuous vapor barrier installed on each exterior face of the house. The floor vapor barrier is one continuous 6-mil polyethylene sheet placed on top of the tongue and groove decking and below the floor underlayment. The ceiling vapor barrier is placed underneath the ceiling joists before the gypsum board is installed. A 12-inch wide polyethylene strip is stapled over the top plate of each interior wall that intersects the ceiling insulation. The wall vapor barrier is stapled to the exterior wall framing and lapped over the floor and ceiling vapor barriers. In addition, caulking is applied where the bottom plate of the exterior wall meets the decking and around all plumbing and electrical penetrations through the vapor barrier.

B. Retrofits

About 75% of residential housing in the United States is more than 10 years old, and 60% is more than 20 years old. With a replacement rate averaging about 1.5% per year [3], substantial conservation efforts must focus on weatherization of this existing stock. Older houses tend to be less tight than newer ones--the result of different construction techniques, aging and weathering. Consequently, opportunities for reducing infiltration in older houses are greater, but it is important to know which infiltration sites in a particular house can be eliminated in the most cost-effective manner.

Important leakage sites generally fall into one of four categories:

1. Building shell components, such as baseboards, windows and doors and their frames. Such leakage sites can be sealed with weatherstripping or caulk.

2. Building shell penetrations, such as plumbing pipes and vents, furnace registers and chimneys. These types of leaks are sealed with caulk or polymeric foam or, in the case of chimneys, installation of a damper or fireplace insert.

3. Design ventilation penetrations, such as kitchen and bathroom vents. These vents can significantly contribute to uncontrolled infiltration when they lack operable dampers.

4. Bypass channels, such as might occur around chimneys and flue pipes, above pocket (sliding) doors, or through stud spaces. Eliminating these sites requires fiberglass, polyethylene, foam, caulk and a

good deal of patience.

III. MEASUREMENT TECHNIQUES

A. Infiltration

Infiltration through a building envelope is the process of air passing through openings and cracks in the structure, such as those around windows, doors, plumbing and electrical penetrations, ducts, flue pipes, fireplaces, chimneys, and baseboards. The quantity of air that passes through a single opening is dependent upon such factors as ambient weather, location of the opening within the building, crack geometry, shielding of the various sides of the building and the surrounding terrain. As a result, air flow through an opening is neither constant from day to day nor equal to that of a similar opening in a near-by structure.

The most common way to directly measure infiltration is through the use of a tracer gas. The tracer--for example ethane, nitrous oxide, or sulfur hexafluoride--is injected into the building and the change of concentration with time is measured. The concentration of a tracer gas in an enclosed space depends upon the volume of gas injected into the space and the volume lost from the space through exfiltration. Several tracer gas techniques exist [4], but the one used most commonly is tracer decay. This involves injection of the gas to a known concentration into a space. After injection is terminated, the decrease in gas concentration as a function of time is measured to determine the rate of dilution of the gas and, therefore, the infiltration of outside air into the structure.

The infiltration rate, also called the "air exchange rate" of the structure, has units of air changes per hour (ach). Since air infiltration is dependent upon various changing conditions, such as wind velocity, inside and outside temperature and occupant behavior, it is not possible to generalize directly from measurements derived from a relatively short-term tracer gas decay test to infiltration rates that may occur under other conditions.

Tracer gas methods, while relatively accurate, are unable to provide information about air leakage sites in houses or to provide a means of determining infiltration under weather conditions different from those at the time of the test. A useful index of the relative "leakiness" of a house is the "effective leakage area," a quantity roughly equivalent to the effective orifice area in the building shell through which air is able to pass. Effective leakage area can be used in conjunction with an infiltration model developed at LBL [5] to calculate infiltration for a particular structure under a variety of meteorological conditions.

Effective leakage area is measured by a technique called "fan pressurization." Infiltration is typically driven by pressure differences across the building shell in the range of 0 to 10 Pascals (Pa) and is characterized by large, short-term fluctuations. Fan pressurization uses a door-mounted, variable-speed fan capable of moving large volumes of air into or out of a structure. When the pressure difference is much greater than 10 Pa, fan flow dominates infiltration and the latter may be disregarded; all air flowing through the fan must also be flowing through the building shell. At a given pressure differential and fan speed, the flow of air through the fan is determined by means of a previously established calibration curve. For each structure, measurements are taken under conditions of both pressurization and depressurization at a series of fixed pressure differentials (for example, from 10 to 70 Pa at a 10-Pa interval), generating a pressure versus flow curve. These data can then be used to find the effective leakage area of the house.

B. Indoor Air Quality

Indoor air quality measurements in the houses included in this report were obtained using two rather different measurement strategies.

During the period from 1978 through 1980 several energy-efficient houses were intensively monitored using a heavily instrumented facility called the EEB Mobile Laboratory. Figure 1 shows it deployed at a test site in Minnesota.

In order to use the mobile laboratory, air sampling lines are installed at several sites within the structure under study and terminated inside the laboratory where the air monitoring instrumentation is located. As a general practice, we also sample the outdoor air to determine the fraction of the pollution indoors that originates outside. For indoor sampling, we select three sites to account for the spatial distribution of pollutant sources and incomplete mixing of the interior air, both of which can cause variations in the pollutant concentration from one room to another. Air is sampled sequentially from these four locations with a microprocessor-controlled sampling and data logging system.

Table 1 lists the various parameters that can be measured by the mobile laboratory, and the relevant method or instrumentation it employs. Most of the gaseous pollutants, as well as air exchange rates and comfort and meteorological parameters can be measured on a continuous basis, as indicated. Several of the pollutants, however, because of instrumentation limitations, must be measured on a time-integrated basis. Often these measurements must be made directly at the sampling site rather than in the mobile laboratory. For example, radon (Rn) measurements are made in the structure under study for a one-week period using a portable battery-operated device which records the alpha decays from decaying Rn atoms. Formaldehyde and total aldehydes are collected over periods up to 24 hours using temperature- and flow-controlled gas bubblers. Other organic contaminants are collected over periods of hours using the porous polymer Tenax-GC as an adsorption medium. Inhalable particulates were fractionated according to size and collected on teflon filters, typically for 24-hour periods.

Recent developments in instrumentation presently permit a different type of field survey. Researchers now have access to inexpensive passive samplers that can measure average values of concentrations of Rn, nitrogen dioxide (NO_2), and formaldehyde. Combining these devices with instrumentation to measure infiltration and respirable suspended particulates opens the possibility of an extensive survey of indoor air quality in houses in the United States to determine the distribution of indoor air quality throughout a large sample of the housing stock.

