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INFILTRATION AND INDOOR AIR QUALITY IN ENERGY EFFICIENT HOUSES IN EUGENE, OREGON

R.D. Lipschutz, J.R. Girman, J.B. Dickinson, J.R. Allen, and G.W. Traynor

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ABSTRACT

Measurements of infiltration rates and indoor pollutant levels in houses incorporating energy-conserving measures can provide important information about the effectiveness and health effects of such measures. Twelve energy-efficient houses in Eugene, Oregon were measured for effective leakage area using blower door fan pressurization. Air exchange rates over a period of several hours were determined by tracer gas decay analysis. The results of these measurements were used in conjunction with the LBL infiltration model to predict average annual and heating season infiltration rates. Measured leakage areas and infiltration rates were found to be quite low in comparison to other groups of test houses in North America. Average specific leakage areas for the 12 houses was 2.8 cm^2/m^2 as compared to 6.4 cm^2/m^2 for post-1975 California housing. The average heating season infiltration rate was calculated to be 0.34 air changes per hour. Infiltration rates measured from tracer gas decay ranged from 0.08 to 0.27 air changes per hour. Indoor concentrations of radon, formaldehyde, and nitrogen dioxide were measured in four of the twelve houses. Radon levels were found to be insignificant. Nitrogen dioxide concentrations were low in all four houses, although levels in the two houses where occupants smoked were slightly elevated by comparison to the two houses without smokers. Levels of formaldehyde comparable to or half of the most restrictive existing guideline were found in all four houses. Furniture and/or building materials are believed to be the source of this pollutant.

Key words: Infiltration, Pressurization,
Leakage Area, Tracer Gas, Air Quality, Radon,
Formaldehyde, Nitrogen Dioxide

INTRODUCTION

Air infiltration constitutes about 25 to 40 percent of the heating season energy load in insulated residential structures [1]. Thus, reduction of this type of energy loss is an important element of energy conservation efforts. Beyond traditional infiltration reduction measures (for example caulking and weatherstripping), new construction techniques such as continuous vapor barriers promise much lower infiltration rates in new residential housing. These techniques are finding increasing acceptance among builders in the United States. Measurements of infiltration rates in houses incorporating these new techniques can confirm their effectiveness. Such measurements are particularly useful because of the feedback they can provide to builders. This is important since careful installation practices make an enormous difference in achieving reduced air exchange rates (and are much more critical than is the case with insulation). However, one important problem associated with low-infiltration buildings is that concentrations of indoor-generated pollutants tend to be higher than those in well-ventilated houses. This is so because a primary pollutant removal mechanism is dilution and flushing with outside air [2].

In order to assess the energy-conserving potential of these new construction techniques and their effect upon indoor air quality, in April and May 1981, two research teams from the Energy Efficient Buildings Program at Lawrence Berkeley Laboratory (LBL), under contract to the Bonneville Power Administration (BPA), performed air infiltration measurements on 12 energy-efficient houses and air quality tests in four of the houses. The measurements were requested as background data for an energy conservation incentive program under development by BPA for home-builders in the Pacific Northwest. The houses were built in Eugene, Oregon between 1976 and 1979 by Modena Homes, Inc. and are part of a special group being monitored for energy consumption patterns by the Eugene Water & Electric Board. Nine of the 12 houses were constructed to meet "Energy Efficient Building Standards" established by the local utility, the Eugene Water & Electric Board (EWEB) [3].

The energy saving features incorporated into the Eugene energy-efficient houses are based on research conducted by Arkansas Power and Light, the Harry Tschumi Company and the U.S. Department of Housing and Urban Development [4]. The energy-efficient construction design used by Modena Homes, Inc. will be referred to as the "Arkansas-style" construction throughout this report.

In order to evaluate the energy-conserving potential of such construction techniques, effective leakage areas and air exchange rates were measured in the twelve houses using blower door fan pressurization and tracer gas decay analysis. In addition, "smoke sticks" were used during building pressurization to identify specific leakage sites through the building envelope. The results of these measurements were used in conjunction with the LBL infiltration model to predict average annual and heating season infiltration rates [5].

Because of concern about the potential effect of reduced infiltration on indoor air quality in houses, four of the twelve houses were selected for an air quality study. Among potentially hazardous indoor pollutants are combustion products (gaseous and particulate chemicals from cooking, heating, and tobacco smoking), odors and micro-organisms from occupants, a broad spectrum of chemicals outgassed by building materials and furnishings, and chemicals (toxic and otherwise) released into the air by cleaning products and other materials used by occupants. Excessive levels of humidity may also be a problem in low infiltration houses. (Table 1 lists some indoor contaminants identified as potential hazards and their sources.) Two of the houses selected for study were Arkansas-style houses and two included many of the Arkansas-style techniques but also incorporated passive solar features. The four test houses were monitored for concentrations of radon-222, formaldehyde, nitrogen dioxide and humidity. In addition, homeowners were asked to keep a log of open doors and windows during the indoor air quality measurements.

Table 1. Summary of sources and types of indoor air pollutants

SOURCES	POLLUTANT TYPES
OUTDOOR	
Stationary Sources	SO_2, NO, NO_2, O_3, Organics, CO, Particulates
Motor Vehicles	CO, NO, NO_2, Pb, Particulates
INDOOR	
Building Construction Materials	
Concrete, stone	Radon and other radioactive daughter elements
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Organics, Lead, Mercury
Building Contents	
Heating and cooking combustion appliances	CO, SO_2, NO, NO_2, Particulates, H_2O
Furnishings	Organics, Odors
Water service; natural gas	Radon
Human Occupants	
Metabolic activity	H_2O, CO_2, NH_3, Organics, Odors
Human Activities	
Tobacco smoke	CO, NO_2, HCN, Organics, Odors, Particulates
Aerosol spray devices	Fluorocarbons, Vinyl Chloride, CO_2, Odors
Cleaning and cooking products	Organics, Odors
Hobbies and crafts	Organics, Odors
Washing, showering	Water vapor

This paper presents the results of the infiltration and air quality measurements made on the Eugene houses. The paper begins with brief descriptions of the test site, the construction techniques used in the energy-efficient houses, and the infiltration and air quality measurement techniques used in the project. Then, we present and discuss results, including the "tightness" of the houses, experimental and calculated infiltration rates for all 12 houses, and observed concentrations of contaminants in the four houses tested for air quality. Finally, we present our conclusions about the effectiveness of the construction techniques used in the Eugene Arkansas-style houses (relative to reducing air infiltration and the effect of these techniques upon indoor air quality. A detailed description of infiltration and air quality measurement theory and techniques can be found in Appendix A and a discussion of the effect of occupant behavior upon formaldeyhde levels in one of the houses can be found in Appendix B.

SITE DESCRIPTION

Eugene, Oregon is located in the Willamette Valley, along the banks of the Willamette River. Low hills are a dominant feature of the local terrain, although 11 of the 12 test houses are located in the very flat former floodplain of the Willamette. Eugene is flanked both to the east and west by mountain ranges. The Coast Range rises about 30 miles west of Eugene, while some 25 miles east of the city is the Cascade Range. These mountain ranges have a moderating effect on climate. Snow is rare but annual rainfall is fairly heavy. Complete or partial cloud cover occurs an average of 290 days per year. Temperatures are moderate throughout the year, generally averaging 39.4°F in January and 66.9°F in July. Mean annual wind velocity is 7.6 mph, ranging from a high of 8.5 mph in March to a low of 6.6 mph in September. Annual heating degree days number 4739 (base 65°F). Storm systems move in a west to east direction throughout the year and prevailing winds are from the southwest during the winter and northwest during the summer.

BUILDING DESCRIPTIONS

Nine of the twelve homes tested in Eugene are built to the energy efficiency standards of the Arkansas-style construction while the remaining three are Arkansas-style homes incorporating passive solar features. The nine non-solar houses are built to meet Energy Efficient Building Standards established by EWEB. These standards are not binding, but a house built according to the EWEB specifications receives a special certificate from the Board.

The EWEB standards apply to the type and installation of windows and doors, construction of floors, walls, ceilings, placement and sizing of heating and cooling systems, installation of dehumidifiers, type and location of combustion air supply to fireplaces and wood stoves, installation of plumbing and electrical systems, type and placement of appliances, and choice of building color. Insulation levels and types of weatherstripping are specified. Houses intended to meet the EWEB standards are inspected three times during construction to ensure compliance.

The energy conserving features in both the energy-efficient and the passive solar houses include: R-38 ceiling insulation, R-19 wall insulation, R-19 floor insulation, double-pane windows, insulated exterior doors with magnetic weatherstripping, and furnace ducts located within the heated space of the building.

The floor areas for the energy-efficient houses range from 870 to 1440 square feet, with six of the nine houses clustered at 1100 to 1200 square feet. The passive solar houses have floor areas ranging from 1200 to 1600 square feet. All of the houses are one-story construction, except for Solar 3 which is two stories. The nine energy-efficient houses are built with post-and-beam floor construction and have ventilated crawlspaces with plastic groundcovers. Two of the passive solar houses have combined crawlspace and slab floor construction while the third is built entirely on a slab. Table 2 summarizes relevant construction data for the 12 houses.

