Title

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September 1987

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DISCLAIMER

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FINAL REPORT TO THE BONNEVILLE POWER ADMINISTRATION

A COMPARISON OF INDOOR AIR QUALITY IN CONVENTIONAL AND MODEL CONSERVATION STANDARD NEW HOMES IN THE PACIFIC NORTHWEST

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ABSTRACT

Ventilation and indoor air quality measurements have been made in 61 new houses located in two regions of the Pacific Northwest. Twenty-nine houses built to Model Conservation Standards (MCS) were compared to 32 Control houses, i.e., new houses built using conventional practices in the region. The MCS houses met the objective of having significantly reduced air leakage area. Yet their their total ventilation rate (infiltration plus mechanical ventilation supplied by air-to-air heat exchangers) was the same as the infiltration rate observed in the sample of Control houses. These ventilation rates in both samples were about 0.3 ach. Indoor pollutant concentrations were observed to be only poorly correlated with ventilation rates, an indication that other variables including pollutant source strengths and occupancy effects may be important. Pollutant measurements made in both samples revealed that 11% of the houses exceeded the BPA mitigation action level of 5 pCi/l for radon concentrations while 16% exceeded the EPA guideline of 4 pCi/l. Thirty percent of the total houses exceed the 100 ppb formaldehyde guideline adopted by many organizations. Indoor pollutant concentrations were seen to vary more between geographic regions than between the two types of house construction.

EXECUTIVE SUMMARY

This study compares ventilation rates and indoor air quality in 61 newly constructed, electrically-heated houses in the Pacific Northwest. Twenty-nine of the houses were built according to energy-efficient Model Conservation Standards (MCS) that included requirements for reduced natural ventilation to 0.1 ach and for supplemental ventilation to 0.6 ach, with air-to-air heat exchangers (AAHX). The remaining 32 houses (Controls) were constructed using current codes and practices and did not include AAHX's. The houses were divided between two climatic regions with 17 MCS and 18 Control houses located in the area around Portland, Oregon and 12 MCS and 14 Control houses located near Spokane, Washington. Control houses ranged up to seven years in age, while MCS were less than two years in age.

The average air leakage area measured by fan depressurization for the MCS houses was approximately 46% lower than for the Control homes. However, measured ventilation rates, determined with a passive perfluorocarbon tracer (PFT) technique are virtually identical for both groups of houses, with a geometric mean of 0.30 ach for MCS houses and 0.26 ach for Control houses yet are still lower than the design of 0.6 ACH. Physical model predictions for ventilation under occupancy, while higher, also show this equivalence (geometric means of 0.44 ach and 0.46 ach respectively). From the data, it is estimated that the AAHX was responsible for providing an average 0.2 ach of additional ventilation to the natural infiltration in the MCS houses.

The discrepancies between measured and predicted ventilation rates are not totally resolved, although the PFT method theoretically is biased 20% - 30% lower than the actual ventilation of a house.

In general, indoor concentrations of radon and formaldehyde exhibited greater dependence on the region in which a house was located than on the construction practices by which it was built. Differences in radon levels between MCS and Control houses by region or for all houses are not considered significant. Radon concentrations were higher in homes in the Spokane/Coeur d'Alene region (geometric mean 2.6 pCi/l) due to the local highly permeable, gravelly soils. Portland area homes had a geometric mean of 1.1 pCi/l. Eleven percent of all houses in this study exceeded the BPA mitigation action level of 5 pCi/l while 16% were above the EPA guideline of 4 pCi/l. Eighteen of the 61 houses (30%) had indoor formaldehyde levels above 100 ppb, a frequently cited guideline. The combined MCS and Control houses in the Portland area had a geometric mean formaldehyde concentration of 92.8 ppb, while Spokane area homes had a geometric mean of 59.5 ppb. This difference was much greater than that between all MCS and Control homes (82 ppb vs. 72 ppb). The regional difference is likely a result of different emission characteristics of pressed-wood products used in the two areas. Indoor formaldehyde concentrations also tended to be lower in older structures suggesting that emission rates of free formaldehyde decrease as construction materials age.

Radon levels in the Spokane area houses and formaldehyde levels in the Portland area houses are weakly, but significantly, correlated with ventilation rates. However, the total effect of variables other than ventilation, particularly pollutant source strength, are more important in determining indoor air pollutant concentrations.

Water vapor concentrations were surprisingly similar both between groups of houses and between regions, even though outdoor concentrations were considerably higher in the Portland area. Average indoor concentrations ranged only from a low of 6.29 g/Kg in Spokane area MCS houses to a high of 6.81 g/Kg in Portland area MCS houses. Control house group averages were between these extremes. Water vapor levels in Control house bedrooms were significantly higher than in other locations in these homes. There were no significant spatial differences in the water vapor concentrations in the MCS houses, presumably due to the more uniform distribution of ventilation air by the AAHX. Average indoor nitrogen dioxide levels were quite low (always below 7 ppb) since few, if any, indoor combustion sources were used.

I. INTRODUCTION

I.A. BACKGROUND OF BPA INTEREST

The Pacific Northwest Power Planning and Conservation Act of 1981 gave the Administrator of the Bonneville Power Administration (BPA) the authority to undertake cost effective conservation programs to meet future electrical load obligations. Conservation programs considered included weatherization of existing residences, retrofit of commercial buildings, and adoption of new construction standards (Model Conservation Standards, MCS) for residences. Each of these programs would reduce ventilation rates in buildings.

At the same time these programs were being developed, the quality of air within buildings was gaining recognition as an issue of concern to the general public (NAS, 1981; DOE/EPA, 1981). The case was made quite simply. Pollutant concentrations within buildings are frequently higher than those outdoors. Since people spend seventy to ninety percent of their time within buildings, exposures to potentially harmful airborne pollutants may be dominated by exposures within buildings. If one is concerned about health effects due to airborne pollutants, one should concentrate on the exposures that occur within buildings.

I.B. PREVIOUS WORK IN NEW HOMES

Often, indoor air quality problems are expected to be associated with new, tight buildings. Construction criteria may affect indoor air quality through modifications to ventilation rates or pollutant sources. Ventilation may change due to construction techniques that are designed to reduce or redistribute building air leakage, landscape design that changes environmental shielding, installation of exhaust fans at localized pollutant sources, or incorporation of a whole building mechanical ventilation system with or without heat recovery. Pollutant sources may be affected by construction techniques favoring new types of building materials that may contain potentially harmful compounds (volatile organic compounds), higher emission rates for some young materials, or lower emission rates from new formulations of urea formaldehyde-bonded wood products (formaldehyde). Radon sources may be modified by the type of substructure and materials and techniques used in the house construction. While this association of indoor air quality problems with new houses seems to be intuitively obvious, it is difficult to find field measurements that support this idea. A search of the literature shows that previous measurements of the impact of energy efficiency on indoor air quality in residences were inconclusive because of: (A) a lack of ventilation measurements; (B) a lack of an adequate group of control houses used as a comparison sample; (C) inadequate justification of the residences as "energy-efficient"; (D) attention to a single pollutant; or (E) an insufficient number of houses for statistical evaluation (Berk et al.,1980; Dumont, 1986; Figley, 1985; Figley, 1986; Fleischer et al., 1982; Hollowell et al., 1980; Lipschutz et al., 1981; Nero et al.,1983; Traynor et al., 1985). Preliminary BPA studies of indoor air quality and ventilation are just recently becoming available on a much larger group of new homes in the Pacific Northwest (Reiland et al., 1985a and 1985b; Harris, 1986 and 1987).

I.C. GOALS OF THIS STUDY

The goals of this study were to survey and compare ventilation rates and indoor air quality in new houses built to Model Conservation Standard (MCS) specifications with those of conventional new houses (Controls) in the Pacific Northwest.

II. EXPERIMENTAL

II.A. SAMPLE DESCRIPTION

The housing sample for this study was selected from two different climatic regions in the Pacific Northwest: the mild coastal region west of the Cascade Mountains including Vancouver, Washington; Portland, Oregon; and Salem, Oregon; and the colder and drier plateau area of eastern Washington and western Idaho. These homes were part of the larger Residential Standards Demonstration Program (RSDP) that include 423 MCS homes and 411 Control homes. The Washington State Energy Office, Oregon Department of Energy, and BPA furnished lists of candidate homes and assisted in the selection of most study homes. Additional Control homes were recruited through independent inquiry. Because the number of houses with interested homeowners was limited, a random sample was not selected.

A total of 61 homes participated in the study consisting of 29 MCS homes and 32 Controls. The MCS homes were built to criteria that were intended to improve the energy performance of residential construction. The standards encouraged the use of thermally-efficient construction materials (insulation and low U-value windows) and techniques to reduce air infiltration to 0.1 or 0.4 ach (depending on the climate zone and conservation package that was selected). The majority of homes were constructed to meet the 0.1 ach criteria. Continuous drywall and polyethylene air barriers were the techniques recommended to limit the natural infiltration. Air leakage was also controlled by the required use of outside combustion air for woodstoves and fireplaces. A whole-house central air-to-air heat exchanger (AAHX) was installed in each MCS home. The AAHX were controlled by humidistats and were intended to provide ventilation in addition to the natural infiltration for a total heating season average ventilation of 0.6 ach. This figure was determined using fan depressurization data and model predictions to be the typical ventilation for conventional construction houses. Homeowners could override the humidistat and control AAHX operation manually. The 32 control homes were structures built since 1979 according to conventional construction practices. Although some of the newer Control homes employed energy conservation techniques similar to the MCS requirements (additional house tightening, vapor barriers, and insulation) none had an air-to-air heat exchanger (Harris, 1986). All homes, with the exception of NCD077C, were electrically heated. Homeowners were asked not to use fireplaces or woodstoves for supplemental heat during the test period.

Table 1 summarizes the characteristics of the two groups of houses by region, number of stories, floor area, substructure type, year of construction, and presence of combustion sources. Seventeen MCS and 18 Control homes were located in the Portland area, while 12 MCS and 14 Control homes were located in the Spokane area. The Control houses tended to be somewhat older than the MCS houses. Seventeen Control houses (53%) were built prior to 1984, the beginning of the MCS program. More Control homes than MCS homes were only one story in height, particularly those in the Portland region. MCS homes were approximately 10% larger in floor area than the Control homes with both sets in the Spokane area larger than their Portland area counterparts. Substructure types were similar for the two sets. Only 10% of all study houses had occupants that smoked tobacco. See Appendix A for more detailed house descriptions.

TABLE 1

SUMMARY
HOUSE CHARACTERISTICS

	SALEM/PORTLAND/ VANCOUVER		SPOKANE/ COEUR D'ALENE		TOTAL	
CLASSIFICATION	MCS	CONTROL	MCS	CONTROL	MCS	CONTROL
No. of Stories:						
1	4	17	4	6	8	23
Split	3	0	5	3	8	3
2	10	1	3	5	13	6
Floor Area:						
< 1000 (Ft^2)	2	7	0	1	2	8
1000-2000	9	9	8	8	17	17
> 2000	6	2	4	5	10	7
Median (Ft^2)	1346	1127	1826	1760	1690	1511
Average (Ft^2)	1691	1285	1875	1815	1767	1517
Substructure Type:						
Basement Only	2	2	8	7	10	9
Crawlspace Only	9	16	0	2	9	18
Slab Only	1	0	0	1	1	1
Combination	5	0	4	4	9	4
Age:						
1978-80	0	1	0	3	0	4
1981-83	0	9	0	4	0	13
1984	13	8	10	5	23	13
1985	4	0	2	2	6	2
Median	11/84	6/83	10/84	1/84	10/84	10/83
Average	10/84	3/83	10/84	1/83	10/84	2/83
Homes with Fireplaces:	5	8	5	7	10	15
Homes with Smokers:	1	1	0	4	1	5
TOTAL	17	18	12	14	29	32
	35		26		61	

II.B. MONITORING PROTOCOL

The test protocol for monitoring the houses required three visits to each house by at least one subcontracted field technician. After houses were selected for participation, a technician visited each house to verify its suitability for use in the study, installed passive samplers, measured the air leakage of the home using a calibrated blower door, noted pertinent construction details and instructed the homeowner in the use of a daily activity log. This log provided the occupant with an opportunity to record daily activities that would affect air quality within the structure (door and window openings, tobacco smoking, AAHX operation, etc.).

The second visit occurred seven to ten days later. During this visit the technician collected the passive samplers for pollutants: nitrogen dioxide (NO_2), formaldehyde (HCHO), and water vapor (H_2O); the short-term ventilation measurement passive samplers and the homeowner activity logs. The third visit occurred 55 to 70 days after the first. During this visit, the radon detectors and perfluorocarbon tracer (PFT) ventilation measurement samplers and sources were removed and a second blower door test performed. Thus two measurements for infiltration were made using the PFT: the first was a seven to ten day measurement that coincided with the NO_2, HCHO, and H_2O passive sampler measurements; and a second, lasting 55 to 70 days, that coincided with the radon measurement in the house.

First visits began in early March, 1985, and continued through mid-April, 1985. Removal of all monitoring equipment started in May and was completed in the last houses in June 1985.

II.C. POLLUTANT MONITORING

Table 2 summarizes the pollutants sampled during monitoring. Passive pollutant samplers fabricated and analyzed at LBL included nitrogen dioxide (NO_2), formaldehyde (HCHO), and water vapor (H_2O). Figure 1 shows a typical deployment package for the passive samplers. These devices sample air by establishing a pollutant-selective concentration gradient within a tubes of known dimensions capped at one end (Palmes et al.,1976; Geisling et al.,1982; Girman et al.,1986). The pollutant is collected on an adsorbent or chemically treated disk(s) at the capped end. The samplers were designed to sample continuously for a seven-day period and, upon analysis, provide a measure of the average pollutant concentration. Depending on house size, indoor NO_2 and H_2O samples were collected at two to five locations in occupied spaces of each house; one outdoor NO_2 and H_2O sample was taken at each house for reference. Because of their comparatively poor precision, replicate HCHO samplers were exposed at each of the indoor and outdoor locations where H_2O and NO_2 were monitored.

Sampling locations were chosen to be away from direct contact with the pollutants being monitored (HCHO: particleboard and other pressed-wood product surfaces, H_2O: bathrooms and laundry rooms, NO_2: combustion sources, Rn: earth-based material surfaces). In addition, sources of temperature extremes, sunlight, and rapid air movement (furnace registers) were avoided as well as areas of air stagnation. Typical sample locations were 6-ft high on interior walls of a room representative of the zone being sampled.

Radon (^{222}Rn) was monitored using a Terradex Type SF passive sampler for a period lasting from 55 to 70 days in each house. Two to five samplers were deployed in the occupied space of each house and typically at the sample location for HCHO, NO_2, and H_2O; one to three additional samplers were deployed in unoccupied regions of the substructure of each house (crawlspaces, basements, and unheated attached utility rooms and storage areas).