In addition to the passive samplers that exist for monitoring Rn, NO_2, and formaldehyde, development has begun on a carbon monoxide (CO) and a carbon dioxide (CO_2) sampler. The advantages of passive samplers are clear. They are inexpensive, unobtrusive, and can be installed easily by relatively untrained personnel. On the other hand, they only can be used for long-term averages (typically one week), have restricted accuracy, and require laboratory analysis remote from a measurement location. If peak exposures are important for health effects, then passive samplers are unsuitable as a monitoring tool unless the source strength profile (e.g., the usage pattern for a combustion appliance) is known. However, if the measurement problem requires information concerning long-term exposures, then a passive sampler is quite adequate. This study contains results obtained using both types of sampling strategies.

IV. HOUSE DESCRIPTIONS

General features of energy-efficient housing design and low ventilation retrofits have been described in Section II. Tables 2 and 3 describe housing features, specific leakage area values, calculated infiltration rates, and measured energy use where available for each of the 36 houses included in this study. The code used to describe each house has the form: State/Heating System/Foundation Type/Occupants (Smoking)/Label. (The label differentiates otherwise identical houses.)

The specific leakage area is the effective leakage area normalized by dividing by the floor area of the house. The infiltration is calculated for the heating season (November through March) using the LBL infiltration model [5].

Figure 2 compares the specific leakage areas in this study with those of other groups of houses in different regions of North America.

V. INDOOR AIR QUALITY MEASUREMENTS

In this section we describe the results of measurements of radon (Rn), formaldehyde (HCHO), and combustion products -- primarily particles carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), and nitrogen dioxide (NO_2) -- that were sampled in the 36 houses described in Tables 2 and 3.

The discussion will proceed at two levels. We first compare the concentrations seen in these houses with available indoor air quality guidelines. We then discuss possible mechanisms that contribute to the results observed.

The comparison between measured pollutant concentrations and appropriate guidelines is difficult because no air quality standards exist for indoor pollutants in a non-occupational setting. Any comparisons we make are therefore tentative and must be considered in terms of the intentions of the various standards.

A. Radon

Measurements of Rn concentrations in 31 of the houses in the sample described in this report are plotted in Fig. 3, which shows Rn concentrations (in nCi/m^3) varying by over two orders of magnitude while the infiltration rate measured [in air changes per hour (ach)] varies by less than one order of magnitude. The geometric mean of the Rn concentrations shown is 1.0 nCi/m^3; the geometric mean of the infiltration measurements made during the Rn sampling is 0.35 ach.

The point corresponding to a Rn concentration of 25 nCi/m^3 is not a measurement error. This measurement was repeated many times with substantially the same result. Clearly, the source strength of Rn in this house is large. Since Rn is the decay product of radium-226 (Ra), an element in the radioactive decay chain of uranium 238 (U), and U is concentrated in certain geographical regions, we investigated the Rn concentrations in 37 additional houses located within 2 km of this house [17]. The results of these measurements are shown as open squares in Fig. 4.

Qualitatively, the two plots have a similar shape. Quantitatively, however, they are considerably different. The geometric mean of the measurements in Fig. 4 is 2.1 nCi/m^3 and 0.32 ach. The two circles connected by a line in Fig. 4 shows the difference in the geometric means of the two samples. Even though the infiltration rates are similar in the two samples, the Rn concentrations measured in the second sample are substantially different. The difference in geometric means is statistically significant at the 99% confidence level using a two-tailed t-test.

This difference is particularly important when we compare the number of measurements in the two samples that exceed a level of concern of 3 to 4 nCi/m^3. Four percent (2 of 53) of the measurements shown in Fig. 3 exceed 4 nCi/m^3, while 30% (11 of 37) exceed this level in Fig. 4.

Since the infiltration rates were similar in the two samples, the differences in concentrations observed must be related to differences in Rn source strengths. As indicated above, the houses sampled to obtain the data shown in Fig. 4 are all located near the single house in Fig. 3 that displayed the largest Rn concentration. The hypothesis that Rn source strength is related to local geological properties of soils is consistent with these observations.

B. Formaldehyde

The level of concern for formaldehyde in field measurements is 120 $\mu g/m^3$ (100 ppb)[7]. Two of the 36 houses in this sample (OR/EHP/SB/OS/A and CA/GFA/SB/OS/A) had average formaldehyde levels above 100 ppb.

The nature of the formaldehyde sources and the responses of sources to changes in environmental parameters (temperature, humidity, ventilation rate) is currently an active area of research. The complex nature of the problem is shown in Fig. 5. The left half of this figure shows the formaldehyde concentrations before and after weatherizing the twelve houses in the state of Washington. The right half of Fig. 5 illustrates changes in formaldehyde concentrations in nine houses in New York that occur when mechanical ventilation was used in this group of low-infiltration houses.

In this figure, an open circle represents the initial combination of air change rate and formaldehyde concentration while the final state is represented by a closed circle. If the formaldehyde source strength were constant and if formaldehyde were non-reactive so that its only removal mechanism were ventilation, the line connecting initial and final states in the figure should have a slope of minus one on a log-log plot. On the other hand, formaldehyde is reactive. Therefore, the slope of the line connecting initial and final states decreases as the reactivity of the gas increases until, in the limiting case that removal by non-ventilation (reactive) processes is much larger than removal by ventilation, the slope goes to zero (i.e., the concentration is independent of the ventilation rate).

The limiting cases, therefore, are states connected by lines having slopes of 0 and -1 if the source strengths remain constant. All other cases should exhibit slopes between these two values. Many of the observed changes shown in Fig. 5 violate this restriction. In some cases we partially understand the observations -- in other cases, we do not. Transitions 9 and 17 in the Washington sample also represent occupant changes as well as ventilation changes. Between the pre- and post-retrofit measurements, the occupants of house seventeen moved to house nine. Household furnishings that had previously caused the high pre-retrofit concentration of formaldehyde in house seventeen, now caused a high post-retrofit concentration in house nine after the move.

In the New York tests, the houses labeled 52 and 43 in Fig. 5 contained mechanical ventilation systems that were equipped with heat exchangers with water-permeable heat transfer surfaces. The results for these two houses suggest that formaldehyde, since it is water soluble, is exchanged along with water vapor between the supply and exhaust airstreams. However, house 49 which also exhibits the same minimal change between initial and final formaldehyde levels, does not have a heat exchanger using the same permeable core. This indicates that formaldehyde source strength variations may be as large as the variations observed in ventilation rates.