Table 2: Description of Eugene, Oregon Houses

House ID	Date of Construction	Floor Area (ft.^{2})	Volume (ft.^{3})	Heating System*	Wood-Burning Appl.**	Bath & Dryer Vents	Floor+	Comments
A	1977	1,152	9,178	HP	FP	3/1	PB/crawl	
B	1977	1,156	9,178	FA	FP	3/1	PB/crawl	
C	1976	1,100	8,790	RC	FP	3/1	PB/crawl	No ductwork in house
D	1976	1,100	8,790	FA	FP	2/1	PB/crawl	FP covered with plastic
E	1977	1,166	9,319	HP	FP	3/1	PB/crawl	Solar water heater
F	1977	1,100	8,790	HP	FP	3/1	PB/crawl	
H	1979	870	6,954	FA	WS	2/1	Ply/crawl	Duplex, party wall with "I"
I	1979	870	6,954	FA	WS	2/1	Ply/crawl	Duplex, party wall with "H"
J	1979	1,440	11,508	HP	FP	3/1	Ply/crawl	
Solar 1	1979	1,507	13,767	HP/PS	WS	3/1	Ply/crawl, slab	Clerestory, thermal storage area
Solar 2	1979	1,200	10,343	HP/PS	WS	2/1	Slab only	Clerestory, 2 sunspaces
Solar 3	1979	1,582	12,990	HP/PS	WS	3/1	Ply/crawl, slab	2 stories; greenhouse, clerestory, thermal storage area

*HP: central heat pump; FA: central forced air electric resistance; RC: radiant ceiling electric resistance; PS: passive solar features

**FP: fireplace; WS: wood stove

+PB: particle board; Ply: plywood; crawl: crawlspace; slab: concrete slab

A continuous vapor barrier is installed on each exterior surface of the building. The floor vapor barrier is one continuous 6-mil polyethylene sheet which is 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 twelve-inch wide polyethylene strip is stapled over the top plate of each interior wall intersecting the ceiling vapor barrier and is held in place by the weight of 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.

The continuous vapor barrier virtually assures that relative humidity in the occupied buildings will exceed 50 percent during the heating season, thereby eliminating any adverse effects of low humidity levels. This leaves only the matter of high relative humidity, which can cause mildew and/or decay in the building itself and/or its contents, and can have an adverse effect on occupant comfort and health [6]. Consequently, all 12 houses include a built-in dehumidifier to hold relative humidity near the 50 percent level. Dehumidifier settings permit adjustment to achieve desired relative humidity down to about the 45 percent level. (EWEB standards suggest an internal relative humidity of less than 60 percent; 50 percent is considered optimal.)

Seven of the twelve houses have central forced-air heat pumps while four are equipped with electric resistance forced-air heating systems. One house has a radiant heating system located in the ceiling. (The passive solar houses use heat pump systems for auxiliary heating as well as summertime cooling.) All twelve houses have either woodburning stoves or fireplaces with glass doors and metal inserts (not necessary for heating, however). Both stoves and fireplaces are equipped with external combustion air inlets with adjustable dampers. No other types of combustion appliances were reported or observed in any of the houses.

MEASUREMENT TECHNIQUES

Infiltration

The two techniques used to measure infiltration in the Eugene energy-efficient homes are fan pressurization and tracer gas decay. Fan pressurization involves the use of a large fan, or "blower door," to push air into (pressurize) or pull air out of (depressurize) a structure. Analysis of the relationship between air flow through the fan and the pressure difference between the inside and outside of the house makes it possible to calculate the "effective leakage area," or simply "leakage area," for the structure. By combining this number with local wind and temperature data and general topographic features, it is possible to estimate seasonal average air exchange rates using a theoretical infiltration model developed at LBL [7].

Fan pressurization measurements were made with each house in two leakage conditions: furnace registers sealed with plastic and registers unsealed. (The latter configuration allows the effects of duct leakage to be isolated from those of the building shell.) Bathroom fans, utility fans, and dryer vents were covered with plastic and kept sealed and fireplace and woodstove dampers and combustion air inlets were kept closed during the entire test. While the house was pressurized, potential leakage sites were inspected using "smoke sticks" in order to visually follow the flow of air through the building envelope.

Tracer gas decay involves injection of a gas (in this case, sulfur hexafluoride or SF_6) into the structure. After mixing with ambient air,some of the tracer gas escapes through the envelope. Thus, measurement of the change in tracer gas concentration allows one to determine the infiltration rate of the structure during the test period. However, because air infiltration is dependent upon various changing conditions, such as wind velocity, inside and outside temperature, and occupant behavior, one cannot directly generalize from the measurements derived from a relatively short-term tracer gas decay test to infiltration rates that may occur under other conditions. It is possible, however, to compare the measured air exchange rate to that predicted by the infiltration model for known weather conditions during the period of the test.

A set of tracer gas decay tests was run immediately following the fan pressurization measurements. The blower door was removed and all registers and vents were unsealed (fireplace and woodstove dampers and combustion air inlets were left closed). Sulfur hexafluoride gas was injected into every room of each test house to a concentration of 75 to 90 ppm as registered by an SF_6 analyzer (Wilkes Model 101). The output of the analyzer was recorded on a single-channel chart recorder. Each test typically lasted from 1-1/2 to 3 hours (although two of the tests ran for longer periods of time). Occupants were asked to keep windows and exterior doors closed during the test, and to turn on the furnace or heat pump fan during the latter part of the test. This latter request was fulfilled in only three of the 12 houses. In those houses, we were able to determine the effect of the circulation fan upon air exchange rate.

Detailed information about the infiltration measurement techniques can be found in Appendix A.

Indoor Air Quality

On the basis of findings from our ongoing studies of indoor air quality, three major contaminants of indoor air were measured--radon-222 (Rn), formaldehyde (HCHO), and nitrogen dioxide (NO_2)--all of which are of concern indoors and can be monitored reliably with minimum inconvenience to house occupants.

Radon, a decay product of radium, is a chemically inert, radioactive gas with a half-life of 3.8 days. It produces a chain of four short-lived radioactive daughters that constitute the primary health hazard to humans. These daughters, unlike the radon itself, can attach themselves to airborne particulates which, if inhaled, can be retained in the tracheobronchial or pulmonary regions of the lung. Subsequent radioactive decay can irradiate surrounding tissues with alpha radiation, leading to an increased risk of lung cancer [8].

Any substance containing radium is a potential source of radon gas. Since radium is present as a trace element in all rock and soil, sources of indoor radon can include the soil under building foundations, building materials such as concrete or brick, and tap water from underground wells.

Formaldehyde is found in furniture and building materials, particularly as urea formaldehyde resin in particleboard. Formaldehyde from these resins is slowly released into the indoor environment, especially when materials are new. The chemical is currently being scrutinized as an allergenic and possibly carcinogenic substance. The National Academy of Sciences reports that exposure to low concentrations of formaldehyde (10 to several hundred ppb) can cause a dry or sore throat, eye irritation, and swollen mucous membranes. The threshold concentration for these effects is uncertain because individual responses to the substance vary widely and some individuals become increasingly sensitive as a result of continued exposure. At very high concentrations (50 to 100 ppm), pulmonary edema, the accumulation of fluid in the lungs, may result [9,10]. Recommended guidelines range from 100 to 200 ppb (see Table 7).

Nitrogen dioxide is a combustion by-product generated in natural gas appliances such as stoves, furnaces, clothes dryers, and water heaters and as a consequence of tobacco smoking. Animal studies have shown that long-term exposure to nitrogen dioxide alters the function of circulatory and respiratory systems. At low concentrations, exposure increases susceptibility to respiratory disease. At high concentrations, it can cause pulmonary edema and even death [11].

Although carbon monoxide and particulates are also hazardous indoor pollutants, neither was measured in this study because of lack of inexpensive instrumentation suitable for long-term sampling in occupied houses.

In addition to the three pollutants described, we also monitored relative humidity because of its effect on occupant comfort and health and its association with mold, mildew and condensation which can cause damage to building materials.

The sampling site for the indoor air quality measurements was a main activity room that was also a central area in each house. The air outside each house was also monitored for formaldehyde, nitrogen dioxide, and relative humidity.

While the indoor air quality measurements were being made, additional tracer gas decay tests were performed. In contrast to conditions during the previous set of infiltration tests, the houses were left as found with respect to house ventilation (for example, windows and doors were left open). This served two purposes: obtaining actual air exchange rates for the indoor air quality test periods and providing information about the variability of air infiltration due to occupant behavior.

Detailed information about the air quality measurement techniques can be found in Appendix A.

RESULTS AND DISCUSSION

Infiltration

Leakage Areas and Seasonal Infiltration Rates

As noted earlier in this report, each house was tested in at least two different leakage configurations. Table 3 shows the results of the fan pressurization tests for the open register condition in all 12 houses. Both effective leakage areas (total areas in cm^2) and specific leakage areas (normalized to house floor areas, in cm^2/m^2) are given. Effective leakage areas for the 12 houses averaged 308 cm^2, ranging from a low of 130 cm^2 to a high of 482 cm^2. Specific leakage areas averaged 2.8 cm^2/m^2 with a range of 1.3 to 4.3 cm^2/m^2. (By comparison, specific leakage areas in post-1975 California housing tested by LBL researchers have been found to average 6.4 cm^2/m^2 [12].)