TABLE 2

Air Sampling Instrumentation and Analytical Techniques

Pollutant	Sampling Device	Analytical Technique
HCHO	LBL Passive Sampler[1]	Spectrophotometric[2]
H_2O	LBL Passive Sampler[3]	Gravimetric
Rn	Terradex Corp. Type SF Track Etch Sampler	Count number of tracks on alpha-sensitive film, performed by Terradex Corp.
NO_2	Palmes' Passive Sampler[4]	Spectrophotometric
Structure Air Leakage Area		
--	Calibrated Blower Door. Retrotec Model RDF501	Depressurization Only. ELA At 4 pa.
Tracer	Ventilation Measurement Device	Analytical Technique
Perfluorocarbons	Source: Permeation Tubes Sampler: Passive Adsorption Tubes	Brookhaven National Lab. AIM System. Thermal Desorption and ECD/GC Analysis[5]

References:

1. Geisling, K.L., M.K. Tashima, J.R. Girman, R.R. Miksch, and S.M. Rappaport (1982). A passive sampling device for determining formaldehyde in indoor air, Environ. Int. 8, 153-158.

2. National Institute of Occupational Safety and Health. 1977. NIOSH Manual of Analytical Methods, 2nd ed., NIOSH 77-157A, Cincinnati OH.

3. Girman, J.R., J.R. Allen, and A.Y. Lee. 1984. A passive sampler for water vapor, Environ. Int. 12:461-465.

4. Palmes, E.D., A.F. Gunninson, J. DiMattio, and C. Tomezyk (1976). Personal sampler for NO_2, Am. Ind. Hyg. Assoc. J, 37:570-577.

5. Dietz, R.N., E.A. Cote. 1982. Air Infiltration Measurements in a Home Using a Convenient Perfluorocarbon Tracer Technique, Environment International, Vol. 8:419-433.

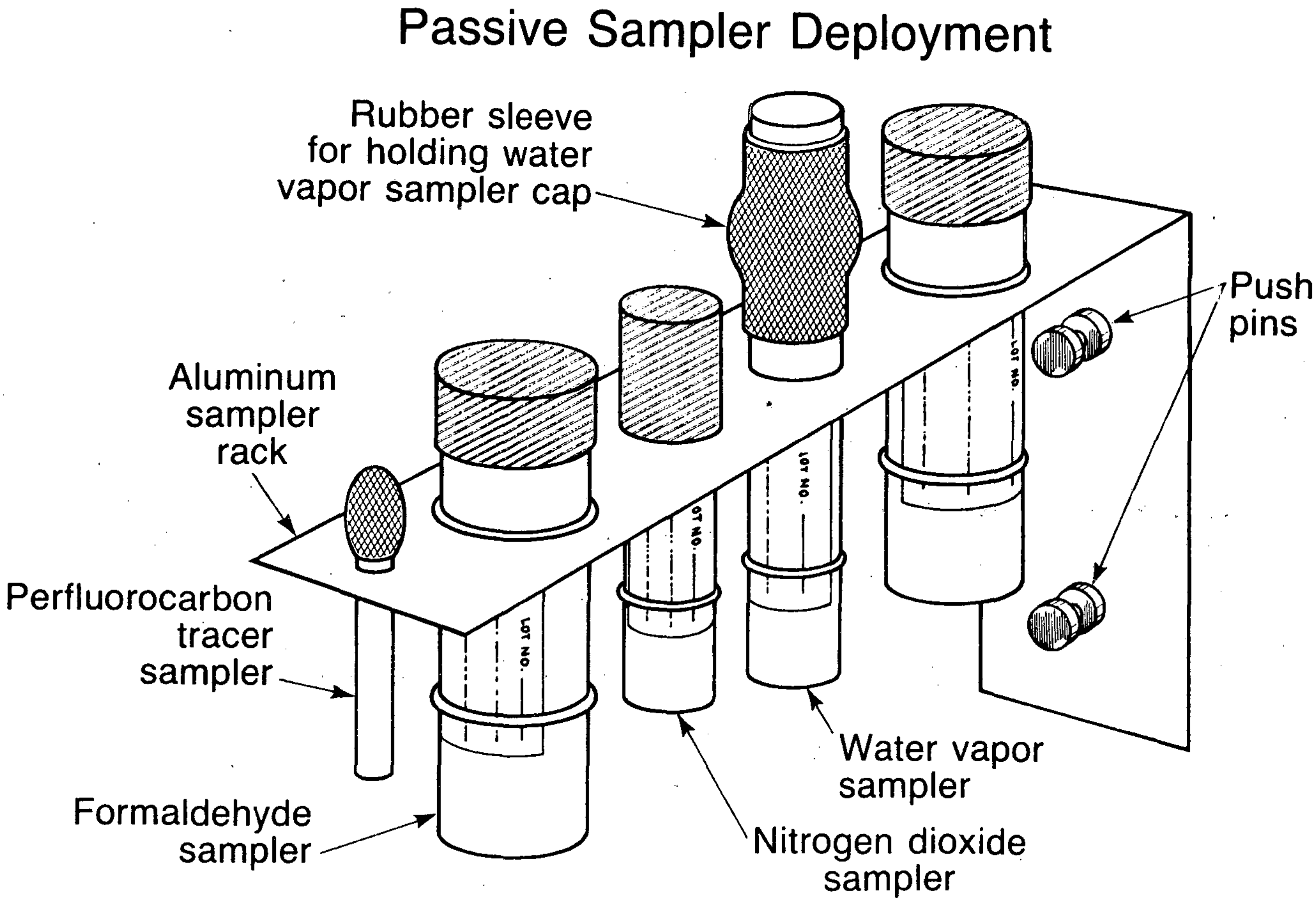

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Figure 1. Passive sampler deployment. This figure shows an aluminum sampler rack containing two formaldehyde samplers, a water vapor sampler, a nitrogen dioxide sampler, and a perfluorocarbon sampler. For approximate scale reference, the HCHO samplers are each 10 cm in length and 2.5 cm in diameter.

II.D. AIR LEAKAGE AND VENTILATION RATE MEASUREMENTS

Measurements of the effective air leakage area (ELA) of the buildings were conducted using a blower door to depressurize the occupied zones of the structure. Large openings such as fireplaces and accessible exhaust vents were temporarily sealed while the test was run to avoid 'swamping' the measurement and to improve the technique sensitivity in these low leakage houses. The ELA was calculated at 4 pascals from a curve fit to higher pressure data. The estimated size of the sealed openings was later added to the blower door-derived ELA for use in a physical model to predict ventilation rates. A second blower door test was made at the conclusion of all monitoring to determine if any changes in house tightness occurred during the period. ELA's were used with weather data for the test period from the nearest weather reporting stations (Salem, Portland, Spokane) in the LBL model by Sherman and Grimsrud (1980) to calculate predicted ventilation rates for the 7-10 day pollutant monitoring period. A second calculation was made incorporating data on window and door openings, exhaust fan operation, and AAHX operation from the daily activity logs for a prediction of ventilation rates under occupancy.

Ventilation measurements were made with a passive perfluorocarbon tracer (PFT) injection and sampling system developed by Dietz at Brookhaven National Laboratory (BNL). This system provides time-averaged ventilation rate measurements (Dietz and Cote, 1982). The perfluorocarbon tracer is released continuously at known rates from small, 3-cm-length permeation tubes. As permeation tubes, the emission rates of the tracer sources are temperature dependent. Therefore these tubes were affixed on or near maximum/minimum thermometers to record temperatures used to correct permeation rates. Approximately one tracer tube was deployed for every 500 ft^2 of floor area in a zone. Up to four separately identifiable perfluorocarbon tracers were used to label separate zones in each building, such as crawlspaces, basements, first floors, and slab-on-grade areas. The tracers are diluted by the building air and are sampled with a cigarette-sized diffusion tube containing an adsorbent and closed with rubber end caps (cf. Fig. 1). Once the sampling was completed, the samplers were capped and shipped to BNL for analysis using thermal desorption and a gas chromatograph with an electron capture detector.

Simultaneous ventilation measurements by another contractor using identical PFT sources took place in several houses. In these situations, a tracer type different from that already deployed was chosen for placement. This permitted two separate but simultaneous ventilation measurements to be conducted by LBL and the other BPA contractor. This contractor who was responsible for monitoring the larger group of RSDP homes also monitored HCHO and radon, but at fewer locations.

III. TEST RESULTS

III.A. LEAKAGE AREA

Figure 2 displays the specific leakage area (SLA) results from the first blower door tests. The specific leakage area is defined as the ELA measured using fan depressurization normalized by dividing by the occupied floor area of the house. We note that the measurement of leakage area in the MCS houses included the leakage area associated with outside and exhaust air ducts in air-to-air heat exchangers that were installed in these houses to provide mechanical ventilation. The SLA data presented here do not include those leakage areas sealed during the blower test. The figure shows the geometric mean (GM) SLA (dots) and the geometric standard deviations (GSD) of the distributions of each of the samples listed. Typical values of the SLA for housing in the United States lie in the range of four to ten cm^2/m^2 (Grimsrud et al., 1983). Thus the MCS and Control houses in the Spokane area and the MCS houses in the Portland area are substantially tighter than conventional U.S. housing.

NEW HOME STUDY (61 HOUSES)

First Test Specific Leakage Area (cm^2/m^2)	Spokane		Portland		All	
	MCS	CONTROL	MCS	CONTROL	MCS	CONTROL
G. MEAN	1.15	2.87	2.93	4.56	1.99	3.73
G.S.D.	1.67	1.54	1.84	1.45	2.08	1.58
NO. HOUSES	12	14	17	18	29	32

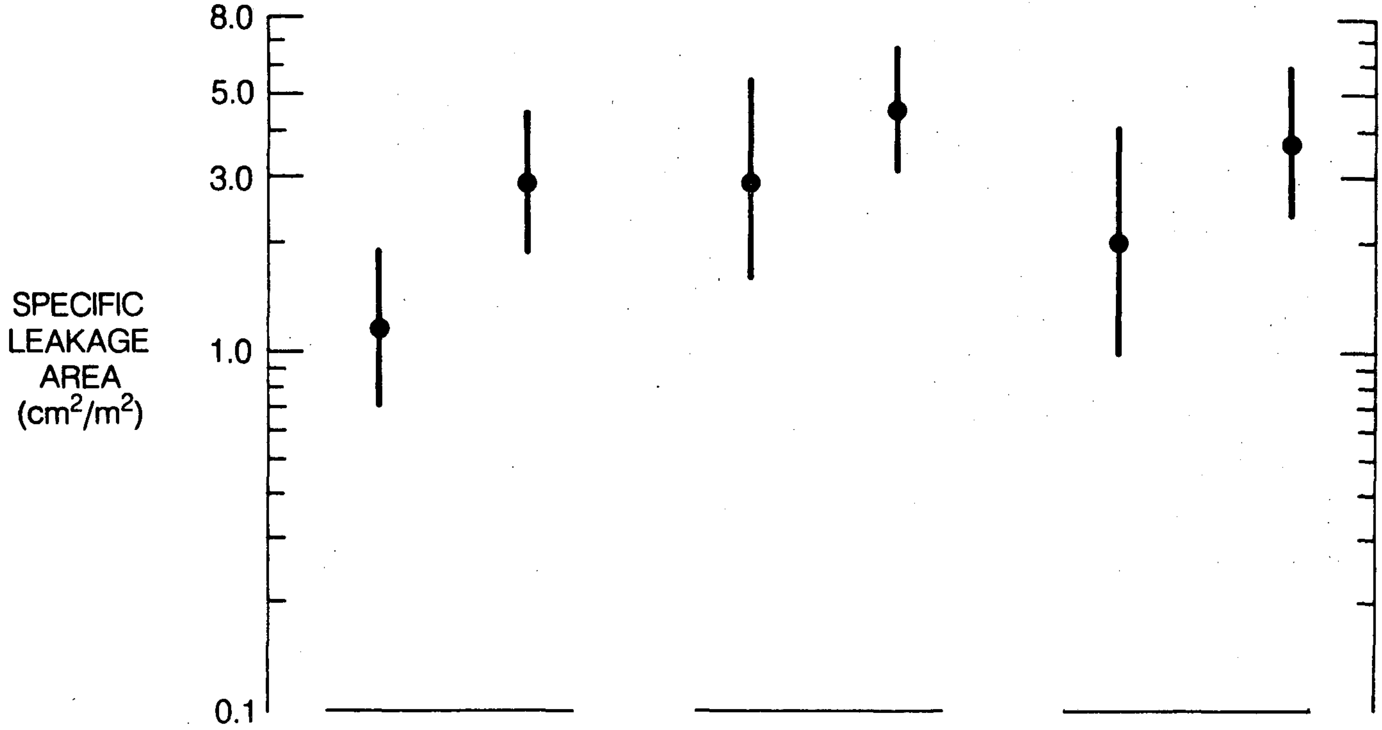

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Figure 2. Specific Leakage Area (SLA) Test Results. The specific leakage area is defined as the equivalent leakage area measured using fan pressurization normalized by dividing by the floor area of the house. The figure shows the mean SLA (dots) and the standard deviations of the distributions of each of the samples listed.

Figures 3 and 4 are histograms of the SLA data from the first blower door test. The figures demonstrate the differences in the distributions by geographic region (Figure 3) and by construction type (Figure 4). Since it is not clear what distribution form should be applied to statistical analysis of the leakage data, a nonparametric, or distribution-free method has been employed. Using a Wilcoxson two-sample one-sided test of significance (from Sokal and Rohlf, 1981), the entire sample MCS SLA is significantly lower than Control SLA by 46% ($P < 0.0005$). Using the same test, the comparison within regions also shows the MCS homes to be tighter than the Control homes at a significance level of $P < 0.001$. Spokane MCS homes are approximately 60% tighter and Portland area MCS homes are 35% tighter. Therefore, one of the primary goals of the Standards, to produce tighter housing, was achieved in the samples surveyed here.

The regional differences within the same construction type (MCS or Control) are even more pronounced. The Spokane MCS homes are 61% tighter than the Portland area counterparts ($P < 0.001$) and the Spokane Control homes are 37% tighter than the Portland area Control homes ($P < 0.005$). Spokane Control homes may even have less normalized air leakage area than the Portland MCS homes. This is likely a reflection of the more severe climate of the Spokane area (6882 degree-days vs. 4691 degree-days) influencing energy conservation-conscious building design and construction.

Data from the second blower door test (conducted approximately two months after the initial test) are compared to the first test for 58 houses in Figure 5. Replication between tests is very good with most points lying along the line of agreement. The first test and second test arithmetic means ($3.35\ \text{cm}^2\ \text{m}^{-2}$ vs. $3.56\ \text{cm}^2\ \text{m}^{-2}$) and geometric means are very close. The mean of the coefficient of variation for the pair of tests for each house is 11.2% and is similar to the variation found in 31 replicates from 25 older houses (Turk, et al., 1987). It indicates that the total variation resulting from changes in individual house leakage areas and blower door test imprecision are close to 10%. The repeatability of results demonstrates the utility of this test as a consistent indicator of building air tightness, See Appendix B for individual house data values.