One final comment is in order. The infiltration values shown in Fig. 5 are not equivalent to one another. The infiltration values for the Midway houses are predicted values for the November through March heating season based on air leakage measurements of the house using fan pressurization. The pre-retrofit formaldehyde measurements are averages of ten twelve-hour samples taken during November. The post-retrofit measurements were made using the same procedure during the following January. Since the weather conditions during November are, on the average, milder than the entire heating season and those in January are more severe, the pre-retrofit infiltration values predicted will tend to be larger than actual while the post-retrofit values predicted will tend to be smaller than those that actually occurred.

The infiltration values reported for the New York study, on the other hand, are averages of measurements made during the same time period as formaldehyde was sampled.

To summarize, formaldehyde concentrations exceeded the 100 ppb level of concern in two of the 36 houses in this sample. Measurements in the same houses before and after significant changes occurred in ventilation rates suggest that (a) source strengths are not constant in time, or (b) site-specific removal mechanisms in addition to ventilation rates are important in determining the average concentration of formaldehyde in the indoor environment, or both. Further investigation of this behavior is continuing.

C. Combustion Products

Combustion products examined include particles, carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, formaldehyde. All studies of residences described in Tables 2 and 3 measured concentrations of formaldehyde and NO_2. The measurements made using the EEB Mobile Laboratory also monitored the other combustion pollutants listed above.

Many houses in this study are located in the Pacific Northwest where electricity is a primary energy source. Of the 36 houses in this report, eight contained combustion appliances and had occupants who smoked, ten contained combustion appliances and had non-smoking occupants and eight had no combustion appliances but occupants who smoked. The remaining houses contained no combustion sources. The house labels in Tables 4 and 5 indicate the houses that fit into each category.

The EEB Mobile Laboratory measured pollutant concentrations in twelve of these houses. The maximum average value of CO_2 measured was 1320 ppm; the maximum average value of CO was 3.3 ppm. Both values are below outdoor and occupational standards.

There is no ambient air standard for NO since there are no established adverse health effects from NO at concentrations observed in outdoor air. Two houses had average NO levels of 70 ppb.

Nitrogen dioxide was measured in all 36 houses. One house, WI/WS/BT/OS/A, contained a concentration of NO_2 (76 ppb) that exceeds the one year National Ambient Air Quality Standard of 50 ppb [8]. This same house also showed excessive levels of respirable suspended particulates (RSP) (92 $\mu g/m^3$). When smoking was stopped in the house for two days, the RSP level dropped to 6 $\mu g/m^3$ and the NO_2 level dropped to 64 ppb. The average difference between indoor and outdoor concentrations of NO_2 was examined for differences that might be related to the presence of combustion sources and/or smoking. The average concentration (indoor minus outdoor) in houses with no combustion sources or smokers was -2.9 ± 4.0 ppb. The average in houses with combustion appliances but no smoking was 1.9 ± 7.9 ppb; in houses with no combustion appliances but smoking, -2.1 ± 5.4 ppb; and in houses with combustion appliances and smoking, -1.9 ± 15.5 ppb. The differences in these means is only statistically significant when the group of houses with no sources is compared to the group having combustion appliances but no smokers. However, the difference in means is small, considerably below existing ambient air standards for NO_2

Two houses in the New York study, NY/EFA/BT/OS/A and NY/GFA/BT/OS/C, showed high levels of RSP (54 and 38 $\mu g/m^3$). Operating the mechanical ventilation caused the RSP levels to drop to 31 and 30 $\mu g/m^3$, respectively. Outdoor concentrations were approximately 12 $\mu g/m^3$ during these measurements. While occupants of both houses were smokers, NY/EFA/BT/OS/A also contained a wood stove that was not used, and NY/GFA/BT/OS/C contained a gas furnace, a gas stove, and a gas water heater.

VI. DISCUSSION OF RESULTS

The sample size of this survey is small -- therefore, it is inappropriate to draw firm conclusions about the characteristics of either energy-efficient houses or low-ventilation houses. However, some trends can be seen and are discussed below.

Measurements of pollutant concentrations yield distributions that are skewed toward high values. The distributions appear to be log-normal, although there are insufficient data to confirm this with any degree of certainty. The distributions of concentrations do show the long tail at higher concentrations which is particularly significant for total pollutant exposure for a large group of people.

The houses described in this study all had low infiltration rates. Yet most also had low pollutant concentrations. The range of concentrations seen was generally much larger than the range of infiltration rates in these houses. These results are consistent with the point of view that indoor air quality in houses is often dominated by pollutant sources rather than by pollutant removal mechanisms (i.e., ventilation).

The significant pollutants observed in these houses are not different than significant pollutants measured in studies of non-energy-efficient residences. There do not appear to be significant differences between building materials or other pollutant sources used in energy-efficient houses and those used in conventional houses.

These results have implications for projects that emphasize residential energy efficiency either in new construction or as a weatherization project in existing homes. One common component of such programs is the goal of reduced ventilation. Uncertainties about indoor air quality may deter implementation of such programs. While the concerns may be appropriate, these results indicate that low ventilation rates do not automatically yield indoor air quality problems.

We are not suggesting that indoor air quality is not an issue that must concern the public. Rather, we are emphasizing the trends reported above -- that indoor air quality is dominated by sources. Therefore, an appropriate strategy for a weatherization program is to include a program component to identify and control as many sources as possible. When uncertainties concerning indoor air quality exist, measurements of pollutant concentrations should be required. As the development of indoor air quality passive samplers expands, this becomes a realistic action to take.

VII. ACKNOWLEDGMENTS

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Table 1

Instrumentation in the EEB Mobile Lab for Monitoring Indoor and Outdoor Air Quality Parameters

Purpose	Method/Instrument	Manufacturer/Model
Continuous monitoring of the following parameters:		
Gases:		
CO_2	NDIR	Horiba PIR 2000
CO	NDIR	Bendix 8501-5CA
SO_2	UV fluorescence	Thermo Electron 43
NO, NO_x	Chemiluminescence	Thermo Electron 14D
O_3	UV absorption	Dasibi 1003-AH
Indoor temperature & moisture:		
Dry-bulb temperature	Thermistor	Yellow Springs 701
Relative humidity	Lithium chloride hygrometer	Yellow Springs 91 HC
Outdoor meteorology:		
Dry-bulb temperature	Thermistor	MRI 915-2
Relative humidity	Lithium chloride hygrometer	MRI 915-2
Wind speed	Generator	MRI 1074-2
Wind direction	Potentiometer	MRI 1074-2
Solar radiation	Spectral pyranometer	Eppley PSP
Infiltration	Automated controlled-flow measurement or tracer gas decay/IR absorption	LBL/Wilkes
Time-averaged monitoring of the following parameters:		
Gases:		
Radon	Electrostatic collection/ thermoluminescence	LBL
Formaldehyde/total aldehydes	Absorption (gas bubblers)/ colorimetry	LBL
Selected organic compounds	Tenax GC adsorption tubes/ GC analysis	LBL
Inhalable particulates (fine & coarse fractions)	Virtual impaction/ filtration	LBL
Data acquisition:		
	Microprocessor	Intel System 80/20-4
	Multiplexer A/D	Burr Brown Micromux Receiver MM6016 AA Remote MM6401
	Floppy disk drive	ICOM FD3712-56/20-19
	Modem	Vadic VA-317S