Table 3 also shows predicted annual and heating season infiltration rates. For all twelve houses, the average heating season infiltration rate is 0.34 air changes per hour (ach), ranging from a low of 0.17 ach to a high of 0.49 ach, while the average annual rate is 0.30 ach, with a range of 0.14 ach to 0.42 ach. (The predicted annual and heating season infiltration rates take into account design ventilation areas such as bathroom and dryer exhaust vents.) It should be noted that both the annual and heating season infiltration rates are generally affected by occupant behavior (heating season less so than annual rates). Therefore, actual annual rates are likely to be higher than those indicated in Table 3 as a result of opening and closing of windows and doors during the warmer months.

No relationship between house floor area and leakage area was found. Houses H and I have the largest specific leakage areas even though they have the smallest floor areas. One of the largest houses, House J, has a relatively low specific leakage area. No relationships were noted between effective leakage area and house volume, surface area, window and door area, or window and door perimeter. We did find, however, that houses in close proximity and of essentially identical age and

Table 3: Effective Leakage Areas (Registers Unsealed) and Predicted Infiltration Rates for Eugene Houses*

House ID	Floor Area (m^2)	House Volume (m^3)	Effective Leakage Area (cm^2)**	Specific Leakage Area (cm^2/m^2)	Predicted Infiltration Rates (ACH)+	
					Heating Season	Annual
A	107	260	410	3.8	0.46	0.41
B	107	260	342	3.2	0.39	0.34
C	102	249	256	2.5	0.32	0.27
D	102	249	230	2.2	0.28	0.25
E	108	264	220	2.0	0.24	0.21
F	102	249	130	1.3	0.17	0.14
H	81	197	350	4.3	0.49	0.42
I	81	197	284	3.5	0.40	0.34
J	134	326	314	2.3	0.29	0.26
Solar 1	140	390	482	3.4	0.37	0.32
Solar 2	116	293	293	2.9	0.35	0.30
Solar 3	147	368	368	2.5	0.34	0.29
Average			308 ± 93	2.8 ± 0.8	0.34	0.30

*Each house measured with furnace registers sealed and unsealed (see Table 4 for comparions. House C tested with fireplace covered with plastic and uncovered. Solar 3 tested in six leakage configurations involving opening and closing of various ventilation systems and a solar greenhouse. Only the two Solar 3 measurements corresponding to the sealed and unsealed register configurations are reported in this paper.

**Estimated error in leakage area assumed to be 10%. See discussion in text and Appendix A.

+Infiltration rates include design ventilation area (bathroom, dryer vents), 10 cm^2 per opening. Estimated uncertainty in infiltration rates is 15%.

construction have similar specific leakage areas (Houses A and B, E and F, and H and I). Surprisingly, despite their large areas of glazing, the passive solar houses did not have significantly larger specific leakage areas than the nine energy efficient houses, perhaps because most of the extra glazing in the passive solar houses is fixed and relatively well-sealed. We suspect, although we cannot confirm, that the metal sliding windows used in all twelve houses constitute a major leakage site; our smoke stick tests did not find these windows to be less leaky than similar windows used in conventional construction.

We believe that, aside from the sliding windows, most of the difference in leakage areas is due to construction quality rather than easily identifiable construction or design features common to all twelve houses. Our smoke stick tests found leakage in many of the obvious places--for example, electric outlets, light switches, baseboards, door framing, and mantlepieces--but none (excepting windows) predominated over all others or could be considered an excessive source of air leakage.

Several points concerning individual houses should be noted. Houses H and I actually comprise the two halves of a duplex. The relatively high specific leakage areas of these houses may be due, in part, to the presence of storage areas above the living space, reached by hatches located above the bedroom closets. These hatches open directly into the attic and may represent a major infiltration path through the building's vapor barrier. While we attempted to tape the hatches shut during the test, use of smoke sticks made it clear that they were still quite leaky.

Solar 1 includes a cupboard-type area of 92 square feet, containing water-filled thermal storage barrels, placed behind 96 square feet of glazing on the building's south side. This thermal storage area is vented through warm air registers directly into the living space. We believe the leakage area of this space to be significant, but we did not attempt to measure its leakage area.

Duct Leakage

Table 4 shows the leakage areas due to the heating ducts in eleven of the twelve houses. Duct leakage averaged 40 cm^2, comprising about 15% of the total leakage area of each house. Most of the houses exhibited some leakage through the duct system; House F and Solar 1 are notable exceptions. House F is an exceptionally tight house and no leakage is attributable to ductwork. Because there are significant differences in duct leakage between the pairs of houses listed earlier (A & B, E & F, H & I), it is unlikely that any significant relationships would be found between duct length or area and duct leakage area. Therefore, we have not attempted to normalize leakage to duct length or surface area.

Table 4: Effective Leakage Areas of Ductwork in Eugene Houses

House ID	Effective Leakage Area		Duct Leakage Area	
	Ducts Unsealed (cm^2)	Ducts Sealed (cm^2)	(cm^2)	% of total
A	410	344	66	16%
B	342	300	42	12%
C*	256	230	--	--
D	230	160	70	31%
E	220	166	54	25%
F	130	128	2	2%
H	350	307	42	12%
I	284	257	27	10%
J	314	272	41	13%
Solar 1	482	468	14	3%
Solar 2	337	288	49	15%
Solar 3	345	258	36	25%
Average			40	15%

*Represents change in effective leakage area when fireplace is covered with plastic. There is no ductwork in this house (radiant ceiling heat).

Tracer Gas Decay

Table 5 presents the results of the tracer gas decay tests performed in conjunction with the fan pressurization tests. The experimental infiltration rates in the table are those measured by tracer gas decay. They range from 0.08 to 0.27 air changes per hour. The calculated rates are derived from the LBL infiltration model, based upon weather conditions at the time of the test. These rates range from 0.08 to 0.37 ach. Also shown are the ratios of experimental to calculated infiltration rates. These ratios should be close to 1.00; in fact, the geometric mean of the ratios for the 12 houses is 0.90.

The effect of the furnace fan on infiltration was also observed in three of the houses. We found the furnace fan to be responsible for roughly 0.05 to 0.14 ach, representing an increase in infiltration during the testing period of 65% to 175%. During the heating season, infiltration through the ducts due to pressurization by the furnace fan will be a smaller fraction of total infiltration.

Some infiltration rates are overestimated by a significant amount, while a few are underestimated. The differences between the calculated and experimental infiltration rates may be due both to construction features in some of the houses and to certain simplifying assumptions made in the infiltration model.

The model as it presently exists is unable to account for multi-chamber structures, and Houses H and I and Solar 1 are not, strictly speaking, single chamber buildings. Houses H and I are joined by a common wall and we would expect there to be some exchange of air between the two. While House H has a relatively large leakage area, it is completely shielded on the west side by House I. As it happens, the prevailing wind was from the west during the time House H was being tested, and the model overestimates infiltration. House I is similarly shielded by House H, but the model underestimates infiltration. During the tracer gas test of House I, the wind was from the north, which is a less shielded direction.

Table 5: Results of Tracer Gas Decay Tests in Eugene Houses

House ID	Shielding Class	Leakage Area* (cm^2)	Weather Conditions: Wind-speed+ (m/s)	Weather Conditions: Inside Temp. (°C)	Weather Conditions: Outside Temp. (°C)	Infiltration Rates (ACH): Exp.	Infiltration Rates (ACH): Calculated from Model	Infiltration Rates (ACH): Ratio of Exp.:Calc.
A	3	450	1.2	26	20	0.20	0.22	0.91
B	3	382	2.2	19	15	0.27	0.25	1.08
C	3	296	2.5	26	24	0.23	0.22	1.04
D	3	260	0.9	24	19	0.09	0.11	0.82
E	4	260	1.6	20	17	0.09	0.11	0.82
F	4	170	1.9	23	20	0.08	0.08	1.00
H	4	380	3.0	23	15	0.21	0.37	0.57
I	4	314	0.9	25	25	0.09	0.06	1.50
J	3	354	2.2	24	28	0.19	0.18	1.06
Solar 1	4	522	2.3	20	13	0.17	0.26	0.65
Solar 2	3	367	1.7	22	17	0.19	0.22	0.86
Solar 3	3	385	2.2	24	19	0.21	0.21	1.00
							Geometric mean	0.90
					Geometric mean of all except H, I, and Solar 1			0.94

*Leakage area includes design ventilation openings (bathroom, dryer vents)

+To convert to MPH, multiply by 2.22. Windspeeds derived from Eugene airport weather data. Temperatures taken on site.

House ID	Infiltration Rates (ACH): Furnace Fan On	Infiltration Rates (ACH): Furnace Fan Off
A	0.22	0.08
E	0.13	0.08
I	0.12	0.07

As noted above, we believe a good part of the leakage observed in Solar 1 to be located in the thermal storage area. However, in the absence of convective flow between this space and the rest of the house (as would be the case on a cloudy day), mixing between the two parts of the house would be poor and tracer gas decay would not show infiltration due to the thermal storage area. The infiltration model is not able to make a distinction between the two chambers and treats leakage area in the thermal storage area in the same way as leakage area elsewhere in the house. If these three houses are removed from the sample, the geometric mean of the ratios of experimental to calculated infiltration rates increases to 0.94.