Unaccountably, one house (NPO742) had an extremely high SLA of $14.99\ \text{cm}^2\ \text{m}^{-2}$, which is in the range of very leaky, older houses. The test was repeated many times, yet no explanation was obvious. Actual measurements of ventilation do not support the finding of a large leakage area. Therefore, we interpret this as evidence of one-way valve-type opening to the outside of the house. The data value is included in all statistical summaries.

III.B. VENTILATION RATE

The MCS houses, because of their design goal of increased building tightness, were expected to have lower infiltration rates than houses of conventional design. Therefore, mechanical ventilation in the form of air-to-air heat exchangers was included in the design standards to insure that a heating season average total ventilation rate of 0.6 ach would be obtained.

III.B.1. MODEL PREDICTIONS

The results of the leakage area measurements discussed above indicate that the MCS houses are, on average, tighter than the Control houses by 46%. That is, the SLA of the MCS sample is 46% smaller than the SLA of the Control sample. Since the infiltration of a house is proportional to its leakage area (Sherman and Grimsrud, 1980; Shaw, 1981), this suggests that the ventilation rate measurements should show a corresponding difference, which would be the case in the absence of mechanical ventilation.

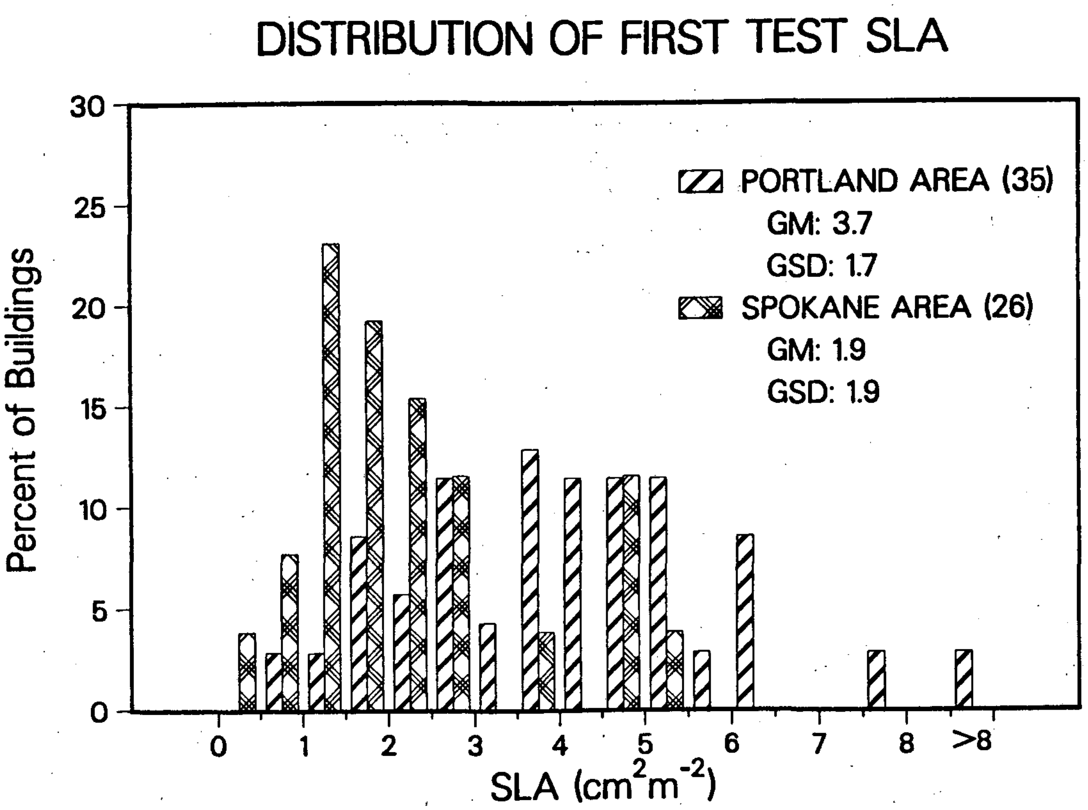


Figure 3. Histogram of first test SLA from 61 homes, by region. It clearly shows the Spokane area houses to have smaller leakage areas.

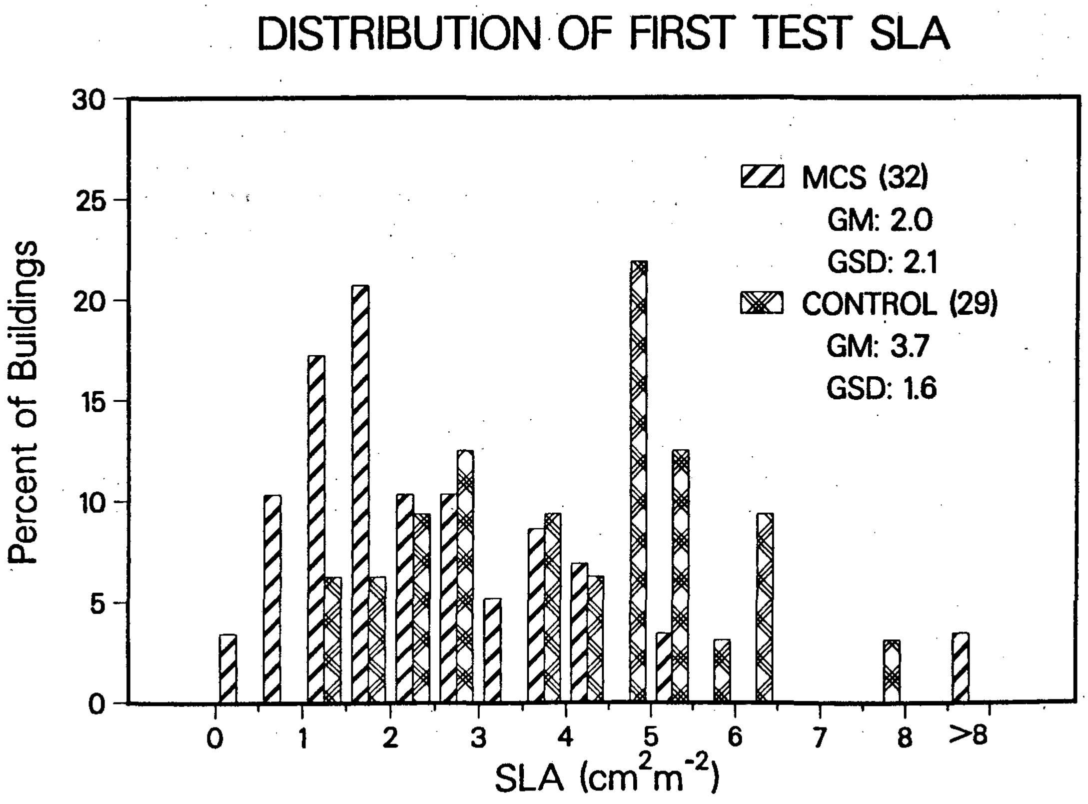


Figure 4. Histogram of first test SLA from 61 homes, by construction type. As seen in Figure 2, MCS houses are tighter as a class than Control houses.

The strong dependence of predicted ventilation on leakage area is shown in Figure 6. Fully 86% of the variation in predicted ventilation is explained by the variation in SLA. The remainder of the variation is determined by other factors, including house height, exposure, leakage distribution, indoor temperature, and outdoor temperature and windspeed which are included in the model so that all data points do not lie on exactly the same fitted regression line. In addition, measured leakage areas and those areas that were sealed during the test are summed for a total structure leakage used in all model calculations of ventilation rates (Reinhold and Sonderegger, 1983). Predicted ventilation in this figure is not corrected for occupancy effects such as door and window openings, and exhaust fan and AAHX operation.

Table 3 summarizes all of the ventilation data. It includes predicted ventilation for the occupied condition. Certain assumptions were made for flow rates of fans, added ventilation due to normal occupancy and fireplace or woodstove operation, added leakage area due to unusual window and door openings, and the estimated additional ventilation of AAHX operation (Traynor, et al., 1985; Modera and Sonderegger, 1980; Sonderegger, et al., 1980, Hekmat and Fisk, 1984; Derochers and Robertson, 1986). Predicted ventilation rates are significantly greater, (Wilcoxson one-tailed test, $P < 0.0005$) approximately 35 - 40%, when these occupancy effects are included for all houses. The increase is more dramatic for the MCS homes (80%) because of the AAHX operation than in the Control homes (15%). Calculations of ventilation rates during occupancy for all homes show very similar means for the MCS and Control groups. Thus the desired effect of additional ventilation from AAHX's is predicted. However, these predictions of ventilation that incorporate occupancy should be considered with caution. Occupancy data was derived from the daily activity logs, maintained by the homeowners, and includes run-time for the AAHX. The quality of this data is questionable. Only 16 of the 29 MCS homes explicitly reported AAHX operation. Of these 16, the majority (11) were from the Spokane area and for some homes the data appears incomplete. Partly for this reason, we find the Spokane area MCS homes showing larger increases in predicted ventilation due to occupancy (144%) than for the Portland homes (42%). Retrospectively, a run-time meter should have been installed on the AAHX to more accurately monitor its operation.

III.B.2. MEASURED VENTILATION

Two ventilation measurements were made in these houses using the PFT system. The first lasting from seven to ten days, coincided with the short-term pollutant passive sampler measurements. The second coincided with the two-month measurements of the radon concentrations in each house. Figure 7 shows the distribution of short-term ventilation measurements plotted as histograms for the MCS and Control samples. The median ventilation values for the two distributions are 0.28 ach for the Control houses and 0.35 ach for the MCS houses. Also shown on the figure are log-normal distributions generated from the calculated geometric mean and geometric standard deviation of each distribution. These values are 0.26 ach and 1.88 for the Control houses sample; 0.30 ach and 1.99 for the MCS sample, and are not significantly different when using a two-tailed t-test at $0.4 > P > 0.2$. Only the Spokane area Control homes can be shown to have significantly lower ventilation than Portland area Control homes (42%) using a one-tailed t-test ($0.01 > P > 0.0005$).

Figure 8 displays similar information from the long-term ventilation measurements. In this case the median ventilation is 0.29 ach for the Control and 0.31 ach for MCS samples. Calculated geometric means and geometric standard deviations are 0.31 ach and 1.80 for the Control distribution; and 0.31 ach and 1.71 for the MCS distribution.

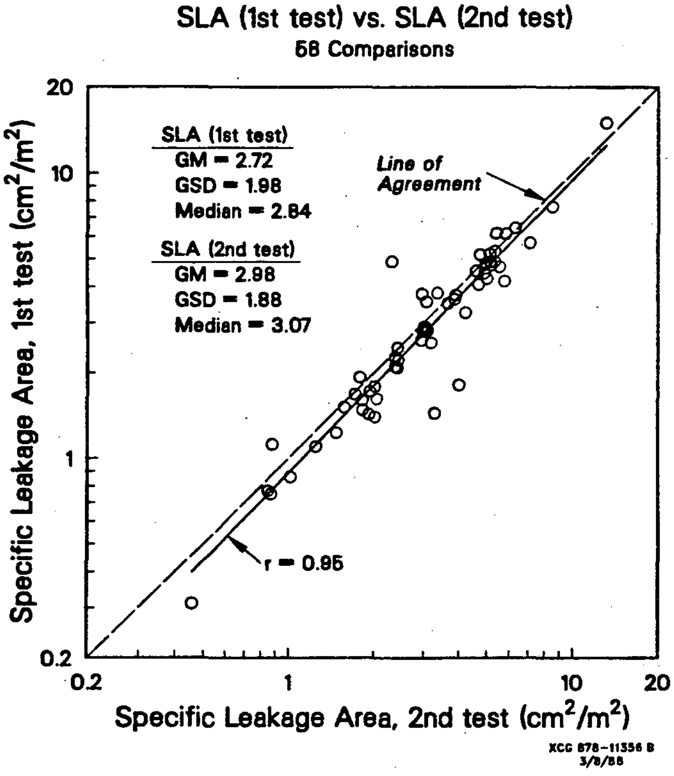


Figure 5. Comparison of SLA from the first and second tests conducted approximately two months apart in 58 houses, both MCS and Control. The coefficient of determination for the fitted line is 0.90.

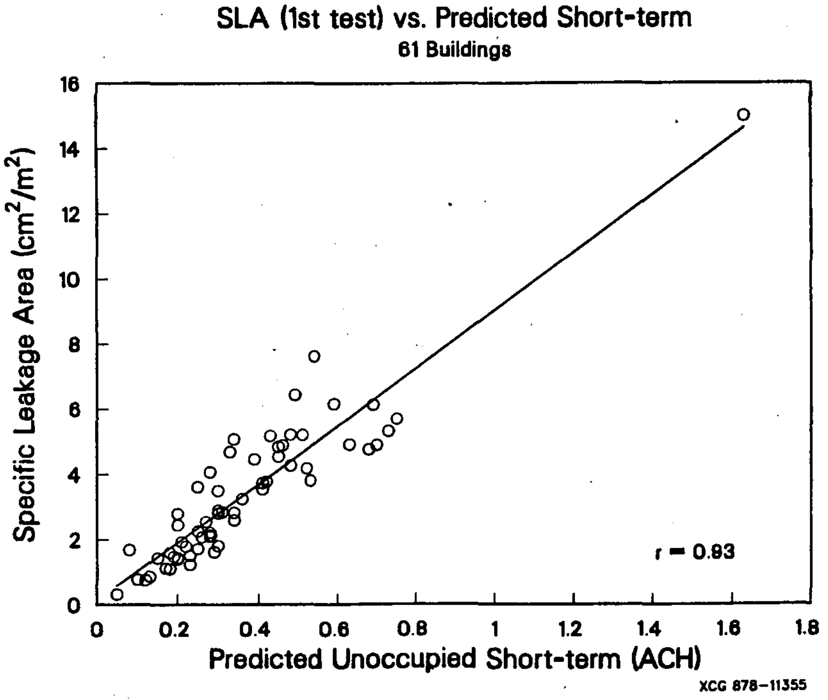


Figure 6. Dependence of model-predicted ventilation on house air leakage area. Predicted ventilation assumes no occupancy effects (including operation of the air-air heat exchanger) for the seven to ten day pollutant monitoring period. The normalized ventilation (air changes per hour - ach) and leakage area (SLA) permit inter-house comparison.