Table 2

General Features of Energy Efficient New Houses*

House Code	Specific Leakage Area (cm^2/m^2)	Infiltration Rate[a] (ach)	Energy Use ($W/^oC-m^2$)	Reference
CA/GFA/SB/ON/A	9.0	0.74	-	9,10
IA/EHP/BT/UN/A	0.9	0.21	-	9,10
MD/EHP/BT/UN/A	-	-	-	10
MN/EFA/BT/ON/A	0.6	0.08	-	9,11
CA/GFA/SB/OS/A	-	-	-	11
MN/HWO/BT/ON/A	0.7	0.12	-	9,11
OR/EFA/CS/OS/A	3.2	0.39	0.50	12
OR/EHP/CS/ON/A	2.3	0.29	0.50	12
OR/EHP/CS/ON/B	3.4	0.37	0.50	12
OR/EHP/SB/OS/A	2.9	0.35	0.50	12
NY/EFA/BT/ON/A	2.4	0.37	1.22	13
NY/EFA/BT/OS/A	2.8	0.42	--	13
NY/EFA/BT/OS/B	1.4	0.23	1.02	13
NY/GFA/BT/ON/A	2.5	0.42	--	13
NY/GFA/BT/OS/A	5.4	0.92	1.31	13
NY/GFA/BT/OS/B	2.0	0.38	--	13
NY/GFA/BT/OS/C	3.5	0.42	--	13
NY/EBB/BT/ON/A	1.4	0.22	0.81	13
NY/GFA/BT/ON/B	3.2	0.56	--	13
NY/GFA/BT/ON/C	2.7	0.40	--	13

*Houses built since 1977
[a]Calculated value for November through March.
House Code Symbols:

State	Heating System	Foundation	Occupants
CA	EBB - Electric Base Board	BT - Basement	ON - Occupants Nonsmoking
IA	EFA - Electric Forced Air	CS - Crawl Space	OS - Occupants Smoking
MD	EHP - Electric Heat Pump	SB - Slab	UN - Unoccupied
MN	GFA - Gas Forced Air		
NY	HWO - Hot Water - Oil		
OR			

Table 3

General Features of Low Ventilation Retrofit Houses

House Code[a]	Specific Leakage Area (cm^2/m^2)	Infiltration Rate (ach)	Energy Use ($W/^oC\text{-}m^2$)	Reference
WI/WS/BT/OS/A	--	--	--	11
OR/EFA/CS/OS/B	--	--	--	14
OR/EFA/CS/ON/A	--	--	--	18
NJ/GFA/BT/ON/A	4.6	--	--	14
WA/EBB/CS/OS/A	3.7	0.38	2.24	15,16
WA/EBB/CS/OS/B	3.0	0.30	2.24	15,16
WA/EBB/CS/ON/A	2.9	0.30	2.24	15,16
WA/EBB/CS/ON/B	2.7	0.28	1.29	15,16
WA/EBB/CS/OS/C	3.6	0.37	1.29	15,16
WA/EBB/CS/OS/D	3.6	0.36	2.24	15,16
WA/EBB/PB/OS/A	2.6	0.26	1.29	15,16
WA/EBB/PB/ON/A	2.5	0.25	2.24	15,16
WA/EBB/PB/ON/B	2.2	0.23	1.29	15,16
WA/EBB/PB/ON/C	2.8	0.28	1.29	15,16
WA/EBB/FB/OS/A	2.8	0.28	1.29	15,16
WA/EFA/FB/UN/A	3.1	0.32	2.24	15,16

[a]House Code Symbols:

State	Heating System	Foundation	Occupants
NJ	EBB - Electric Base Board	BT - Basement	ON - Occupied Nonsmokers
OR	EFA - Electric Forced Air	CS - Crawl Space	OS - Occupied smokers
WA	GFA - Gas Forced Air	PB - Partial Basement	UN - Unoccupied
WI	WS - Wood Stove		

Table 4. Pollutant Concentrations in Energy Efficient Houses

House Code[a]	Reference	CO_2[b] (ppm)	NO[c] (ppb)	NO_2[d] indoor/outdoor (ppb)	RSP[e] (μg/m^3)	CO[f] (ppm)	HCHO[g] (ppb)	INFIL[h] (ach)	Notes
NY/EFA/BT/ON/A	13			1/7			36	0.22	HX[i] off
				3/10			19	0.47	HX on
NY/EFA/BT/OS/A	13	830	16	4/16	54	0.8	29	0.38	HX off
		560	3	4/13	31	0.4	22	0.66	HX on
NY/EFA/BT/OS/B	13			1/9			7	0.30	HX off
				5/25			<5	0.61	HX on
NY/GFA/BT/ON/A	13			23/9			33	0.38	HX off
				20/12			19	0.78	HX on
NY/GFA/BT/OS/A	13			6/11			17	1.17	
NY/GFA/BT/OS/B	13			2/14			28	0.37	HX off
				6/29			29	0.61	HX on
NY/GFA/BT/OS/C	13	740	38	11/15	38	1.4	30	0.42	HX off
		650	35	16/11	30	1.3	29	0.64	HX on
NY/EBB/BT/ON/A	13			3/12			64	0.28	HX off
				1/11			62	0.73	HX on
NY/GFA/BT/ON/B	13			10/15				0.50	HX off
				9/18			18	0.61	HX on
NY/GFA/BT/ON/C	13			12/18			57	0.33	HX off
				13/18			42	0.52	HX on
CA/GFA/SB/ON/A	9,10	580	24	24/14		3.1	72		
IA/EHP/BT/UN/A	9,10	520	9	12/9		2.5	47	0.19	
MD/EHP/BT/UN/A	10	610	5	9/18	8	1.2	82	0.15	
MN/EFA/BT/ON/A	9,11	1180	5	15/16	7	0.5	69	0.1	HX off
		720	2	16/15	7	0.4	73	0.3	HX on
MN/HWO/BT/ON/A	9,11	1320	70	19/16	20	0.7	80	0.1	HX off
		480	5	20/13	8	0.4	64	0.3	HX on
CA/GFA/SB/OS/A	11	690	44	42/36	33	1.4	214	0.4	
OR/EFA/CS/OS/A	12			7/9			50	0.27	
OR/EHP/CS/ON/A	12			2/7			55	0.19	
OR/EHP/CS/ON/B	12			2/9			94	0.17	
OR/EHP/SB/OS/A	12			5/8			100	0.19	