There are several assumptions made in the model that may also result in over- or underestimates of infiltration rates. For example, when outside temperatures are mild and inside-outside temperature differences are small, infiltration due to this temperature difference (the "stack" effect) is also small. Under these conditions, the preponderance of infiltration is caused by the wind, and large uncertainties in wind velocity during a test will result in a large estimated error in the calculated infiltration rate. While infiltration is directionally dependent--that is, the direction of the wind, the location of local shielding, the site of leaks may not be the same on all sides of a house--the model contains no directional dependence and this may introduce an error. The model assumes stack-induced infiltration to occur through the floor, ceiling and walls, and wind-induced infiltration to take place through the walls. If the relative proportion of leakage sites through the six building surfaces is incorrect, the model may over- or under-estimate infiltration through each of these surfaces.

Another significant uncertainty arises in the choice of the shielding coefficient used to calculate the magnitude of wind-induced infiltration. As can be seen in the table, the individual shielding coefficients (which can range from 1 to 5) vary. The choice of coefficient depends upon several factors, including shielding by nearby houses or fences, direction of the prevailing wind at the time of the calculation, presence of party walls (in a duplex), and the location of glazing with respect to the prevailing wind. Because the shielding coefficient treats all four sides of a building as being the same (which is, of course, not true), infiltration may be over- or underestimated.

Comparison with Other Measurements

Figure 1 compares the specific leakage areas for the twelve Eugene houses with measurements made by LBL researchers and others on groups of houses located in other parts of North America. Figure 2 does the same for heating season infiltration rates [13]. As can be seen from both figures, the Eugene houses are among the tightest houses tested. They compare in specific leakage area to a group of energy-efficient houses in Rochester, New York and to the twelve "post-retrofit" houses in Midway, Washington [14]. Because of the relatively mild weather conditions in Eugene the calculated heating season infiltration rates are quite low.

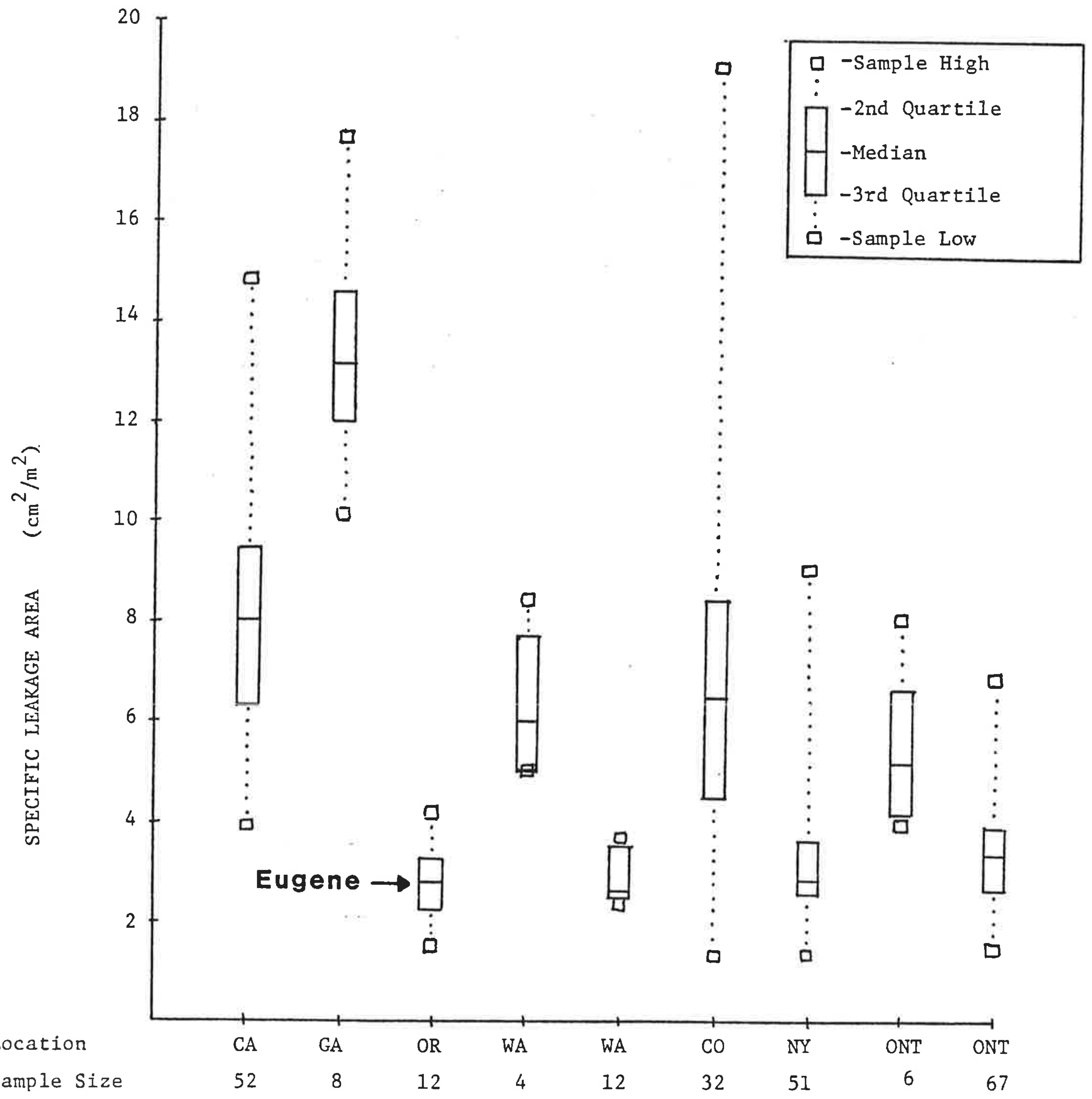

Figure 1: Specific Leakage Areas for Selected Groups of Houses Tested by LBL Researchers and Others

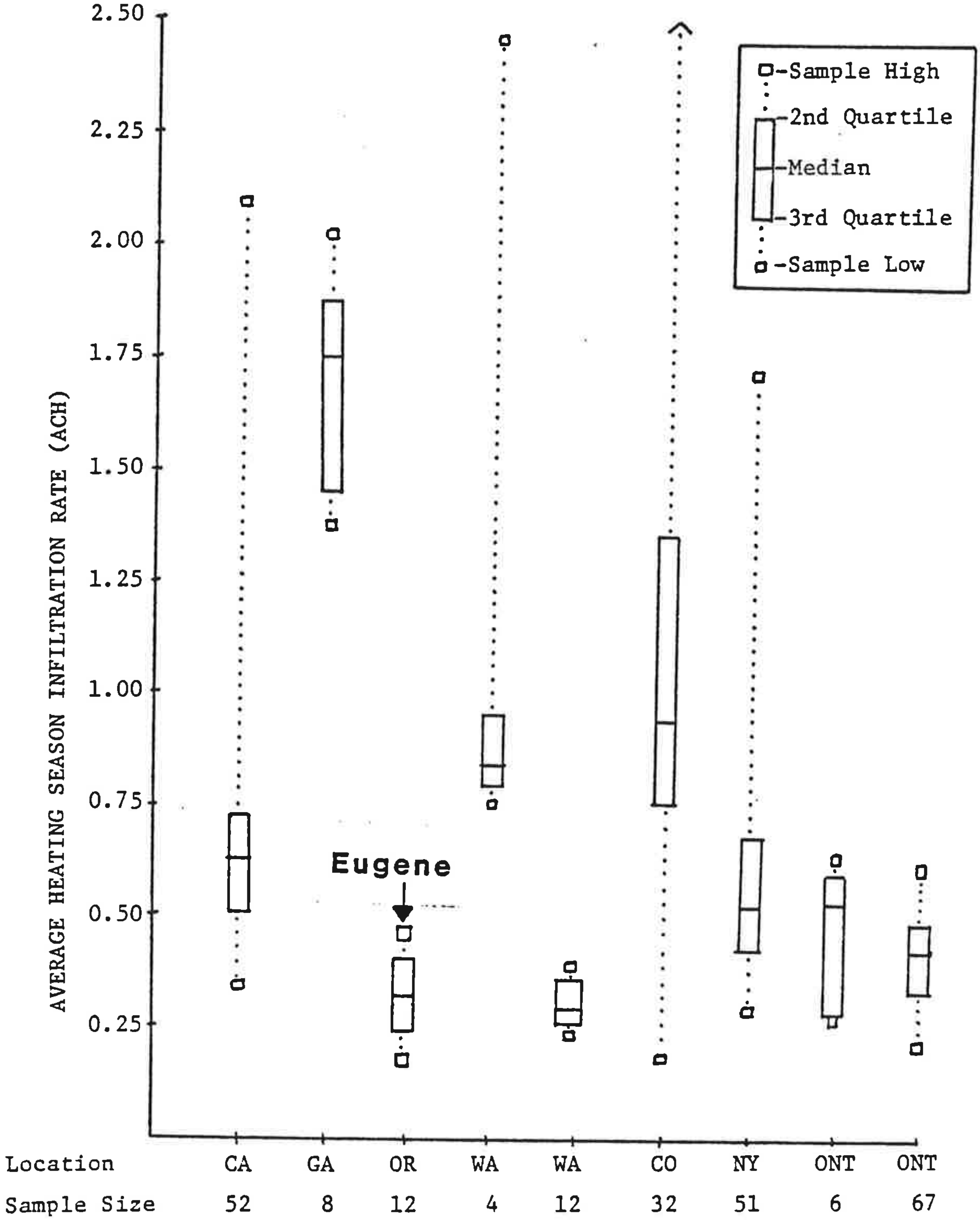

Figure 2: Heating Season (November-March) Infiltration Rates for Selected Groups of Houses Tested by LBL Researchers and Others

Indoor Air Quality

Table 6 summarizes the results of the indoor air quality measurements. The radon levels observed in the four houses were all less than 1 picocurie per liter, within the normal range. Formaldehyde levels in all four houses were found to be well above outdoor levels and of particular interest in two of the houses. Nitrogen dioxide levels were lower than outdoor levels, however, slightly-elevated levels were observed in the two houses with smokers.