TABLE 3

VENTILATION DATA SUMMARY
(ACH)

RATE/MEASUREMENT	SPOKANE/COEUR D'ALENE		PORTLAND/SALEM/VANCOUVER		ALL		
	MCS	CONTROL	MCS	CONTROL	MCS	CONTROL	TOTAL
PREDICTED SHORT-TERM							
UNOCCUPIED							
AM	0.19	0.37	0.39	0.46	0.30	0.42	0.37
ASD	0.07	0.16	0.34	0.18	0.28	0.17	0.24
GM	0.18	0.34	0.31	0.43	0.24	0.39	0.31
GSD	1.65	1.49	1.93	1.53	1.93	1.53	1.81
N	12	14	17	18	29	32	61
OCCUPIED							
AM	0.49	0.41	0.52	0.58	0.51	0.51	0.51
ASD	0.23	0.18	0.34	0.26	0.30	0.24	0.27
GM	0.44	0.38	0.44	0.53	0.44	0.46	0.45
GSD	1.66	1.48	1.73	1.60	1.68	1.58	1.63
N	12	14	17	18	29	32	61
PFT MEASURED							
SHORT-TERM							
AM	0.32	0.23	0.39	0.36	0.36	0.30	0.33
ASD	0.21	0.13	0.21	0.15	0.21	0.15	0.18
GM	0.26	0.19	0.32	0.33	0.30	0.26	0.28
GSD	1.88	2.06	2.08	1.53	1.99	1.88	1.93
N	12	14	17	18	29	32	61
LONG-TERM							
AM	0.31	0.29	0.38	0.42	0.35	0.36	0.35
ASD	0.15	0.18	0.19	0.22	0.17	0.21	0.19
GM	0.28	0.25	0.33	0.37	0.31	0.31	0.31
GSD	1.66	1.83	1.76	1.68	1.71	1.80	1.75
N	11	14	16	15	27	29	56

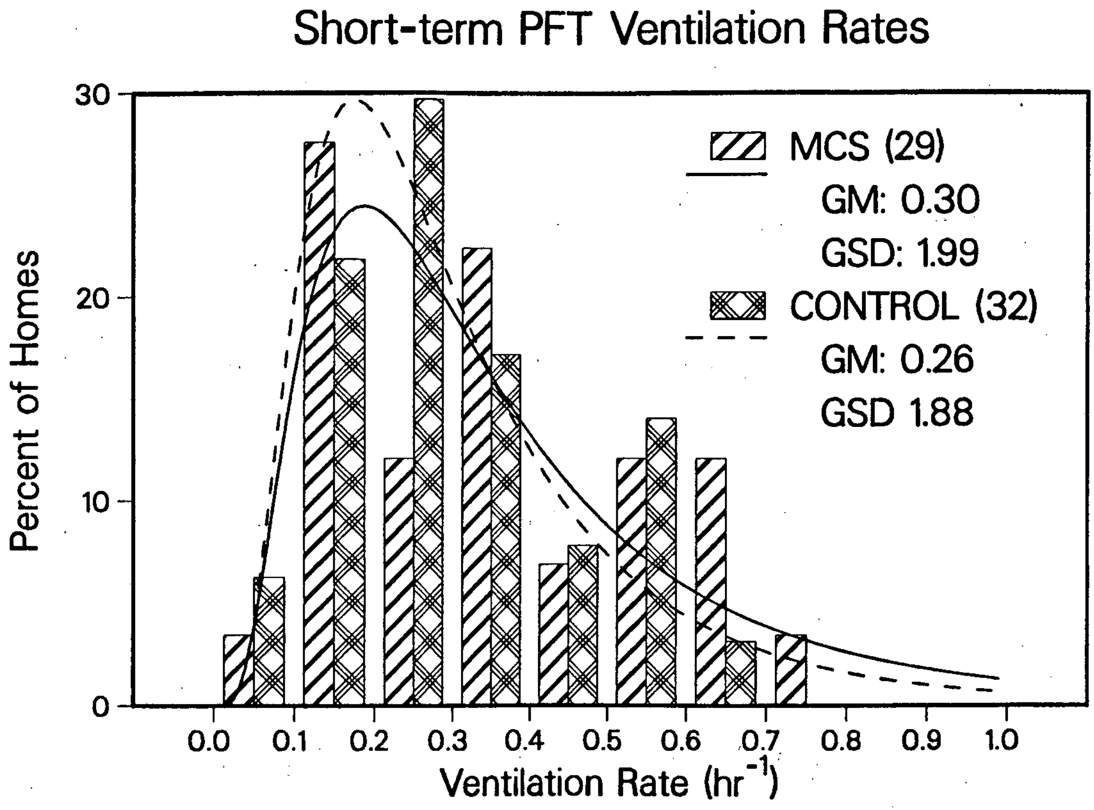


Figure 7. Short-term ventilation measurements in the MCS and Control houses. The solid and dashed lines are log-normal distributions calculated for the geometric means and geometric standard deviations of the two distributions.

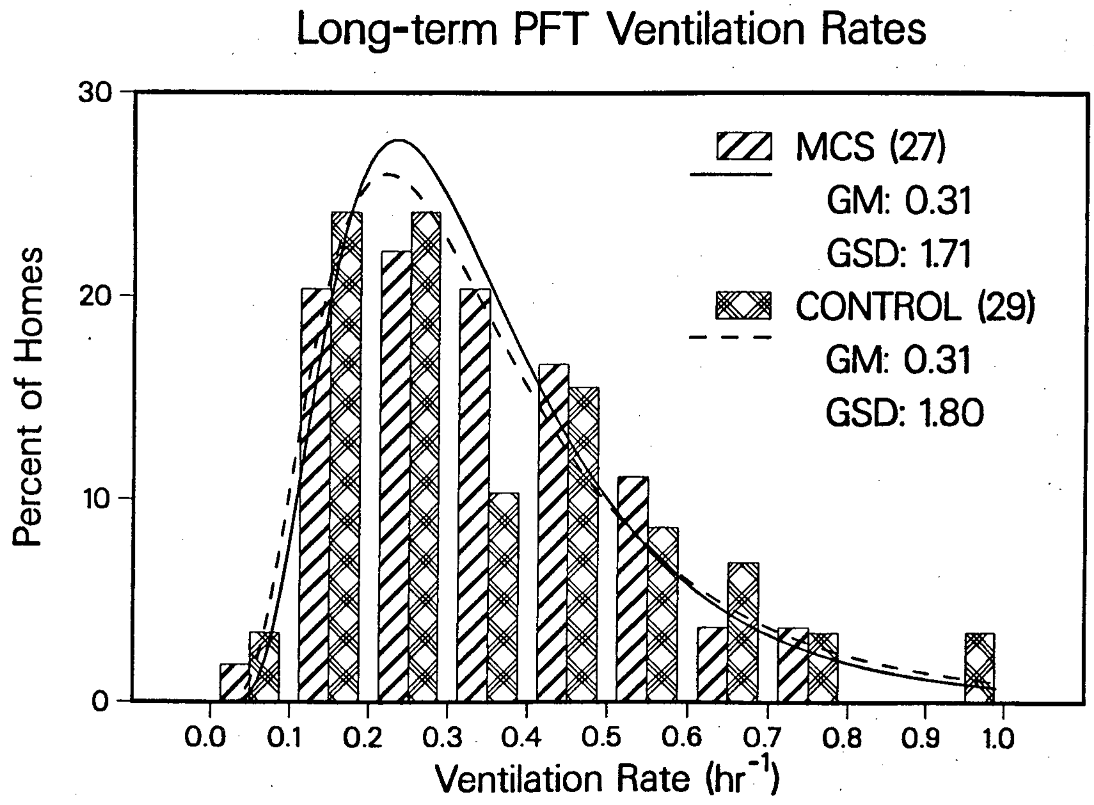


Figure 8. Long-term ventilation measurements in the MCS and Control houses. The solid and dashed lines are log-normal distributions calculated for the geometric means and geometric standard deviations of the two distributions.

Long-term and short-term distributions for the 56 houses in which long-term measurements were made are directly compared in Figure 9. The slight difference between the two distributions (geometric mean, 0.27 vs. 0.31 ach; geometric standard deviation, 1.93 vs. 1.75 ach) is not significant, $(0.5 > P > 0.4)$ using a two-tailed t-test. On a house-by-house basis, the data also show good agreement for the comparisons, with the best fit line lying close to the line of agreement (Figure 10). Examination of the sub-group means (Table 3) indicates that the long-term measurements are always higher than the short-term, although there is no statistical significance to the observed difference between the various means (two-tailed t-test, $0.9 > P > 0.5$).

Arguments (conflicting) can be posed on physical grounds that the two distributions should be different. The short-term measurements from different houses were not coincident in time and probably were subjected to a larger range of weather extremes. Therefore, they should exhibit more scatter than the long-term measurements which average over a longer and more overlapping period. The long-term measurements sampled into the warmer late spring and early summer months. It is expected that ventilation rates could be either very low (with windows closed) because of the small indoor-outdoor temperature differences typical during these months or they could be quite high when doors and windows are likely to be open.

Mathematically, PFT results tend to be biased low due to the natural variation in instantaneous ventilation rates. The PFT technique does not provide a true average of ventilation unless the ventilation rate is constant throughout the period. When variations occur and are aggravated by a long sampling period, the inverse of the average concentration (as measured by the PFT sampler) is no longer the true average ventilation rate for that period. Underpredictions may be 20 - 30% according to Sherman (1987), based on theoretical calculations.

The results for the long-term and short-term measurements in this study do not indicate a bias between the two measurement periods. However, the offsetting effects of higher actual ventilation rates due to warm-weather door and window openings and exaggerated underprediction due to the long sampling period do not allow a valid comparison to be made.

Clearly both short-term and long-term measurements demonstrate that the MCS houses do not have significantly lower ventilation rates than the Control houses as one would predict if ventilation were supplied only by infiltration. On the other hand, only two of the 27 MCS houses in which long-term ventilation measurements were made and five of 29 in which short-term measurements were made had ventilation rates at or above 0.6 ach, which was the design objective.

PFT short-term ventilation rates are compared by age of structure in Figure 13. Both MCS and Control Homes are included. No MCS homes in this study were built before 1984, so all homes older than that are Controls. There are no differences in ventilation rates in this study's sample that are a function of building age.

Predicted ventilation rates and PFT-measured ventilation rates for the short-term monitoring period are compared in Table 3 and Figures 11-12. Differences in the means for a subgroup range up to 50%, when comparisons are made using unoccupied or occupied predictions. Average predicted rates for the occupied condition are always higher than average PFT rates, whereas predicted rates without occupancy are only higher for the Control homes. The individual house-house correlation is extremely poor and yields scatter plots such as Figure 11 and 12. The lack of correlation is disconcerting, especially when the intra-method replications are good. While the PFT technique may be expected to yield results 20 - 30% lower than actual average ventilation, the large scatter for individual houses requires further explanation. There are many opportunities for introduction of error in the PFT technique: improper source placement and room air mixing, inaccurate analysis, poor handling protocol, or occupant interference. Many assumptions for the model calculations could also introduce large uncertainties.

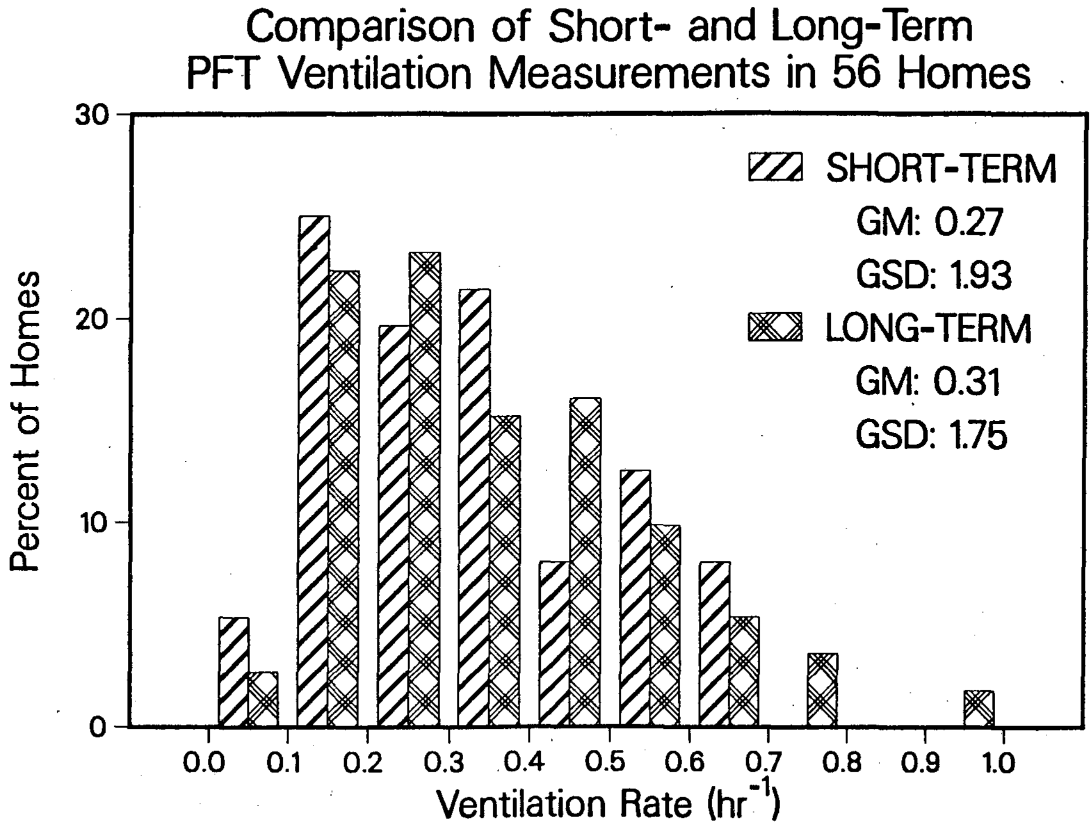


Figure 9. Histogram of short-term and long-term ventilation measurements made using the PFT samplers in the 56 houses in which both measurements were made. The two distributions are indistinguishable at the 0.5 > P > 0.4 level of significance.

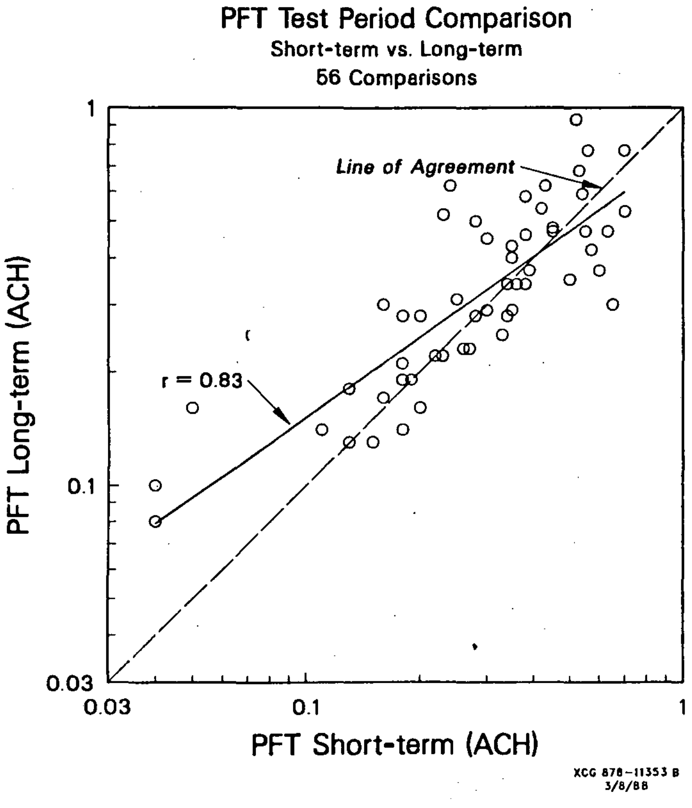


Figure 10. House-by-house comparison of short- and long-term PFT measurement period data. Correlation is good and the best fit line lies close to the line of agreement for the 56 comparisons.