[a]House Code Symbols:

State	Heating System	Foundation	Occupants
CA	EBB - Electric Base Board	BT - Basement	ON - Occupants Nonsmoking
IA	EFA - Electric Forced Air	CS - Crawl Space	OS - Occupants Smoking
MD	EHP - Electric Heat Pump	SB - Slab	UN - Unoccupied
MN	GFA - Gas Forced Air		
NY	HWO - Hot Water - Oil		
OR			

[b]CO_2 = Carbon Dioxide
[c]NO = Nitric Oxide
[d]NO_2 = Nitrogen Dioxide
[e]RSP = Respirable Suspended Particulates
[f]CO = Carbon Monoxide
[g]HCHO = Formaldehyde
[h]INFIL = Infiltration Rate
[i]HX = Heat Exchanger

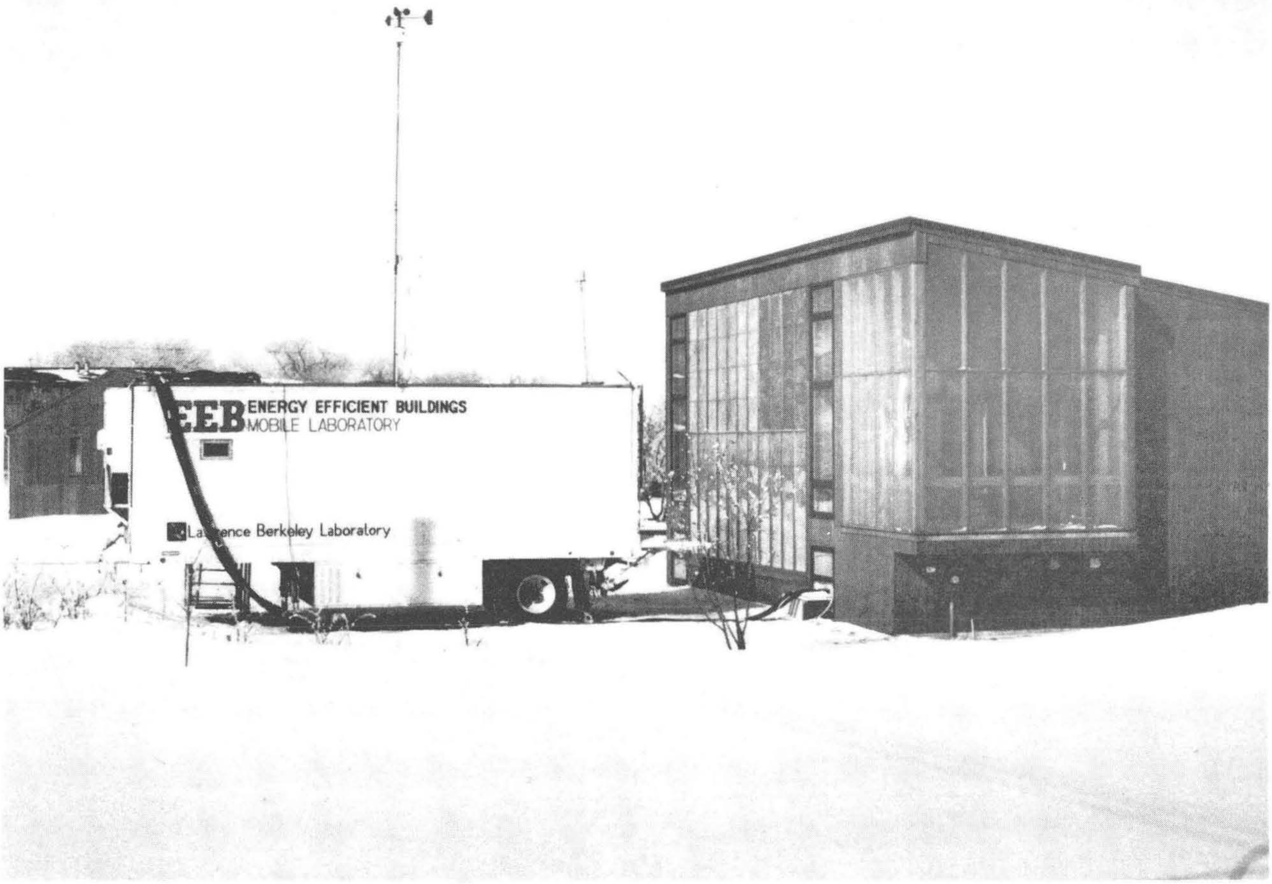
Table 5. Pollutant Concentrations in Low Ventilation Retrofit Houses.

House Code[a]	Reference	CO_2[b] (ppm)	NO[c] (ppb)	NO_2[d] indoor/outdoor (ppb/ppb)	RSP[e] ($\mu g/m^3$)	CO[f] (ppm)	HCHO[g] (ppb)	INFIL[h] (ach)	Notes
WI/WS/BT/OS/A	11	1130	72	76/38	6	2.2	53	0.3	No smoking
				64/35	92				Smoking
OR/EFA/CS/OS/B	14	700	4	6/8	20	0.4	55	0.43	Pre-retrofit
		885	7	4/7	22	0.3	53	0.30	Post-retrofit
OR/EFA/CS/ON/A	14	820	9	4/11	12	0.3	68	0.49	Pre-retrofit
		830	8	4/11	10	0.3	51	0.35	Post-retrofit
NJ/GFA/BT/ON/A	14	800	53	27/15	12	3.0	22	0.44	Pre-retrofit
		740	48	31/20	8	3.3	19	0.39	Post-retrofit
WA/EBB/CS/OS/A	15,16			2/3			<5	0.50	Pre-retrofit
				2/3			21	0.38	Post-retrofit
WA/EBB/CS/OS/B	15,16			4/3			5	0.43	Pre-retrofit
				3/2			17	0.30	Post-retrofit
WA/EEB/CS/ON/A	15,16			3/2			28	0.44	Pre-retrofit
				3/3			24	0.30	Post-retrofit
WA/EEB/CS/ON/B	15,16			1/3			12	0.36	Pre-retrofit
				2/3			8	0.28	Post-retrofit
WA/EEB/CS/OS/C	15,16			4/1			34	0.39	Pre-retrofit
				3/2			16	0.37	Post-retrofit
WA/EEB/CS/OS/D	15,16			3/2			15	0.42	Pre-retrofit
				3/3			10	0.36	Post-retrofit
WA/EEB/PB/OS/A	15,16			1/3			<5	0.33	Pre-retrofit
				3/4			69	0.26	Post-retrofit
WA/EEB/PB/ON/A	15,16			2/2			19	0.36	Pre-retrofit
				2/3			31	0.25	Post-retrofit
WA/EEB/PB/ON/B	15,16			1/2			44	0.25	Pre-retrofit
				2/2			49	0.23	Post-retrofit
WA/EEB/PB/ON/C	15,16			3/2			<5	0.40	Pre-retrofit
				3/2			19	0.28	Post-retrofit
WA/EEB/FB/OS/A	15,16			2/2			79	0.37	Pre-retrofit
				1/3			13	0.28	Post-retrofit
WA/EFA/FB/UN/A	15,16			2/3			<5	0.46	Pre-retrofit
				1/4			7	0.32	Post-retrofit