Table 6: Summary of Indoor Air Quality Measurements in Four Eugene, Oregon Houses

House ID	Radon (pCi/L)	Formaldehyde (ppb) Indoor/Outdoor	NO_2 (ppb) Indoor/Outdoor	Relative Humidity (%) Indoor/Outdoor
B	<1	50/<2.5	7/9*	53/71
J	<1**	55/3	2/7	57/72
Solar 1	<1	94/<2.5	2/9	59/73
Solar 2	<1	100/<2.5	5/8*	59/70

*Tobacco smokers in residence

**Measurement from crawlspace rather than interior living space (see text)

We have compiled in Table 7, a listing of outdoor standards for nitrogen dioxide (U.S.), recommended indoor standards for formaldehyde (U.S. and Europe), and region-specific guidelines for radon (Florida, U.S.) in order to provide some framework for evaluating the results of this study. Ideally, our measurements would be evaluated against established indoor air quality standards. However, non-occupational indoor air quality standards for the United States do not exist for the three pollutants in question.

Table 7: Selected air quality guidelines

Pollutant	Concentration	Country	Status	Reference
Formaldehyde-Indoor	200 ppb - maximum	U.S. (California)	Proposed	1
	200 ppb - maximum	U.S. (Wisconsin)	Proposed	2
	120 ppb - maximum	Denmark	Recommended	3
	100 ppb - maximum	The Netherlands	Recommended	4
Nitrogen Dioxide-Outdoor	50 ppb - annual average	United States	EPA Standard	5
Radon-Indoor	.015 WL - annual average	United States	Proposed standard for buildings contaminated by uranium processing	6
	.02 WL - annual average	U.S. (Florida)	Recommendation to Governor of Florida for buildings on reclaimed phosphate mining land	7
	.02 WL - annual average	Canada	Policy statement by AECB	8

References

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2. State of Wisconsin, Department of Labor and Human Relations, Safety and Buildings Division. Proposed Formaldehyde Rule, Wis. Adm. Code, November 1979. (Not enacted as of July 11, 1980.)
3. I. Andersen, "Formaldehyde in the Indoor Environment - Health Implications and Setting of Standards," paper presented at the Indoor Climate Symposium, Copenhagen, Denmark, August 30-September 2, 1978.
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5. U.S. Environmental Protection Agency, National Primary and Secondary Ambient Air Quality Standards for Nitrogen Dioxide, 40 CFR 50.11.
6. U.S. Environmental Protection Agency, "Interim Cleanup Standards for Inactive Uranium Processing Sites," Federal Register 45, pp. 27366-27368, April 22, 1980.
7. U.S. Environmental Protection Agency, "Indoor Radiation Exposure Due to Radium-226 in Florida Phosphate Lands: Radiation Protection Recommendations and Request for Comment," Federal Register 44, pp. 38664-38670, July 2, 1979.
8. Atomic Energy Control Board (of Canada) (AECB), "Criteria for Radioactive Clean-up in Canada," AECB Information Bulletin 77-2, April 7, 1977.

Radon

All radon measurements reported are two-week time-averaged concentrations. The concentrations are expressed in picocuries per liter (pCi/L), a measure of radioactivity per liter of air. A picocurie is equivalent to 2.2 radioactive disintegrations per minute.

Although an attempt was made to compare radon concentrations in the crawlspaces and living spaces of Houses B and J, technical difficulties prevented the completion of this part of the experiment. Consequently, the radon concentration reported for House J is from the crawlspace rather than the inside living space; the data for House B is only for the living space.

The guidelines for radon, listed in Table 7, are expressed in working levels (WL), a measure of potential alpha energy concentration specifically devised to indicate relative health hazards [15]. The concentration of radon equivalent to the 0.02 WL guideline depends on the radioactive equilibrium between radon and its daughters. Given typical indoor equilibrium factors of 0.3 to 0.7 [16], the 0.02 WL guideline corresponds to radon concentrations in the range of 3 to 6 pCi/L.

All of the radon concentrations observed were less than one pCi/L, well below the guideline and less than what we believe to be the sensitivity limit of the radon detection device (described in Appendix A).

Formaldehyde

With one exception, the formaldehyde values reported in Table 6 represent week-long averages of the seven 24-hour samples taken both indoors and outdoors at each location. The sole exception occurred with the samples from Solar 2 where five 24-hour samples and one 48-hour sample were taken. Including the 48-hour sample had no effect upon the formaldehyde average reported.

Two of the houses, B and J, had moderate average formaldehyde concentrations of 50 and 55 ppb, respectively. Solar 1 had an average concentration of 94 ppb, just below the most stringent guideline listed in

Table 7, while the concentration in Solar 2 of 100 ppb was just at this guideline.

Three of the four houses had outside formaldehyde concentrations below the detection limit of 2.5 ppb. The only house with a detectable outdoor formaldehyde concentration was House J, where sawdust was being applied to flowerbeds and constructon was occurring across the street during the week of sampling. Either or both of these activities could have caused this just measurable, but insignificant, concentration.

Since the recommended or proposed formaldehyde standards listed in Table 7 are set maximum concentrations that are not time-averaged, daily formaldehyde concentrations (rather than the week-long averages) are more appropriately compared to these guidelines. However, even these daily averages are certain to be lower than the maximum instantaneous concentrations that probably occurred in these houses. The daily time-weighted average concentrations are listed in Table 8. In the two houses with the highest formaldehyde levels, half of the daily concentrations were at or above the most stringent guideline of 100 ppb; however, none were above the 120 ppb guideline.

Table 8: Daily 24-Hour Average Formaldehyde Concentrations in Four Eugene, Oregon Houses (in ppb)

House ID	1st Day	2nd Day	3rd Day	4th Day	5th Day	6th Day	7th Day	Weekly Average
B	73	60	37	53	45	44	38	50
J	52	51	53	52	66	64	46	55
Solar 1	85	85	82	90	107	110	97	94
Solar 2	96	112	101*	101*	100	92	101	100

*These values are the result of a single 48-hour sample, rather than two individual 24-hour samples.

As noted, the formaldehyde concentrations in the four houses separate into two groups: Houses B and J with concentrations near 50 ppb, and Solar 1 and 2 with concentrations near 100 ppb. An attempt was made to identify any differences between the two groups of houses that could account for the difference in concentrations.

If one assumes that building materials containing urea formaldehyde resins are the principal source of formaldehyde and that similar types and quantities of building materials were used in all four houses, then the age of House B (completed in 1977) might account for its lower formaldehyde concentration. The other houses were completed in 1979. Formaldehyde emissions from building materials decrease with time, as the formaldehyde in the materials is depleted. However, age alone is not sufficient to account for the large difference in concentration observed between the two groups of houses, particularly as House J, with a construction date of 1979, has a concentration comparable to House B.

Similarly, the difference in floor underlayment materials cannot explain this large difference in concentration. House B, with a moderate formaldehyde concentration, was built with particleboard underlayment. Solar 2, with a higher concentration, has a concrete floor with no underlayment. Both House J and Solar 1 have plywood underlayment. While this material probably incorporates a formaldehyde-based resin, we would expect it to contain less than particleboard. (In both cases, the resin acts as a binder, but more resin is used in particleboard.)

New furniture is often a source of formaldehyde emissions and has been identified as a major source in some homes [17,18]. Solar 2 contains a large quantity of relatively new furniture (about 1-1/2 years old). The furniture in Houses B and J is more than 10 years old. The furniture in Solar 1 is reported to be five to six years old. While this may be fairly old in terms of formaldehyde emissions, it might account for the difference between the lower levels observed in the houses with older furniture (Houses B and J) and the higher levels seen in the houses with newer furniture (Solar 1 and 2).

There is one obvious difference between the two groups of houses: the two houses with the lower formaldehyde concentrations are ordinary Arkansas-style, while the two with higher levels have passive solar features. It is possible that enhanced solar gain might cause locally elevated temperatures of building materials and furniture and there is evidence to suggest that formaldehyde emissions increase with increasing temperature [19,20].

We suspect that furniture and/or some undetermined feature of the passive solar houses caused the higher observed formaldehyde concentrations. We cannot, however, discount the possibility that the large difference in observed formaldehyde concentrations was caused by some other factor that we have not explored (for example, occupant behavior as discussed in Appendix B).