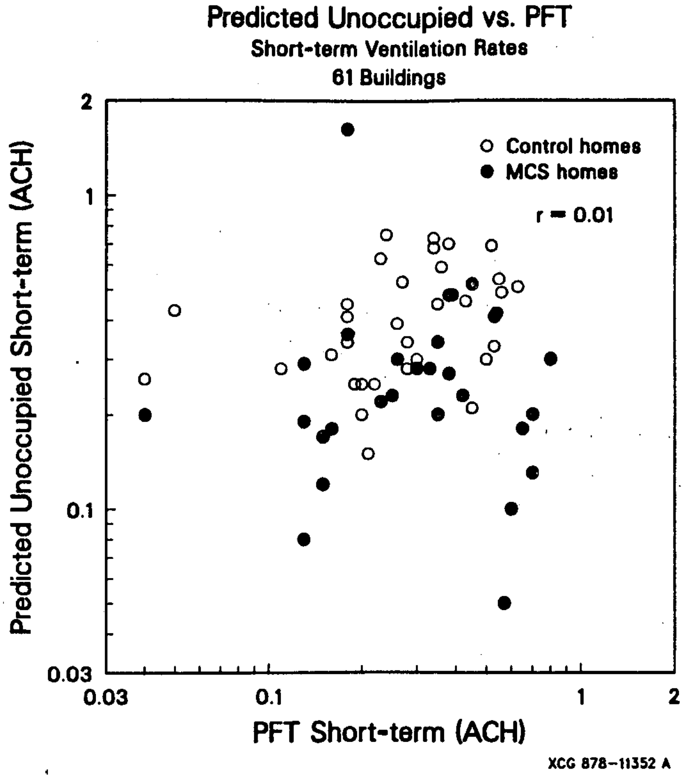


Figure 11. Comparison of PFT short-term ventilation rate measurement with model-predicted rates assuming no occupancy effects. There is no correlation for the 61 building comparisons.

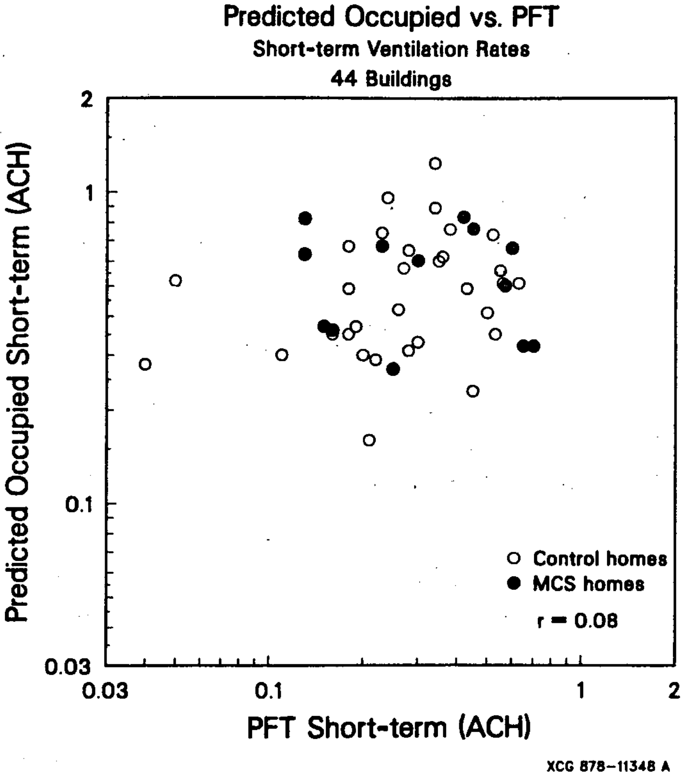
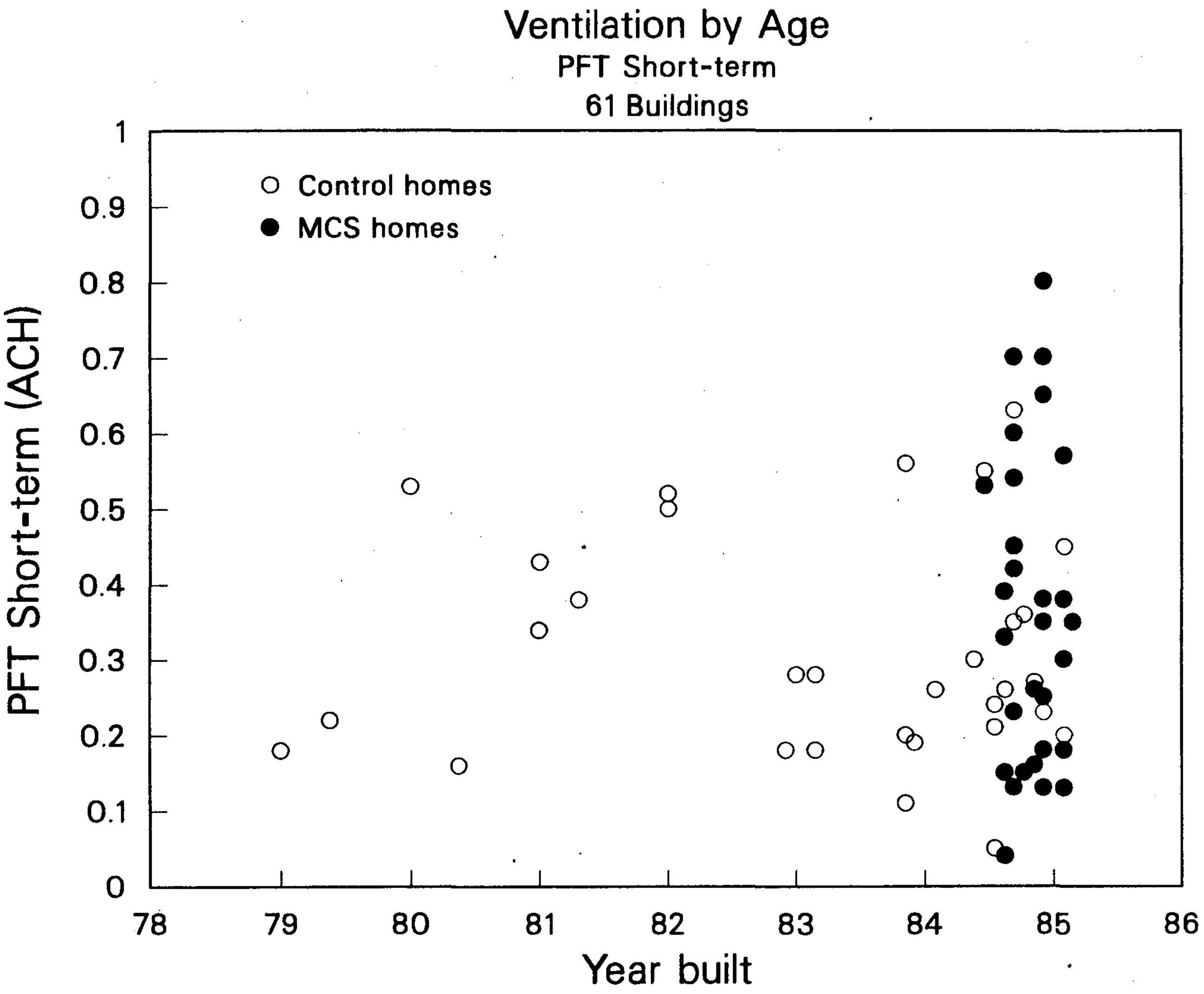


Figure 12. Comparison of PFT short-term ventilation rate measurement with model-predicted including occupancy effects in 44 buildings.



XCG 878–11347

Figure 13. PFT short-term ventilation rates as a function of construction date. No differences are observed.

General assumptions are made by the field technicians for the distribution of leakage area terrain classification, and shielding classification. The LBL model makes no adjustment for house configuration (other than house height) and wind direction. The effect of these assumptions along with the PFT bias may be sufficient to result in the observed scatter and difference in means.

III.C. RADON

Radon is an inert, radioactive gas that because of its health risks BPA has adopted an action level of 5 pCi/l for remedial action in homes participating in their weatherization program. The Environmental Protection Agency (EPA) guideline is 4 pCi/l. Radon concentrations were measured in all houses for periods of 55 to 70 days using Track Etch passive samplers. The measurements reported here for each house are averages of the two to five measurements made in the occupied areas of each house. Outdoor concentrations measured at both geographic regions averaged 0.5 pCi/l.

Figure 14 is a histogram of the results for the MCS and Control houses. The distributions for the two groups of houses are statistically indistinguishable (two-tailed t-test, $0.9 > P > 0.5$). The MCS houses had a GM of 1.5 pCi/l, GSD of 2.8 pCi/l, while the Control houses had a GM of 1.7 pCi/l with GSD of 2.8 pCi/l. Seven houses or eleven percent of the sample (four MCS and three Control) have concentrations that exceed the BPA action limit of 5 pCi/l. Ten homes (16%), five of which are MCS, exceed the EPA guideline.

Figure 15 aids in interpreting the results displayed in Figure 14. It presents the geometric mean and geometric standard deviation of the radon concentrations in the Portland area housing groups and the Spokane area groups. This figure indicates a larger variation in concentrations between regions than between the two housing groups in the same region. The geometric mean concentration for all Spokane area houses is 2.6 pCi/l (GSD of 2.99 pCi/l) while for the Portland area homes it is 1.1 pCi/l (GSD of 2.17 pCi/l). Only the Spokane Control house mean radon (3.5 pCi/l) is significantly higher than the Portland area Control house mean (1.0 pCi/l) using a one-tailed t-test, $P < 0.0005$. Between these same groups of houses, we find that the long-term PFT measurements of ventilation are significantly lower for the Spokane Control houses (one-tailed t-test, $0.05 > P > 0.025$) and may, to a small degree, account for the higher radon levels. Six of the seven homes over 5 pCi/l (eight of ten over 4 pCi/l) are located in the Spokane area.

Generally, though the data do not demonstrate a strong association between radon concentration and long-term ventilation rates in the housing samples. Figure 16 displays the radon concentration measured in the occupied zones of the Portland-area houses plotted as a function of the long-term ventilation rate. Figure 17 is a plot of the same information for the Spokane-area measurements. No correlation between radon concentration and ventilation rate was seen in the Portland area houses. A slight dependence of radon concentration on ventilation rate is seen in the Spokane results. However, the 95% confidence limit lines indicate that the dependence is marginally significant (the slope of the may have an equal probability of being zero). If indoor radon concentrations were solely dependent on ventilation, one would expect a regression line of slope = -1 on these log-log plots. It is important to note that these figures are not the final arguments that radon has little dependence on ventilation rates. Rather, that large house-house variations in other parameters including soil characteristics, house-soil coupling, indoor-outdoor temperature differences, and house construction have a large impact on indoor radon levels.

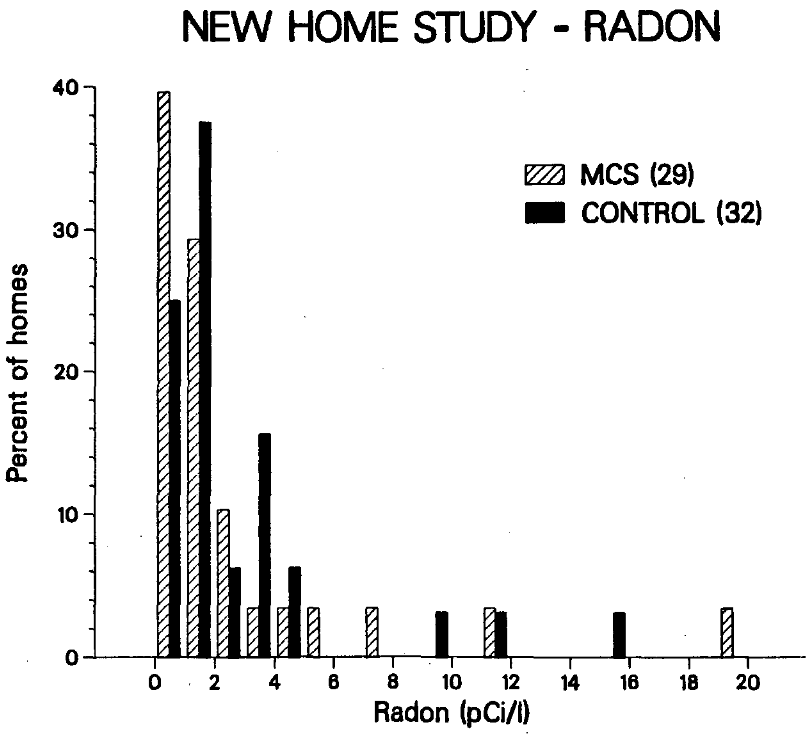


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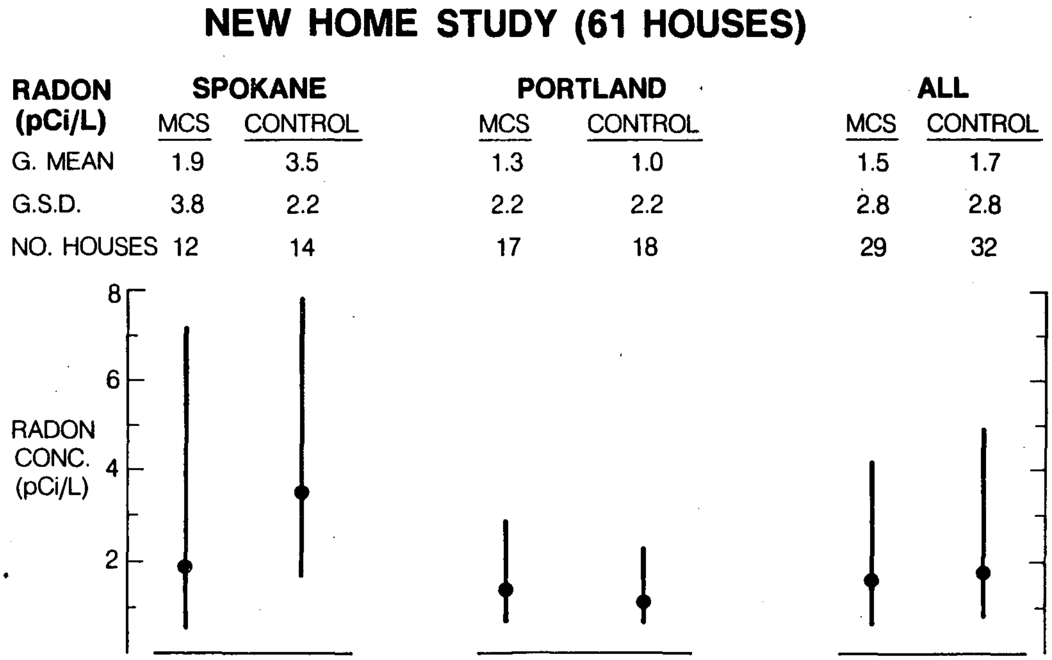
Figure 14. Histograms of radon concentrations in the MCS and Control houses.