[a]House Code Symbols:

State	Heating System	Foundation	Occupants
NJ	WS - Wood Stove	BT - Basement	OS - Occupied Smokers
OR	EFA - Electric Forced Air	CS - Crawl Space	ON - Occupied Nonsmokers
WA	EEB - Electric Baseboard	PB - Partial Basement	UN - Unoccupied
WI	GFA - Gas Forced Air	FB - Full Basement	

[b]CO_2 = Carbon Dioxide
[c]NO = Nitric Oxide
[d]NO_2 = Nitrogen Dioxide
[e]RSP = Respirable Suspended Particulates
[f]CO = Carbon Monoxide
[g]HCHO = Formaldehyde
[h]INFIL = Infiltration Rate



CBB 806-7077

Figure 1 The EEB Mobile Laboratory at a field measurement site in Minnesota.

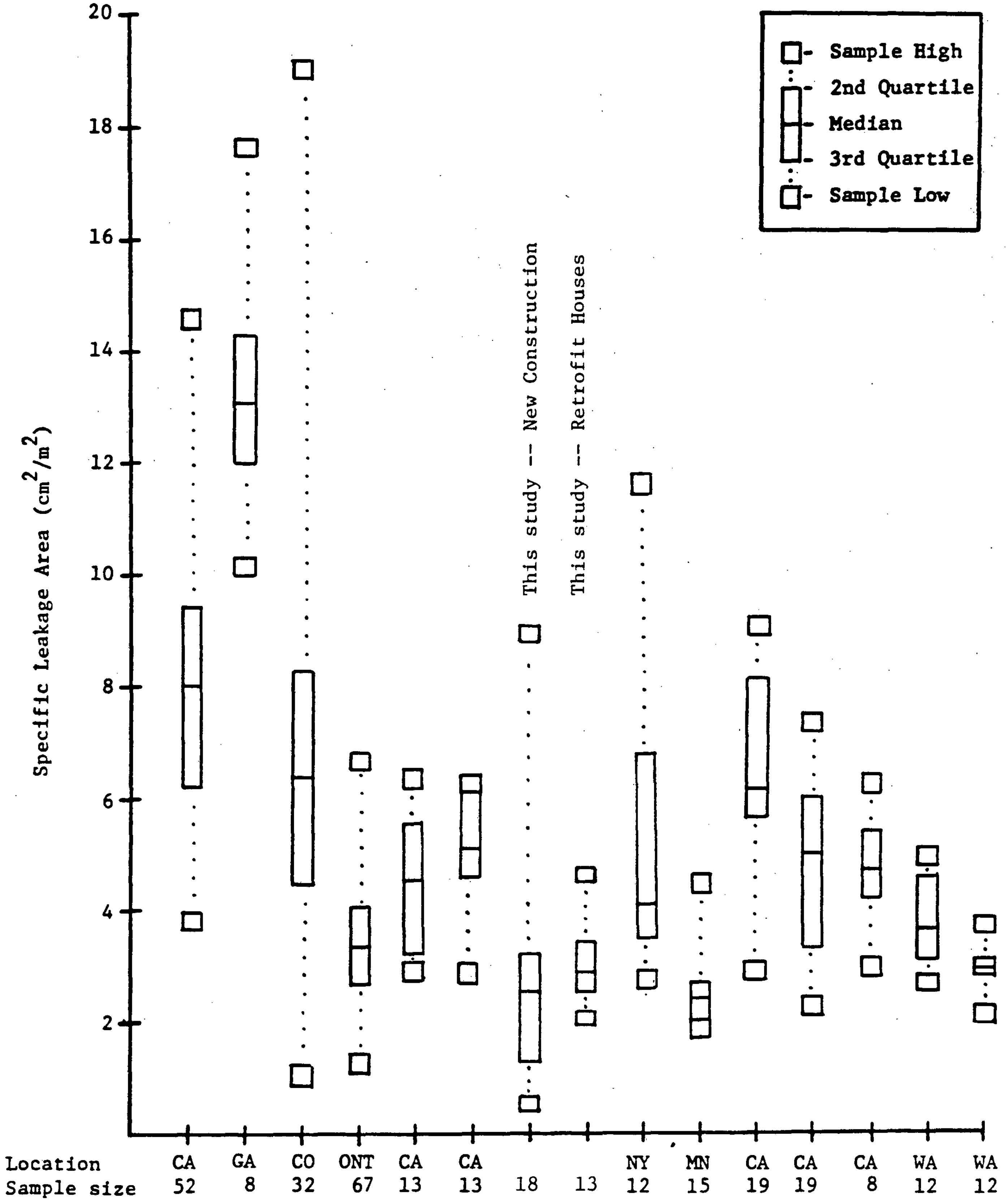


Figure 2 Specific leakage areas of houses in this study compared to other groups of measured houses.