Nitrogen Dioxide (NO_2)

The indoor and outdoor NO_2 concentrations reported in Table 6 were all measured by NO_2 passive monitors, which yield one-week time weighted average concentrations. We sampled for two one-week time periods, and because the week-to-week variations were small, we report an average for the two weeks. The outdoor levels were all similiar and are somewhat low compared to outdoor levels we have observed in other suburban areas.

Indoor NO_2 concentrations were all lower than outdoor levels. This is typical of houses without major indoor NO_2 sources from combustion appliances, as was the case here. (This is so because outdoor NO_2 levels due to automobile exhaust tend to be higher in built-up areas.) Tobacco smoking, a less important NO_2 source, occurred in House B and Solar 2. The indoor/outdoor NO_2 ratio in these houses was elevated as compared to the the other two houses. However, none of the NO_2 concentrations observed approached the EPA long-term outdoor standard of 50 ppb.

Humidity

The humidity measurements reported in Table 6 represent the average of several days of spot readings for each test period. These average indoor relative humidities ranged from 53 to 59%, well within health and comfort guidelines [21]. The outdoor relative humidity ranged from 70 to 73% during this same period. These average relative humidities are, at best, an approximation, since they were compiled from instantaneous daily measurements.

CONCLUSIONS AND RECOMMENDATIONS

Infiltration

We have found the 12 Arkansas-style houses tested in Eugene, Oregon to be quite tight, with an average specific leakage area of 2.8 cm^2/m^2, as compared to 6.4 cm^2/m^2 for new California housing. Seasonal infiltration rates, too, were calculated to be low compared to other houses tested, although climatic differences between the locations of test groups of houses do not allow direct comparisons. Leakage area attributable to ductwork was also low in absolute terms, averaging 40 cm^2 per house, or about 15% of total leakage area in each house. This should be compared to an average of 95 cm^2, or 13% of total leakage area, for duct leakage in a group of houses with leakier shells recently tested by LBL researchers [22]. Tracer gas decay measurements indicated fairly low short-term infiltration rates; however, these tests were conducted during a period of relatively mild weather, when infiltration rates would be expected to be low even in houses with moderate or high specific leakage areas.

Based upon the results from the Eugene houses and measurements made on houses in other locations, we can conclude that the construction techniques used in the Arkansas-style houses are very effective in reducing leakage areas and infiltration rates. Larger leakage areas were observed where there were major penetrations through the vapor barrier, such as in the storage areas of Houses H and I and in the thermal storage area of Solar 1. The continuous vapor barrier appears to play an important role in the tightness of these houses, although other techniques used in construction are undoubtedly also effective. Inclusion of the ductwork within the building envelope also helps to reduce leakage areas. However, we believe there to be some residual leakage through remaining perforations through the vapor barrier. In the future, we recommend that, if possible, vapor barrier edges be taped rather than simply lapped in order to increase the barrier's effectiveness.

We were not able to measure the effective leakage areas of the horizontal sliding aluminum windows used in all 12 houses. We found that the three passive solar houses did not have significantly larger specific leakage areas (2.9 cm^2/m^2) than the nine "conventional" Arkansas-style houses (2.8 cm^2/m^2), perhaps because almost all of the extra glazing in the solar houses is fixed. It is possible that the sliding windows represent a large percentage of the leakage area and we recommend in future construction that more attention be paid to ensuring tightness of movable windows.

We found the duplex we tested (Houses H and I) to be somewhat leakier than the average for all 12 houses, which may be due to the bedroom storage areas. It is also possible that the party wall between the two apartments contains undetected bypass leaks, but we were not able to determine what effect, if any, the shared wall has upon the leakage area of the two units.

Finally, while it is clear that the Eugene houses are as tight as or tighter than other test groups of houses, we did not compare these Arkansas-style houses with other new construction in the Eugene area. Thus, we do not know whether the 12 houses are actually tighter (or how much tighter) than their "non-energy-efficient" counterparts in Eugene. We do know that they have higher levels of insulation, vapor barriers, and so on, and use less energy, but this does not provide a comparison of tightness. Therefore, it would be very useful to perform a similar series of tests on a control group of houses in Eugene in order to provide a valid basis for comparing and evaluating the Arkansas style of construction.

Indoor Air Quality

The pollutant measurements made in these houses constitute a preliminary study of indoor air quality in energy-efficient houses. Radon, nitrogen dioxide and formaldehyde levels were measured in four of the 12 Arkansas-style houses. Particulates, carbon monoxide and organics other than formaldehyde were not measured.

The four houses in which indoor air quality measurements were made are very tight and we would expect to observe high levels of indoor-generated pollutants if source strengths were large. We did not, however find radon levels to be higher than existing guidelines. No nitrogen dioxide sources (aside from smoking) were present in the houses and therefore very low levels were measured in all four houses. Formaldehyde levels in two of the four houses were comparable to one recommended guideline. It should be understood that the guidelines to which we refer are, at the present time, the only "standards" available to us. There is an urgent need, therefore, for comprehensive studies of the health risks associated with indoor air pollutants so that such guidelines will be more meaningful to indoor air quality issues.

Radon does not appear to be a problem in these houses, probably because both local soil and building materials used in construction are low in radium content. Nitrogen dioxide concentrations were also low, despite the presence of smokers in two of the houses. This is consistent with the minor role played by smoking as a nitrogen dioxide source (as compared with combustion appliances).

Formaldehyde is the major pollutant of concern in the four test houses. Several daily formaldehyde concentrations in the two solar houses approached or exceeded the most stringent guideline of 100 ppb. The formaldehyde may be emanating from the furniture but the high concentrations might be caused by some feature related to the solar design of the houses (for example, locally elevated temperatures). The former reason is consistent with previous research findings, but we were not able to identify what solar features, if any, could cause the higher formaldehyde levels. Clearly further research is needed before proper control measures can be implemented with confidence and before the impact of conservation programs on indoor air quality can be assessed.

* * *

This study of a group of houses in Eugene, Oregon represents a first step in the evaluation of the building stock of the Pacific Northwest in terms of energy efficiency and indoor air quality. A more comprehensive characterization of housing in the region would include:

1. Measurements of infiltration in both old and new housing in the Northwest and the relative effectiveness of various infiltration reduction techniques;

2. Measurement of the contribution of various building components (for example, windows and vents) to infiltration in the housing stock;

3. Evaluation of the importance of construction quality in minimizing air leakage in order to provide feedback to builders;

4. Monitoring of indoor air quality in other groups of houses in the Northwest, particularly with respect to formaldehyde;

5. Measurement of indoor radon levels in other parts of the region (that is, are low radon levels characteristic only of the Willamette floodplain, the entire Eugene area, or all of the Northwest);

6. Measurement of indoor nitrogen dioxide levels in those houses with gas- or oil-burning appliances.

APPENDIX A

MEASUREMENT TECHNIQUES

Fan Pressurization and Determination of Leakage Area

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 and flue pipes, fireplaces and chimneys, baseboards and so on. 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, shielding of the various sides of the building, the surrounding terrain, and crack geometry. Consequently, air flow through a particular opening is not constant from day to day nor is it the same from structure to structure.

Natural infiltration is typically driven by pressure differences (ΔP) 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 ΔP is held constant, all air flowing through the fan must also be flowing through the building envelope. When ΔP is much greater than 10 Pascals, fan flow dominates natural infiltration and the latter may be disregarded. At a given pressure differential and fan speed (in RPM), the flow of air through the fan is determined by means of a previously established calibration curve. For each house, 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 10 Pa intervals), generating a pressure versus flow curve. This data is then used to find the effective leakage area of the house.

Air flow through a building envelope is a combination of viscous flow and turbulent flow. The former is proportional to ΔP while the latter is proportional to the square root of ΔP. Hence, air flow through the envelope can be characterized by the equation:

$$Q = K\,\Delta P^{n} \tag{1}$$

where: Q=air flow through the envelope (m^3/s);
ΔP=applied pressure across the envelope;
K=semi-empirical constant; and
n=semi-empirical constant in the range $0.5 < n < 1.0$.

The curves generated by fan pressurization are extrapolated to a ΔP of 4 Pa (assumed to be representative of natural infiltration) using Equation 1. Next, it is assumed that in the pressure differential ranges characteristic of natural infiltration (-10 to +10 Pa), the flow versus pressure behavior of a building more closely resembles square-root (turbulent) than linear (viscous) flow and can be described by:

$$Q = A_{eff}\sqrt{(2/\rho)\Delta P} \tag{2}$$

where: Q=air flow through the envelope (m^3/s);
A_{eff}=effective leakage area;
ΔP=applied pressure of -10 to +10 Pa ($kg/m\text{-}sec^2$)
ρ=density of air ($1.2\ kg/m^3$)

Thus, the effective leakage area is a quantity that characterizes the air leakage of a structure. Using the LBL infiltration model, the leakage area can be combined with local weather data to predict average seasonal air exchange rates. These rates, however, neither provide information about instantaneous infiltration nor take into account uncontrollable factors such as occupant behavior. Generally one can assume that many occupant effects, such as opening and closing windows, are less likely to occur during the heating season when outdoor temperatures are low, windspeeds high, and infiltration rates are greatest.