NEW HOME STUDY (61 HOUSES)

RADON (pCi/L)	SPOKANE MCS	SPOKANE CONTROL	PORTLAND MCS	PORTLAND CONTROL	ALL MCS	ALL CONTROL
G. MEAN	1.9	3.5	1.3	1.0	1.5	1.7
G.S.D.	3.8	2.2	2.2	2.2	2.8	2.8
NO. HOUSES	12	14	17	18	29	32

XBL 858-11668

Figure 15. Regional variations in radon concentrations.

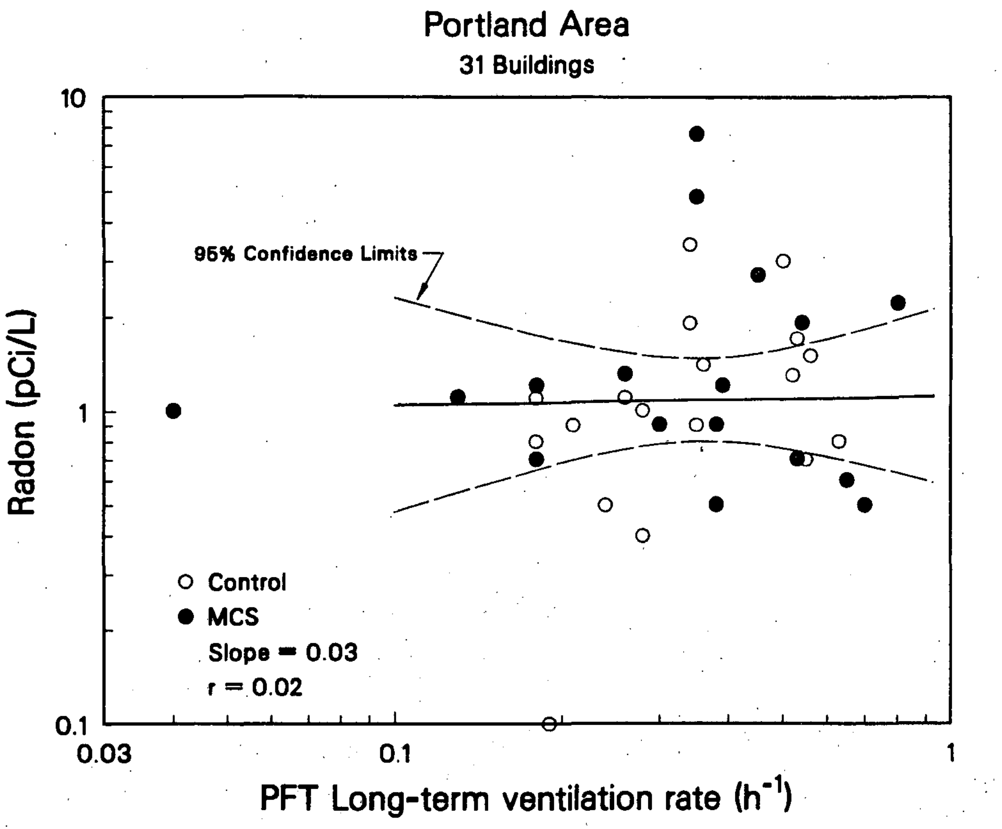


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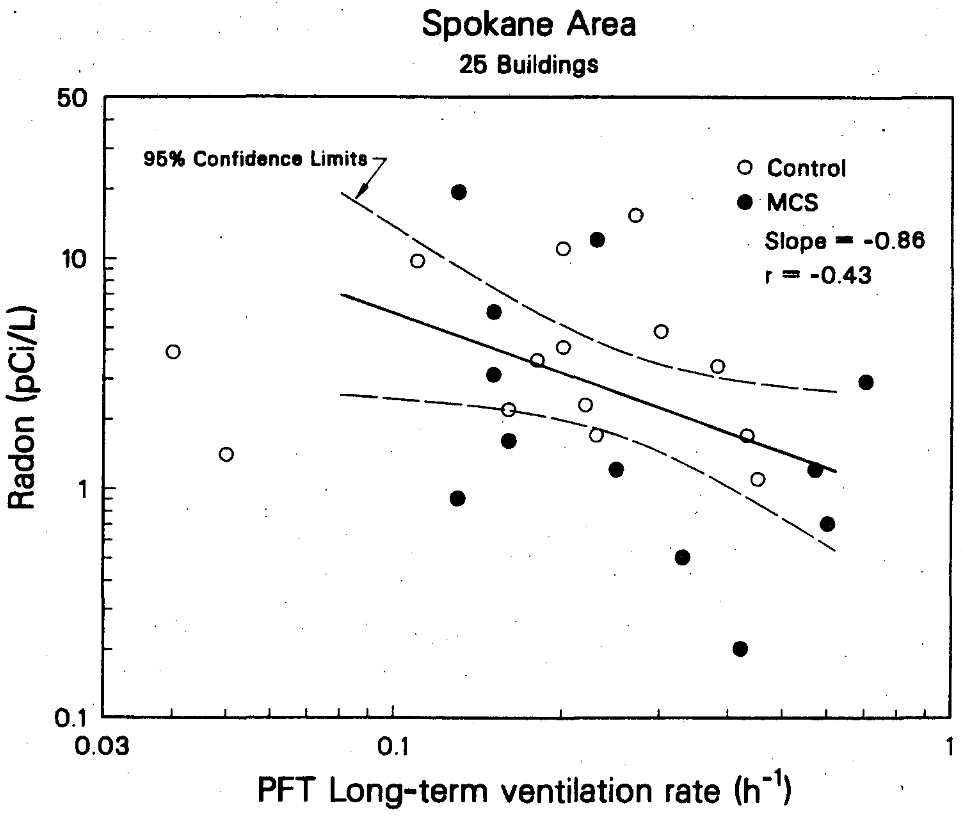
Figure 16. Portland area radon concentrations plotted as a function of long-term ventilation rate. 95% confidence limits for regression estimates are shown. There is no correlation of radon to ventilation in these data.



XCG 878-11341 A

Figure 17. Spokane area radon concentrations plotted as a function of long-term ventilation rate. The 95% confidence limits show that the slope of the regression line is significantly different from zero, indicating that for these data radon is inversely correlated with ventilation.

A geographical analysis of the Spokane results indicates that the houses with elevated ^{222}Rn levels tended to be clustered in the Spokane River Valley and Rathdrum Prairie of Northern Idaho. Subsequent mitigation of the high radon concentrations in two of these houses, NCD077C, NSP204 (Turk et al.,1986) indicates that control of source entry rate is the most effective mitigation strategy for these houses. Thus in this sample of MCS and Control houses, high radon concentrations are associated with local source conditions rather than housing class (MCS or Control) or ventilation rate.

III.D. NITROGEN DIOXIDE

All inside concentrations of nitrogen dioxide were always less than seven ppb and were generally near the detection limit of the NO_2 sampler (2 ppb). No major combustion sources of NO_2 were present in the houses and their construction proved to be an effective barrier against the penetration of high outdoor NO_2 concentrations into the indoor air. Outdoor concentrations at all homes had a GM of 6.6 ppb and a GSD of 2.36 ppb. A separate discussion of NO_2 reactivity, K, as calculated from data collected in this study appears in Appendix C.

III.E. WATER VAPOR

Figure 18 shows water vapor concentrations (measured in g water vapor per kg dry air) in the different samples of houses. What is striking about these results is the small *range* of averages of water vapor concentrations seen in all the houses. As seen by examining the 95% confidence limits in Figure 18, there are no significant differences between any of the various groupings of houses. The outdoor humidity ratios are quite different in the two geographical regions. All outdoor samples from the Spokane area houses averaged 3.72 g/kg, while those from the Portland area houses averaged 5.44 g/Kg. [For reference, at 70°F (21°C) a water vapor concentration of 6.5 g/kg corresponds to a relative humidity of 42 percent.] The data from the two new housing samples appear to come from the same distribution, independent of differences in outdoor humidity. In fact, only 28% of the variation in indoor water vapor concentrations for all 61 homes can be related to the variation in outdoor concentrations (Figure 19). Sources for the remaining variation offer explanations for the uniformity of the indoor levels. These include indoor sources, temperature, the storage and release of water vapor by the building materials and furnishings (Kusuda, 1983), initial drying of the new construction, and occupant control to maintain a comfortable indoor relative humidity. Measurement error has been eliminated as a possibility. The water vapor passive sampler that was used for these measurements is the most precise of the passive samplers; calibrations and quality control checks throughout the project verified its accuracy.

The suggestion that the new houses are dominated by initial drying of the building materials but reach a saturation level that is determined by storage processes within the structure is refuted by Figure 20. Figure 20 demonstrates that there is probably no relationship between age and indoor H_2O vapor. In this plot, indoor concentrations are normalized by outdoor water vapor concentrations, with the result that there is no apparent age dependence.

III.F. FORMALDEHYDE

The results for formaldehyde are displayed in Figure 21. The concentrations from the MCS and Control houses in the Spokane area are statistically indistinguishable at $P > 0.9$ and in the Portland area at $0.4 > P > 0.2$ (using two-tailed t-test).

NEW HOME STUDY (61 HOUSES)

WATER VAPOR (g/kg air)	SPOKANE		PORTLAND		ALL	
	MCS	CONTROL	MCS	CONTROL	MCS	CONTROL
MEAN	6.29	6.39	6.81	6.80	6.59	6.62
95% CONF.	6.93	7.15	7.40	7.18	7.02	7.01
INTERVAL	5.65	5.63	6.22	6.42	6.16	6.23
NO. HOUSES	12	14	17	18	29	32

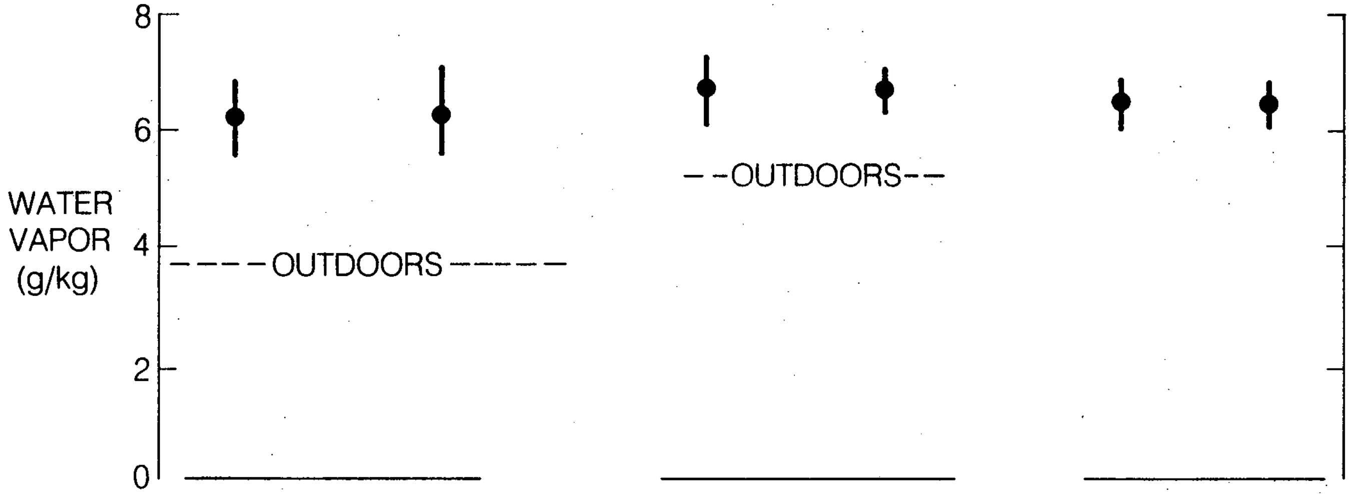


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Figure 18. Arithmetic means and 95% confidence intervals for the water vapor concentrations measured in the housing samples in the Spokane and Portland areas. The outdoor water vapor concentrations are shown as dashed lines on the figure.

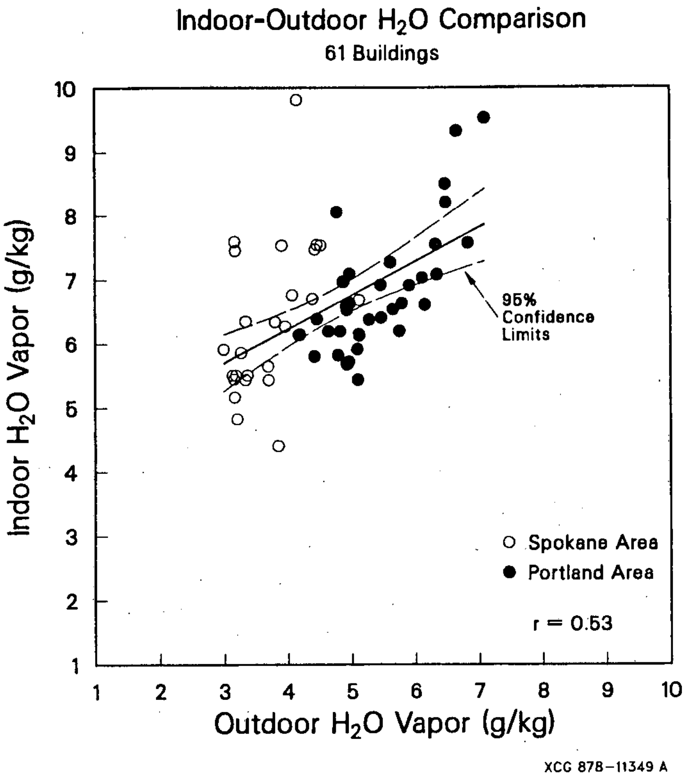

Figure 19. Dependence of indoor water vapor concentrations on outdoor water vapor levels. Approximately 50% of variation in indoor levels is related to outdoor levels as signified by solid line for 61 houses.