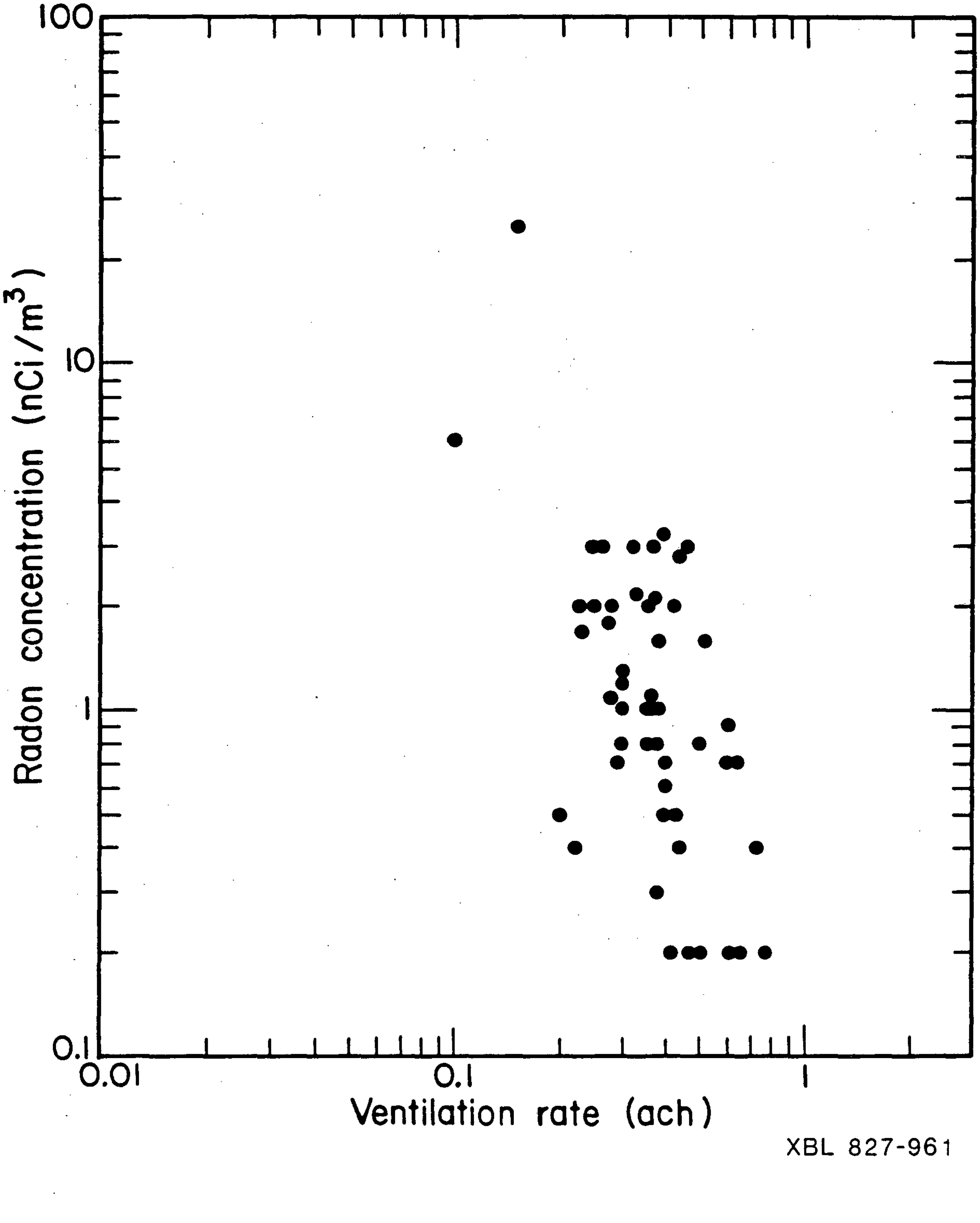


Figure 3 Radon concentrations and infiltration rates in 31 energy-efficient houses. The geometric mean of this distribution is 1.0 nCi/m^3 and 0.35 ach.

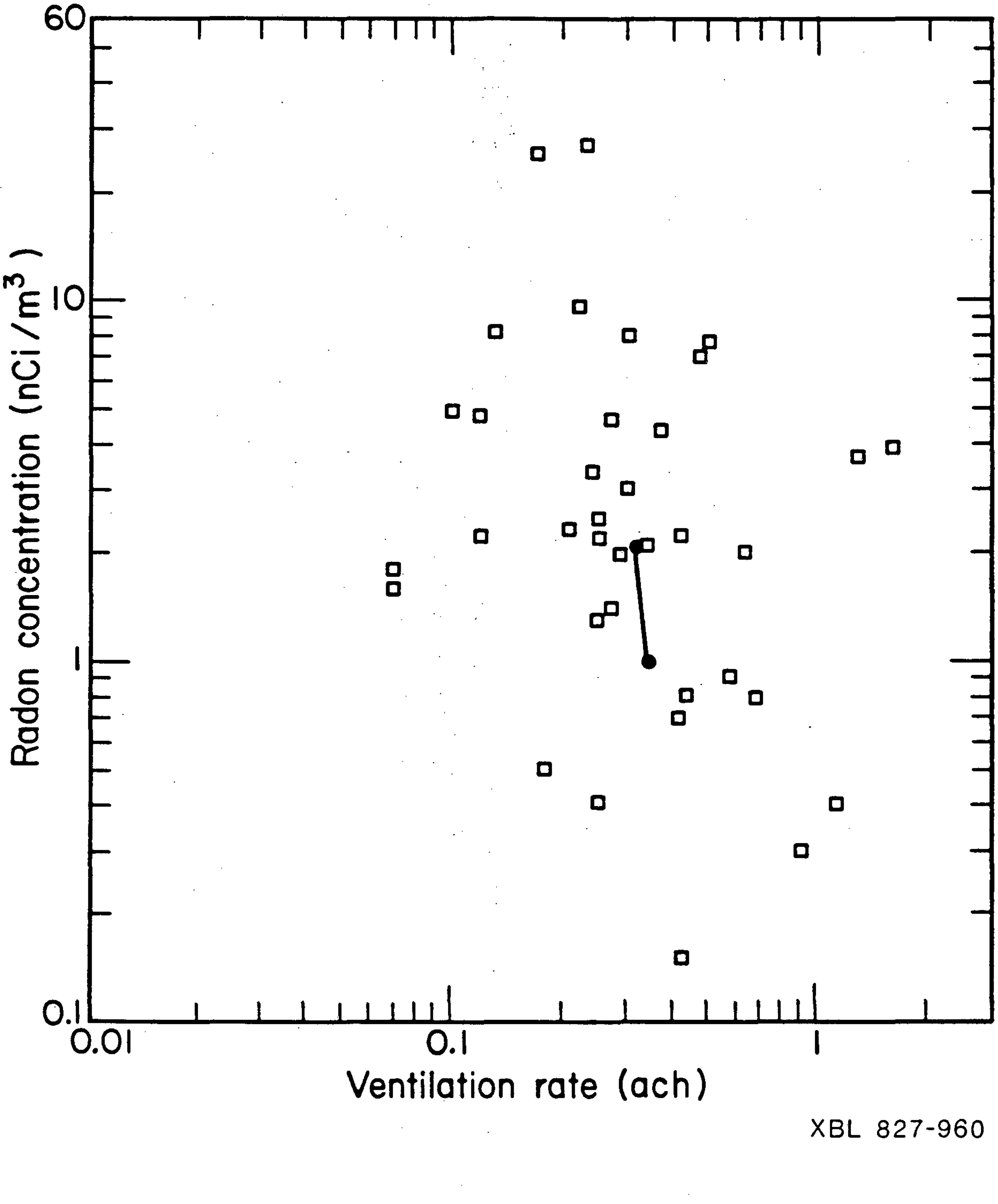


Figure 4 Radon concentrations and infiltration rates in 37 houses in Carroll County, Maryland. The circles indicate the geometric means of Figure 3 and this Figure.