We estimate the cumulative error in the fan pressurization measurements to be 24%, due to uncertainties in the original blower door calibration process and the actual measurements made in the 12 houses. In particular, there are rather large errors in the low pressure/low flow regimes corresponding most closely to natural infiltration, where the behavior of the house structure and its components may not be well understood. For example, under high ΔPs, windows may bow, with a resulting change in effective leakage area [23]. The low flow/low pressure points do not include the leakage area due to this effect. At higher flows and pressures, measurement errors decrease and, therefore, the procedure for calculating leakage areas takes this source of error into account by weighting the high flow and pressure measurements more heavily than the low ones. Hence, the final estimated error in the calculated leakage areas is less than that in the calibration and measurement process. We believe it to be on the order of 10%.

Average seasonal infiltration rates derived by the LBL model are subject to two main sources of error: approximations in the model itself and uncertainties in the variables entered into in the model, such as wind velocity, temperatures, local shielding and building dimensions. For the purposes of calculating average annual and heating season infiltration rates, monthly Eugene weather data was used. The estimated error for average wind velocities derived from this data is approximately 10%, while the estimated error for temperatures is about 5%. Combining these with the 10% estimated error in leakage area gives a cumulative estimated error in the average seasonal rates on the order of 15%.

Tracer Gas Decay

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. Tracer gas decay involves injection of the gas into a space to a known concentration. Subsequently, no more gas is released into the space. By measuring the decrease in gas concentration as a function of time, it is possible to determine the rate of dilution of the gas and, therefore, the infiltration of outside air into the structure. (We assume that the concentration of tracer gas outside the space is negligible).

The dilution of the gas occurs at an exponential rate, according to the equation:

$$C(t) = C_o e^{\frac{-Q}{V} t} \tag{3}$$

where: $C(t)$=average concentration of tracer gas at time=t;
C_o=concentration at t=0;
Q=infiltration (m^3/hr);
V=volume of the space (m^3); and
Q/V= infiltration rate (hr^{-1}).

The infiltration rate, Q/V, is also called the "air exchange rate" of the structure, and has units of air changes per hour or "ach." It is a quantity that characterizes infiltration from all sources during the period of the test. For the tracer gas tests, we calculated Q/V over ten minute intervals and fit an exponential curve to the points. This allowed a determination of experimental infiltration rate.

The estimated error in the tracer gas decay measurements is about 8%, due to occupant and experimenter behavior, wind and temperature changes, and analyzer instability. A detailed discussion of such estimated errors in tracer gas decay measurements can be found in Sherman, et al [24].

In order to compare experimental results with theoretical infiltration rates during the test period, we used the LBL infiltration model. Several uncertainties arise in attempting to apply the model over short periods of time. On a short-term basis, wind velocities fluctuate greatly. We generally took only one windspeed measurement during each test. Where possible, therefore, we have used wind data from the Eugene airport, extrapolated to the test houses. We estimate a 10% error in this wind data. During the course of a tracer gas measurement, both indoor and outdoor temperatures are likely to change. We made only spot temperature measurements during the tracer gas tests and estimate an error of about 5% in this quantity. Finally, the estimated error in measured leakage areas--about 10%--must also be included. Therefore, the cumulative estimated error in the infiltration rates calculated by the LBL model for the period of the tracer gas tests is approximately 15%.

Indoor Air Quality

Radon

A portable, battery-operated device, the Passive Environmental Radon Monitor (PERM) [25] was used for radon measurements. As shown in Figure 3, radon atoms diffuse through the desiccant and filter into the metal funnel. Positively charged radon daughters formed by the decay of radon are electrostatically collected onto a thermoluminescent dosimeter (TLD) fastened to the negative electrode at the bottom of the funnel. The TLD chip in the PERM is made of lithium fluoride, which is very sensitive to alpha radiation emitted from the collected radon daughters. After a suitable period of exposure, usually one or two weeks, the TLD chip is removed and the recorded alpha activity is read in an analyzer. The cumulative alpha activity is directly proportional to the time-weighted average concentration of radon in the living space. Because TLD chips are also sensitive to background gamma radiation, a reference chip kept in a small plastic vial is placed near the detection chip. Since both chips are exposed to the same amount of gamma radiation, the measurement can be corrected for background exposure by subtracting the reading of the reference chip from that of the detection chip. From our laboratory testing, we have estimated that the relative standard deviation of a measurement made at an exposure of 5 pCi/L for one week is ± 25%.

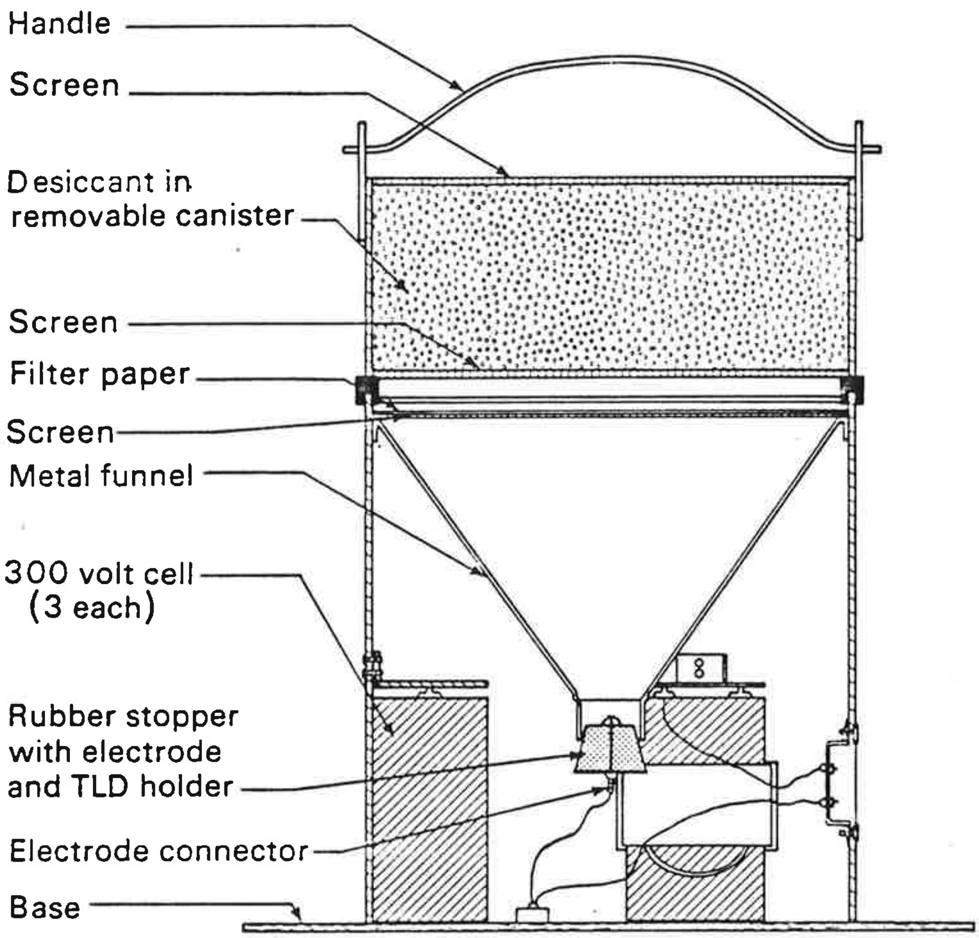

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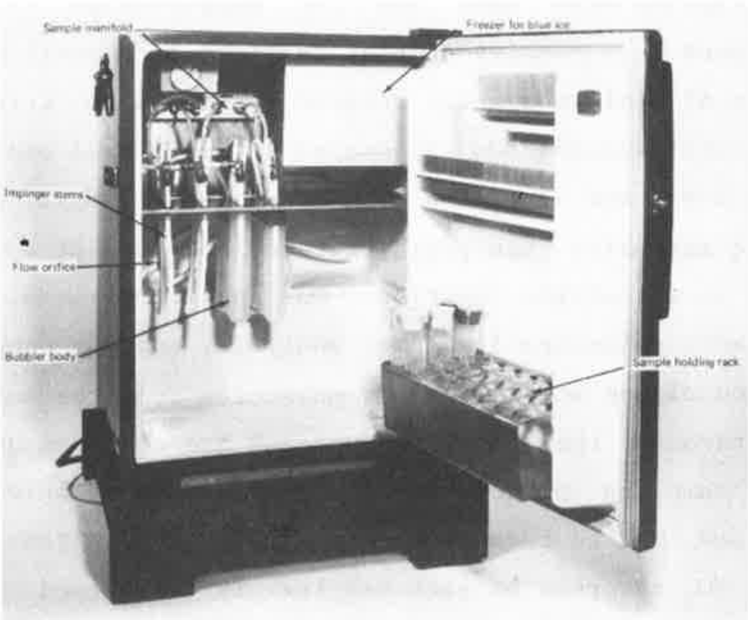
Figure 3. Schematic Drawing of Passive Environmental Radon Monitor (PERM)

Formaldehyde

A special sampling system developed at LBL, and depicted in Figure 4, was used for formaldehyde measurements. The system consists of a pump box, sampling lines, and a sampler. The pump box contains a timer, two vacuum pumps and a vacuum regulator. The sampler is a small, portable refrigerator with four sampling trains built inside, two for outside air and two for indoor air. Each train consists of two water-filled bubblers backed by a flow orifice for controlling the sampling rate. One line is run from the back of the sampler to an outdoor site and another line is similarly run to an indoor site. Each bubbler is filled with 10 ml of distilled water. An unexposed sample of distilled water, analyzed later with the exposed samples, serves as a blank. The timer in the pump box operates the vacuum pumps for a selected sampling period ranging from 12 to 24 hours. The vacuum regulator and flow orifice ensure a constant flow rate of 2 cubic feet per hour (± 5%) in each sample train, and the refrigerator maintains the proper temperature for optimum collection efficiency. Samples are collected daily and stored inside the refrigerator. At the end of each sampling period (approximately one week), the accumulated samples are packed with ice in an insulated container and shipped via air express to LBL for analysis. (Formaldehyde samples degrade significantly at room temperatures and must be kept chilled at all times.) The formaldehyde collected in the samples is analyzed with an improved pararosaniline technique developed at LBL [26]. Knowing the concentration of the samples, the volume of air sampled, and the collection efficiency, one can calculate the time-weighted average concentration of formaldehyde. We estimate that the relative standard deviation of a measurement made at an exposure of 50 ppb for 12 hours is ± 15%.