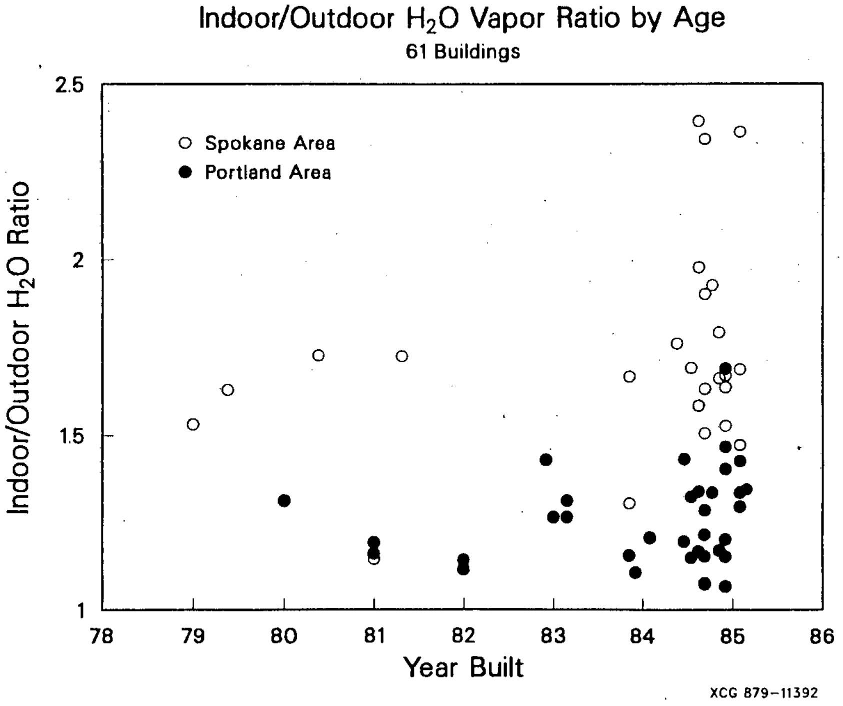

Figure 20. Indoor water vapor concentrations normalized by outdoor concentrations compared to dwelling age. These data do not demonstrate any relationship.

NEW HOME STUDY (61 HOUSES)

FORMALDEHYDE (PPB)	**SPOKANE**		**PORTLAND**		**ALL**	
	MCS	CONTROL	MCS	CONTROL	MCS	CONTROL
G. MEAN	60.1	59.0	103	84	82	72
G.S.D.	1.5	1.6	1.7	1.8	1.7	1.8
NO. HOUSES	12	14	17	18	29	32

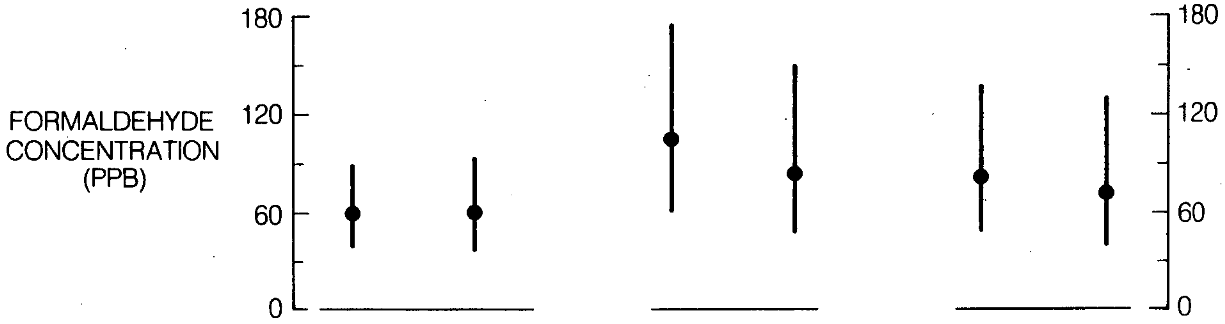

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Figure 21. Geometric means and geometric standard deviations of formaldehyde concentrations in Portland area housing classes and Spokane area housing classes.

A surprising feature of these results is the difference in concentrations between the Spokane area and Portland area data sets for this pollutant. The regional differences between average concentrations are greater than the differences seen between the MCS and Control houses within a single region. For all Spokane area houses, the geometric mean indoor concentration of 59.5 ppb (GSD of 1.5 ppb) is significantly lower (one-tailed t-test, $P < 0.0005$) than in Portland area houses with a GM of 92.8 ppb (GSD of 1.78 ppb). This may be the result of different emission characteristics of pressed-wood products used in the two regions.

Formaldehyde emission depends on many factors. These include temperature, humidity, material age, type of product, surface area of product, concentration of formaldehyde in the air, and presence of surface barriers. This list is not exhaustive.

The data of Figure 22 provide further evidence that indoor air formaldehyde concentrations decrease from high initial values with age of the structure. The figure shows the concentration of formaldehyde plotted as a function of the year of construction of the house in the test. Meyer and Hermanns' (1984) predictions of formaldehyde release from aging particleboard show a similar relationship (see Figure 23). Evidently, long-term depletion of free HCHO in the UF-bonded materials is the mechanism for this frequently observed phenomenon.

To determine the decay constant for decreasing indoor formaldehyde levels, the following function was fitted to the data for the two regions.

$$C = C_o e^{-\lambda t}, \quad \text{where:}$$

C = Measured concentration (ppb)

C_o = Initial concentration (ppb)

λ = $\frac{1}{T}$, = Time constant $(\text{years})^{-1}$

t = Time interval from constructions of building (years)

For the Portland homes, the decay time constant was 5.9 years with 95% confidence limits of $L_1 = 3.2$ years and $L_2 = 34.1$ years. For the lower concentration Spokane homes, there was no correlation. Reviewing these results permits the observations that 1) the curve fit is poor because of house-specific variables such as ventilation rates, house volume, humidity, temperature, type and amount of formaldehyde-emitting materials, and 2) there is a distinction in the type and perhaps application of formaldehyde-emitting materials between the two regions. Harris (1986) offers the explanation that the use of more exterior grade subfloor materials in Washington State and more interior grade subfloor material in Oregon may account for the difference. However, it does not explain the higher concentrations in the Vancouver, WA homes.

Factors such as humidity have been demonstrated as having a significant impact on HCHO levels (Mathews, et al., 1986). Figure 24 looks at the effect of indoor water vapor concentrations on indoor formaldehyde levels. A linear regression was performed on HCHO and H_2O data from the two regions, yielding distinctly different fits. The greater sensitivity of formaldehyde to water vapor in Portland area homes could also be explained by differences in the type, composition, and exposure of building materials. [Curve fits using a power curve of a form similar to physical models for HCHO had lower coefficients of determination than the linear form.] The dashed lines represent the 95% confidence limits for the regression estimates and indicate the considerable uncertainty in our curve fits.

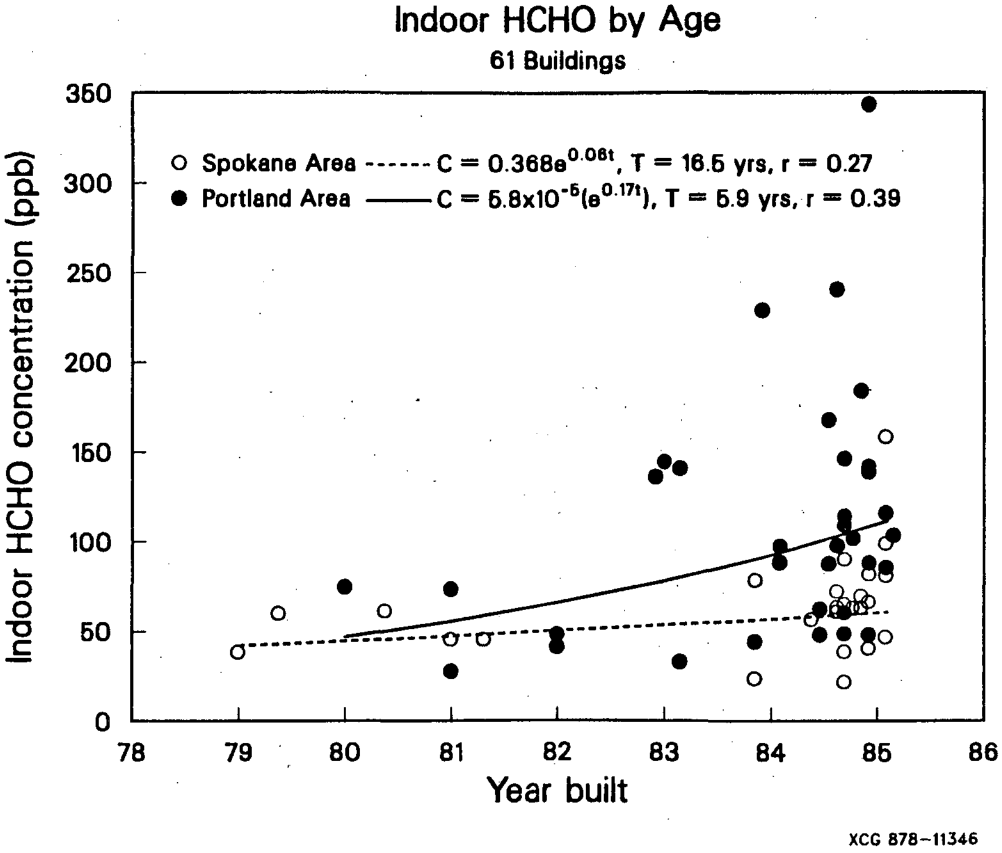
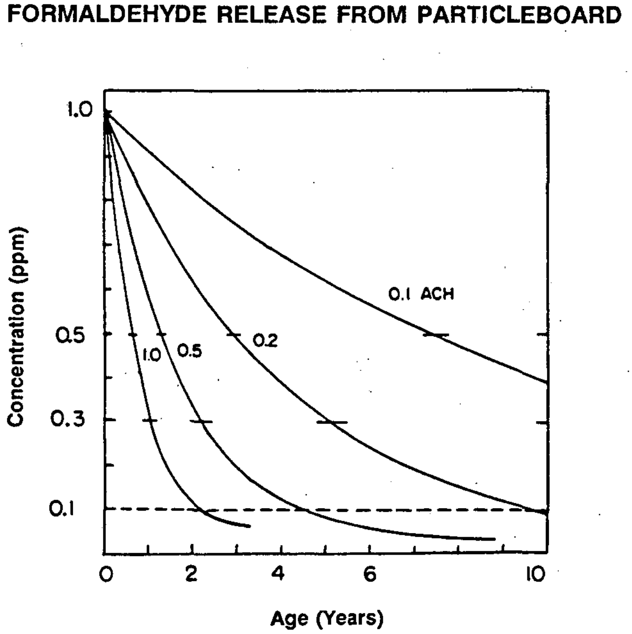


Figure 22. Formaldehyde concentration plotted as a function of the year of construction of the house. Exponential fits are shown for Portland area houses and Spokane area houses. The fit is poor with the 95% confidence limits of T for the Portland homes, being 3.2 years and 34.1 years.



(From Meyer and Hermanns, 1984)

Figure 23. Formaldehyde release from particleboard as a function of age and ventilation rate. From Meyer and Hermann (1984) using model incorporating Swedish field study data.

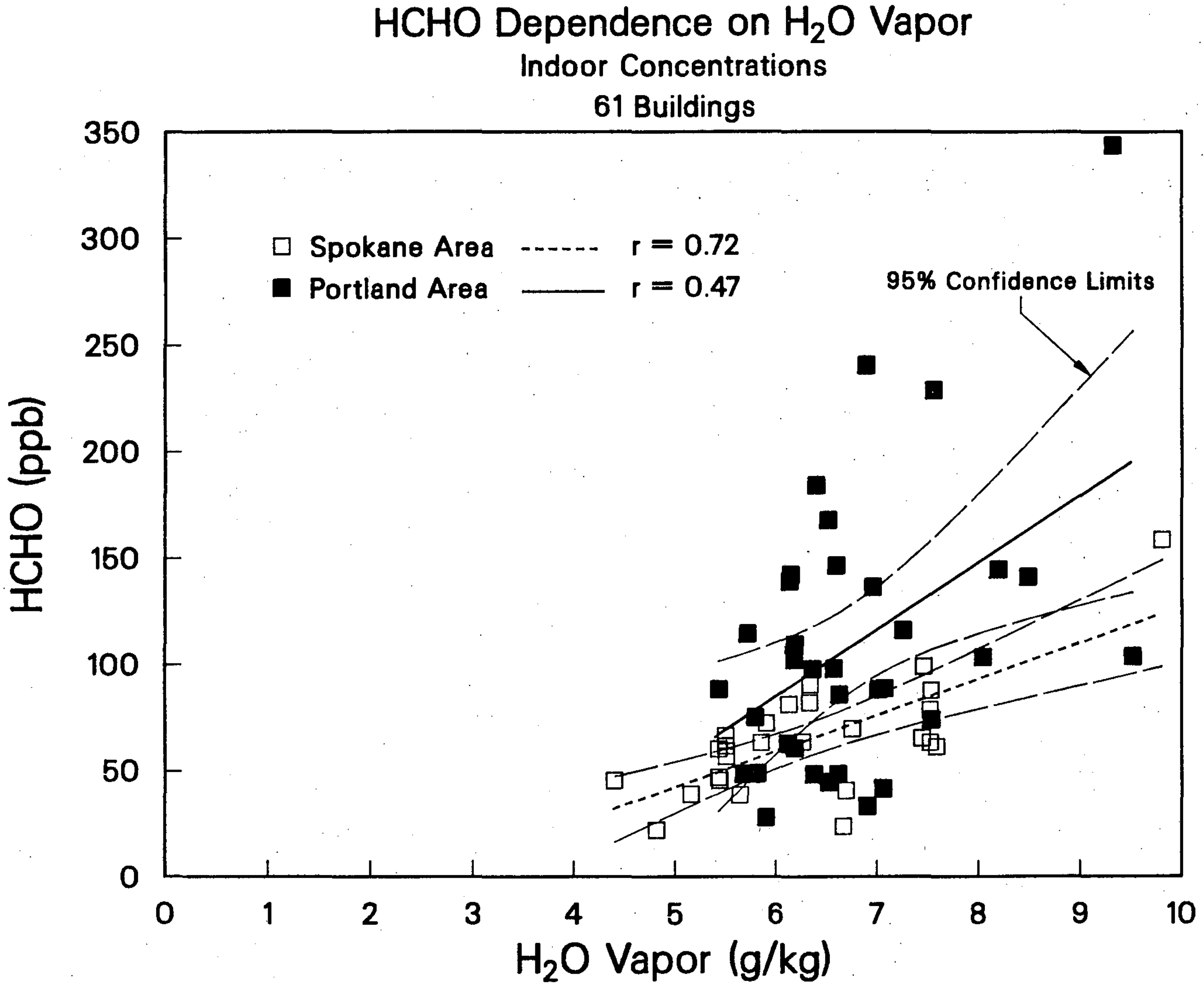


Figure 24. Indoor formaldehyde concentration and its relationship to indoor water vapor concentration. Linear regression best fit lines with 95% confidence limits are shown separately for Portland and Spokane area houses.