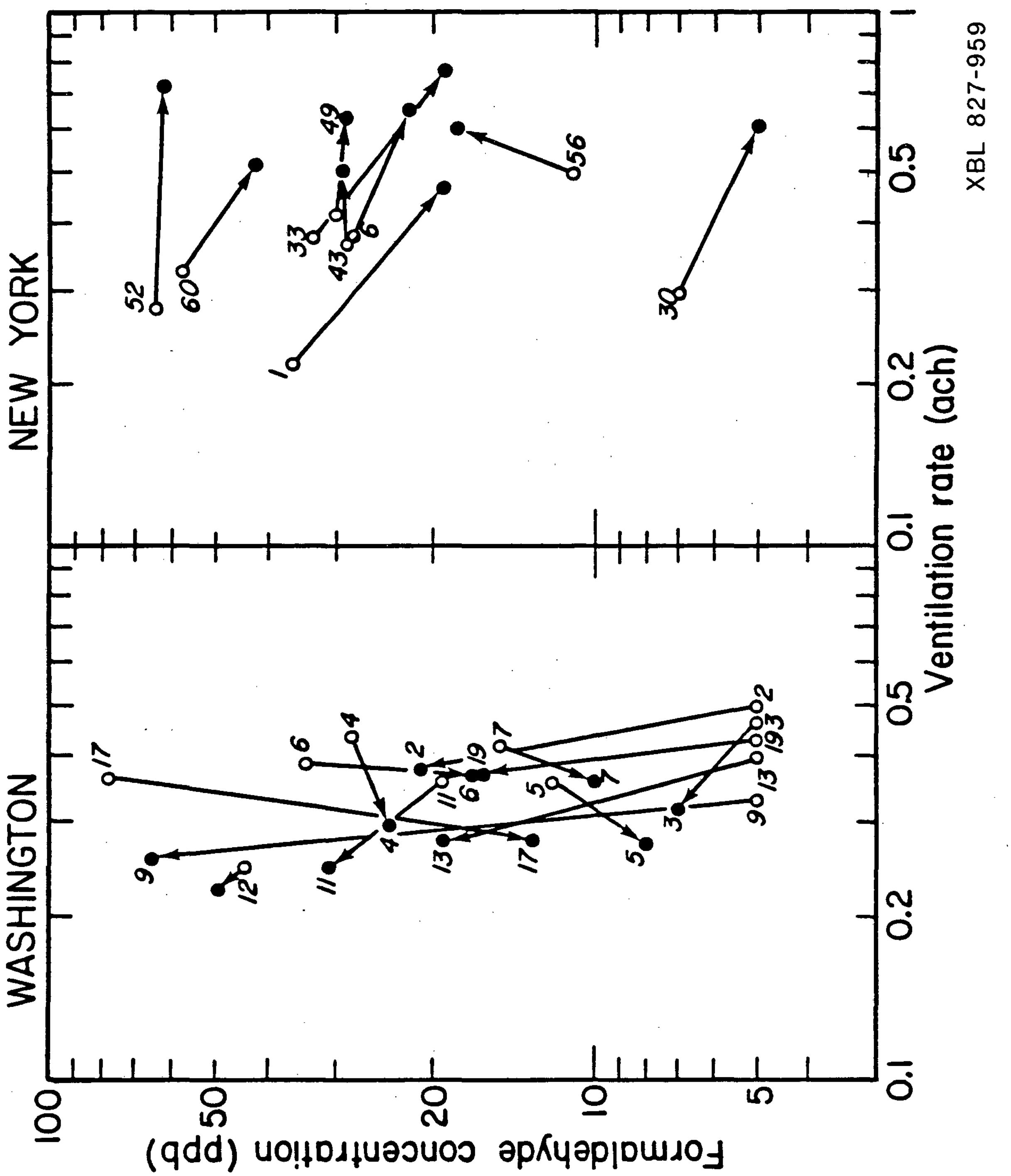


Figure 5 Changes in formaldehyde concentrations with changes in ventilation rate in studies in Washington and New York. The open circle represents the initial combination of concentration and air change rate; the closed circle, the final combination.

Appendix A

House Designations in Other References

House Code (This paper)	Alternate House Code	Reference	Alternate House Code	Reference
CA/GFA/SB/ON/A	Med-1	10		
IA/EHP/BT/UN/A	ISUERH	10		
MD/EHP/BT/UN/A	ERHM	10		
MN/EFA/BT/ON/A	Northfield	11		
CA/GFA/SB/OS/A	Mission Viejo	11		
MN/HWO/BT/ON/A	Dundas	11		
WI/WS/BT/OS/A	Rio	11		
OR/EFA/CS/OS/B	House #1	14		
OR/EFA/CS/ON/A	House #2	18		
NJ/GFA/BT/ON/A	Cranbury	14		
OR/EFA/CS/OS/A	B	12		
OR/EHP/CS/ON/A	J	12		
OR/EHP/CS/ON/B	51	12		
OR/EHP/SB/OS/A	52	12		
NY/EFA/BT/ON/A	1	13		
NY/EFA/BT/OS/A	6	13		
NY/EFA/BT/OS/B	10	13		
NY/GFA/BT/On/A	33	13		
NY/GFA/BT/OS/A	37	13		
NY/GFA/BT/OS/B	45	13		
NY/GFA/BT/OS/C	49	13		
NY/EBB/BT/ON/A	52	13		
NY/GFA/BT/ON/B	56	13		
NY/GFA/BT/ON/C	60	13		
WA/EBB/CS/OS/A	2	16	1	15
WA/EBB/CS/OS/B	3	16	2	15
WA/EBB/CS/ON/A	4	16	3	15
WA/EBB/CS/ON/B	5	16	4	15
WA/EBB/CS/OS/C	6	16	5	15
WA/EBB/CS/OS/D	7	16	6	15
WA/EBB/PB/OS/A	9	16	7	15
WA/EBB/PB/ON/A	11	16	8	15
WA/EBB/PB/ON/B	12	16	9	15
WA/EBB/PB/ON/C	13	16	10	15
WA/EBB/FB/OS/A	17	16	11	15
WA/EFA/FB/UN/A	19	16	12	15

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