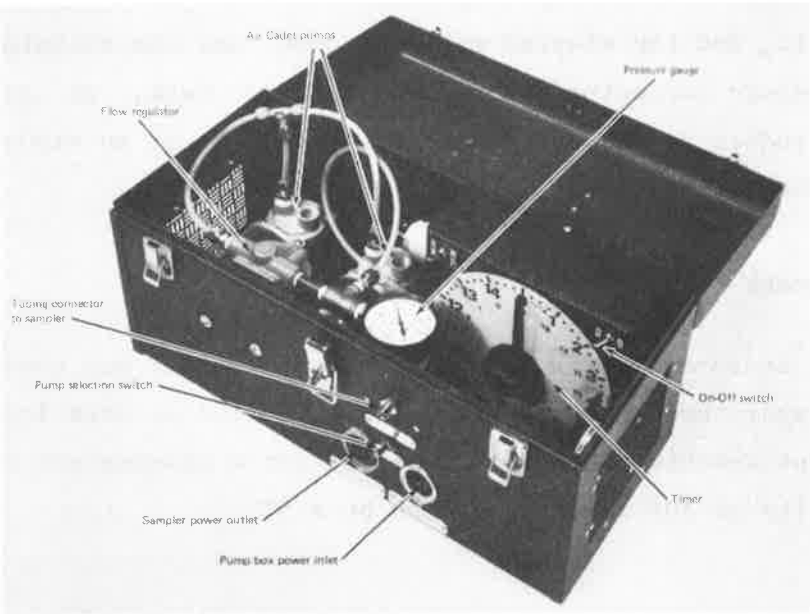


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Figure 4: Above - Refrigerated Formaldehyde Sampler
Below - Formaldehyde Sampler Pump Box

Nitrogen Dioxide (NO_2)

Small passive samplers were used for NO_2 measurements [27]. As illustrated in Figure 5, a passive sampler consists of a small acrylic plastic tube. A set of stainless-steel screens coated with triethanolamine, a substance that absorbs NO_2, is placed in the closed end of the sampling tube. The other end is fitted with a removable cap. In the field, samplers are assembled into packs of three and hung at a central indoor location and at an outside location. One pack of samplers is left capped as a zero reference for later analysis, and the others are uncapped for a period of one week. The NO_2 molecules from the surrounding air diffuse through the sampling tube and are absorbed onto the screens. When the sampling period is completed, the samplers are removed, capped, and mailed back to LBL for analysis. In the laboratory, the amount of NO_2 absorbed by each sampler is developed with a Saltzman reagent and determined calorimetrically. Knowing the amount of nitrogen dioxide collected in the samplers, the diffusion rate through the sampling tube, and the elapsed exposure time, one can calculate the time-weighted average concentration of NO_2. In this case, we estimate the relative standard deviation of a measurement made at an exposure of 15 ppb for one week to be ± 10%.

Humidity Measurement Technique

For humidity measurements, a fan-powered psychrometer was used. Wet- and dry-bulb temperatures were recorded daily in five or more locations in each house. The relative standard deviation for a measurement made at a relative humidity of 50% is estimated to be ± 5%.

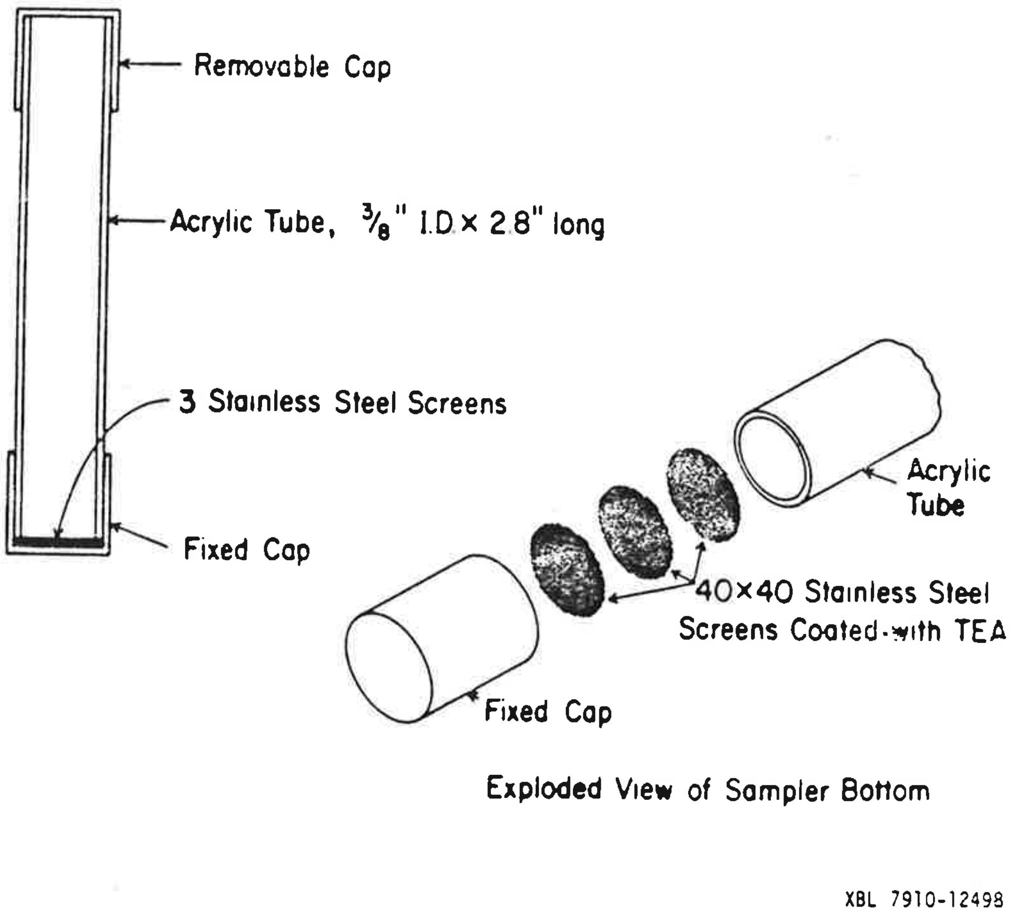

Figure 5. Schematic Drawing of NO_2 Passive Sampler

APPENDIX B

OCCUPANT BEHAVIOR AND INDOOR AIR QUALITY

Occupant behavior, such as the opening of doors and windows, can have a significant impact on the indoor air quality of a residence. In order to monitor the effect of occupant behavior on indoor pollutant concentrations, the four homeowners were asked to keep a daily log of opened windows and doors as well as operation of any outside vented fan (for example, a bathroom fan) or appliance (such as a dryer or non-recirculating air conditioner). Only the occupant of Solar 1 completed a log in sufficient detail to allow a correlation between daily activities and daily formaldehyde concentrations in his house. Formaldehyde was used in this comparison because it was the only pollutant that was measured on a daily basis. Table B.1 lists formaldehyde levels and the time-weighted average area of open doors and windows during the seven day period Solar 1 was monitored.

Table B.1: Formaldehyde Levels versus Time-Weighted Average Area of Open Windows and Doors in Solar 1, Eugene, Oregon

Day #	Time-Weighted Average Area of Open Windows and Doors (cm^2)	Formaldehyde Concentration (ppb)
1	4,790	85
2	520	85
3	360	82
4	1,570	90
5	50	107
6	1,150	110
7	0	97

These results seem to indicate that indoor formaldehyde concentrations at the single probe location in the house were insensitive to the opening of doors and windows. Three of the four homes tested showed this near-constant formaldehyde behavior (see Table 8). It is possible that the open doors and windows did not significantly affect the air exchange rate during the testing period, hence the relatively constant concentration. Alternatively, the sampling location may have been much closer to the formaldehye sources than to the windows and doors, at a point where concentration was relatively insensitive to the openings in the shell. Another possible explanation for the near-constant measurements is that formaldehyde emission varies directly with the air exchange rate in the house.

While no firm conclusions can be drawn from this data, it does point out the need for further investigation of the problem in order to understand the interrelationship between the opening of doors and windows, the house air exchange rate, the formaldehyde emission rate, and various chemical and physical formaldehyde removal processes, all of which can affect the final indoor formaldehyde concentration.

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