Figures 25 and 26 examine the dependence of formaldehyde concentrations on ventilation rates in the Spokane samples (Fig. 25) and the Portland samples (Fig. 26). The open circles in the two figures represent the Control houses, the closed circles, the MCS houses. Poor correlation between the variables is seen for homes in both regions, although the linear regression curve fit is better for the Portland area sample where approximately 31% of the variation in HCHO levels may be due to variation in ventilation rates. Once again, there is large uncertainty in the curve fits especially for the Spokane houses where the slope has an equal probability of being zero. If the one outlying point with a ventilation rate of 0.04 ach and HCHO of 240 ppb (NPO 747) is deleted and the fitting procedure conducted again, the R^2 is 0.25 and the slope changes to -0.61. Other researchers have observed that reductions in HCHO levels do not scale proportionally to increases in ventilation. Presumably, additional ventilation results in increased emission rates by increasing the concentration gradient at the surfaces of HCHO-containing materials. As in the case of radon, these figures do not necessarily demonstrate that HCHO has little dependence on ventilation rates. The house-to-house differences in building volume; amount type, and exposure of pressed-wood materials; temperature; and other factors complicates the interpretation of the plots and indicates the importance of a physical-based model incorporating these variables for understanding the true response of indoor HCHO levels.

Of the 61 houses in this sample, 18 (or 30%) exceed the 100 ppb level of concern. It is of interest to determine if ventilation rates are lower for these high concentration houses. The geometric mean PFT short-term ventilation rate for these 18 houses is 0.26 ach (GSD of 1.89 ach) as compared to 0.28 ach (GSD of 1.95) for the remaining 43 houses below 100 PPB. Using a two-tailed t-test, there is no significant difference in the mean ventilations at $P > 0.5$. When ventilation rates are reduced *excessively*, without additional mechanical ventilation, problems are likely to occur unless source strengths for the pollutant sources are low. For those three houses above 200 PPB, the geometric mean ventilation rate of 0.10 ach (GSD of 2.25) is significantly lower (two-tailed t-test, $0.01 > P > 0.005$) than that of the 43 homes below 100 ppb.

III.G. DISTRIBUTION OF POLLUTANTS INSIDE HOMES

Since from two to five locations were monitored inside of each home, the data has been aggregated according to common location-type to determine the variations in occupied zone-to-zone pollutant concentrations arising from diffuse pollutant sources. Table 4 summarizes these data for Rn, H_2O, and HCHO. Sample location by house height is grouped into three levels for 12 of the study houses that had three or more levels. Level 1 was the first occupied floor which in some cases was a below grade basement and in other houses was the first floor above a crawlspace. The results for radon show relatively uniform mixing between levels (not significantly different at $P > 0.2$ using a two-tailed t-test) which differs from data in other studies of high radon homes (Turk, et al., 1986). The largest difference between levels occurs for HCHO. Concentrations on level 1 which are significantly lower than level 3 and 4 concentrations (one-tailed t-test, $0.02 > P > 0.01$). Level 1 concentrations may be lower because some level 1's are basements which are often lower in temperature and have a smaller area of pressed-wood products. Water vapor concentrations are higher on level 3 and 4 than other levels (one-tailed t-test, $0.05 > P > 0.025$) possibly because more H_2O source-areas such as bathrooms and bedrooms (see below) are located on upper levels of houses.

When locations are grouped by family or living room, hallways, bedrooms, or other locations (which included utility rooms, kitchens, offices, or other special use rooms), we find bedrooms in Control houses have slightly, but statistically significant (one-tailed t-test, $0.005 > P$), elevated concentrations of water vapor over the other locations. This is not surprising because when these rooms are occupied, doors to the remainder of the house are often closed, permitting accumulation of occupant-generated moisture. Presumably, HCHO levels have then increased in response to the higher humidity in the Control house bedrooms, MCS bedrooms do not exhibit this same increase in H_2O vapor and are not significantly different than other locations (two-tailed t-test, $P > 0.05$).

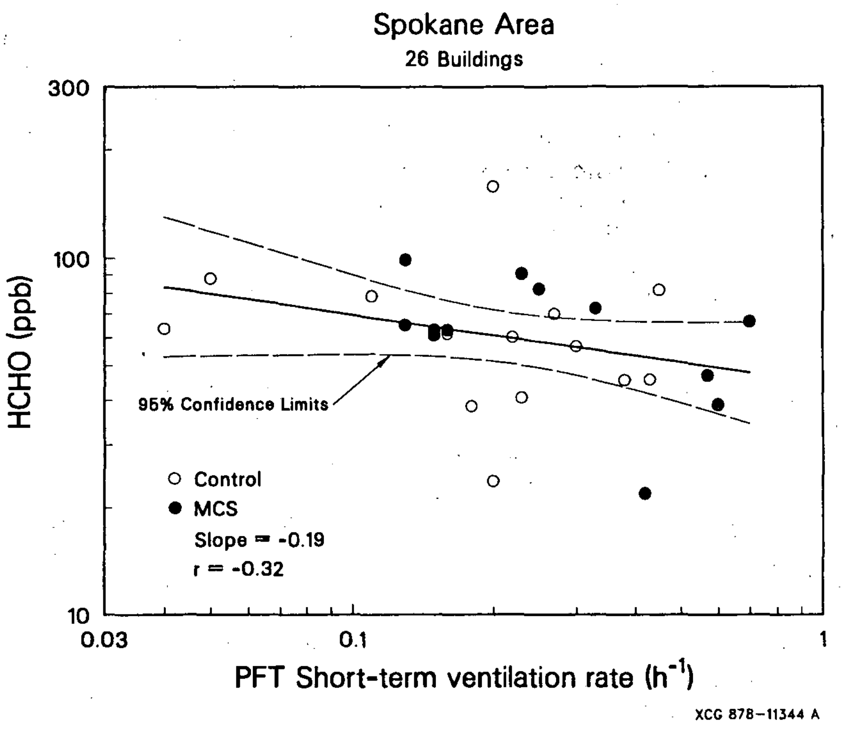


Figure 25. One week average measurements of formaldehyde concentrations in the houses in the Spokane region plotted as a function of the ventilation rates measured during the sampling times. Closed circles represent the MCS houses, open circles the Control houses. 95% confidence limits indicate that these data show no correlation of HCHO to ventilation rate.

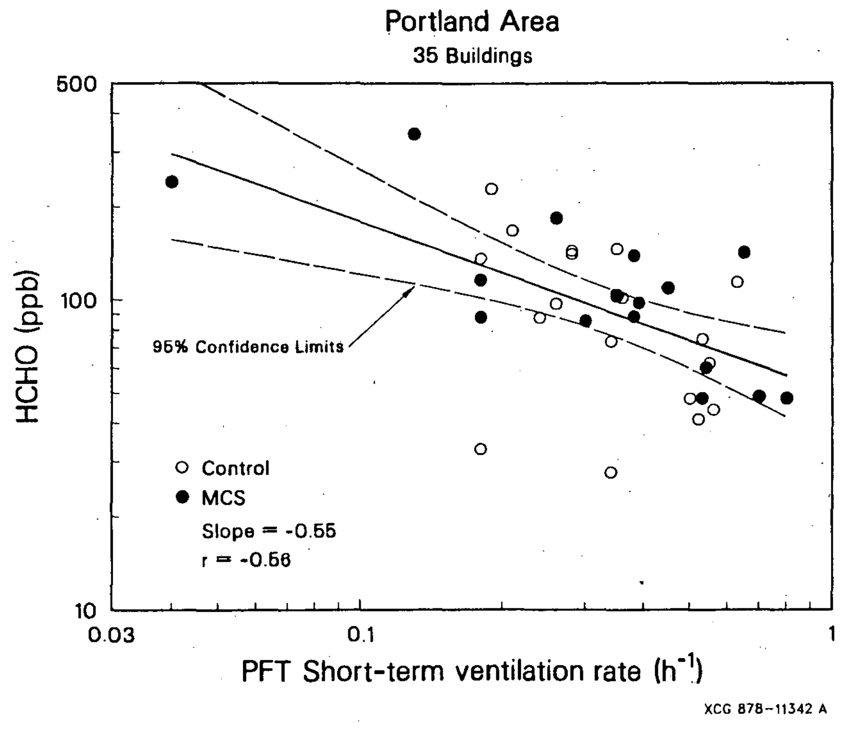


Figure 26. One week average measurements of formaldehyde concentrations in the houses in the Portland region plotted as a function of the ventilation rates measured during the sampling times. Closed circles represent the MCS houses, open circles the Control houses. Formaldehyde is inversely correlated to ventilation rates for all Portland area houses as indicated by the solid line and the 95% confidence limits.

TABLE 4

NEW HOME
INDOOR POLLUTANT DISTRIBUTION
61 HOMES

GROUPING/ SAMPLE LOCATION	RADON ($pCiL^{-1}$)			WATER VAPOR (gKg^{-1})			FORMALDEHYDE (PPB)		
	NO. SAMPLE LOCATIONS	GEOMETRIC MEAN	GEOMETRIC STD. DEV.	NO. SAMPLE LOCATIONS	ARITHMETIC MEAN	ARITHMETIC STD. DEV.	NO. SAMPLE LOCATIONS	GEOMETRIC MEAN	GEOMETRIC STD. DEV.
<u>ALL HOUSES</u>									
Level 1	14	2.1	4.72	15	6.26	1.604	15	43.3	2.26
Level 2	12	1.1	2.82	13	5.79	0.935	13	55.1	1.80
Level 3 and 4	22	1.8	3.23	22	6.63	1.351	22	71.4	1.72
Family/Living Rms	69	1.5	2.93	68	6.41	1.097	68	68.8	1.96
Hallways	47	1.6	2.97	49	6.54	0.911	49	71.1	1.81
Bedrooms	40	1.6	3.05	42	7.16	0.958	42	76.9	1.88
Other Locations	31	1.7	3.78	28	6.16	0.925	28	57.5	1.95
<u>CONTROL HOUSES</u>									
Family/Living Rms	34	1.9	2.90	34	6.50	1.005	34	62.0	1.98
Hallways	25	1.6	2.45	26	6.50	0.936	26	66.7	1.93
Bedrooms	17	2.2	3.34	17	7.19	1.551	17	75.0	1.95
Other Locations	11	2.8	2.75	10	6.00	1.092	10	63.6	1.94
<u>MCS HOUSES</u>									
Family/Living Rms	35	1.3	2.90	34	6.32	1.191	34	76.4	1.92
Hallways	22	1.5	3.65	23	6.59	0.903	23	76.6	1.68
Bedrooms	23	1.2	2.66	25	6.68	1.125	25	78.3	1.84
Other Locations	20	1.3	4.16	18	6.26	0.934	18	54.3	1.97

However, for unknown reasons the MCS 'Other' locations were, on average, significantly lower in HCHO than the remaining locations (one-tailed t-test, $0.05 > P > 0.025$). Overall, the airborne pollutants become well-mixed throughout the structure, particularly in the MCS homes that have lower coefficients of variation for radon (10.1%), and water vapor (3.4%), but not formaldehyde (17.0%), than the Control homes (25.6%, 7.9%, 9.2%). The AAHX installed in the MCS houses may be responsible for more air movement and mixing within + these homes.

IV. DISCUSSION

We have seen in this study of 61 new houses that the Model Conservation Standards have resulted in tighter houses. Based on fan depressurization tests of air leakage for the entire sample, MCS houses are 46% tighter than the Control houses. The difference is sharper when regional sets are compared. In the Spokane area, MCS houses are 60% tighter than the Control house sample, while in Portland the MCS houses average 35% tighter than their Control counterparts.

On the other hand, average predicted ventilation rates during occupancy are not different for the MCS and Control houses (0.44 ach vs. 0.46 ach). Since infiltration scales with house leakage area to the first order, we can attribute the additional ventilation calculated for the MCS houses to the mechanical ventilation supplied by the air-to-air heat exchangers installed in each of these houses. Without the benefit of these units, we would expect the ventilation rates for MCS houses to be lower than for the Control houses in proportion to their smaller air leakage areas.

Actual measurements of ventilation with PFT's likewise do not demonstrate a corresponding difference between the housing groups. Both short-term (0.30 ach vs. 0.26 ach) and long-term (0.31 ach vs. 0.31 ach) measurements of total ventilation in the MCS and Control samples show distributions that are statistically indistinguishable.

However, PFT-measured short-term ventilation rate means are 32% lower than model-predicted ventilation rate means (accounting for occupancy effects) for MCS houses and 43% lower for the Control houses. These values are slightly outside of the 20 - 30% range theorized for undermeasure bias assuming good mixing for the passive ventilation measurement technique. While the passive PFT technique is not suitable for estimating energy loads due to ventilation, it does provide the appropriate measure of "effective" ventilation for constant source pollutants (Sherman, 1987). The assumption of a constant pollutant source strength may not be strictly valid during the measurement period for the two pollutants of primary concern here, formaldehyde and radon. During periods of diurnal heating, formaldehyde emission rates may increase by factors of three to five from solar-heated surfaces (Meyer and Hermans, 1984). Radon source strength may also vary by factors of ten or more due to diurnally changing pressure-driven flow rates or periodically due to precipitation-related entry pulses (Sextro et al., 1987). It may be that under these conditions of changing source strength, the adequacy of the ventilation measurement technique is compromised. In lieu of further investigation into this difficulty, the passive PFT technique data is considered adequate for this study.

Both housing samples have PFT-measured ventilation rates whose corrected median or geometric mean values (using the underbias previously mentioned) are approximately 0.33 - 0.43 ach. This is considerably lower than the 0.5 to 0.6 ach recommended in standards and guidelines in the United States and Northern Europe. However, it is not far from the 0.35 ach recommended in the revised version of ASHRAE 62-1981. If the PFT-measured ventilation rates are corrected for bias, we find a mean ventilation rate for MCS houses of 0.38 ach to 0.43 ach, which is still below the study design criteria of 0.6 ach. A corrected mean ventilation rate for the Control homes would be 0.33 to 0.37 ach. The Control homes in this study also fail to meet the design criteria. Therefore, while the MCS homes do not meet the criteria ventilation that was presumed to exist in conventionally-constructed new homes in the Pacific Northwest, the data from Control homes in this study suggest that the design criteria were not indicative of what actually occurs. Lower than expected natural ventilation or AAHX ventilation rates or both have resulted in the MCS homes falling short of the ventilation objective.

Natural ventilation rates in the MCS homes are probably actually higher than expected. The original MCS design stipulated a reduction in the natural ventilation rate of 83% from 0.6 ach to 0.1 ach that would then be supplemented with 0.5 ach supplied by the AAHX. Model-predicted natural ventilation rates (without occupancy effects or AAHX operation) in the MCS houses have a GM of 0.24 ach, only 31% lower than for bias-corrected PFT-measured current conditions in Control houses (0.35 ach). This is corroborated by the model-predicted natural ventilation GM of 0.39 ach for the Control houses. The MCS 0.24 ach mean is also only 60% lower than the original current condition assumption of 0.6 ach. Therefore, natural ventilation rates in the MCS are most likely higher than design.

The air-to-air heat exchangers have apparently also fallen short of the objectives to add 0.5 ach. In comparing the model-predictions for 0.24 ach of natural ventilation in MCS homes to the bias-corrected PFT-measured total ventilation of 0.38 - 0.43 ach, we find the added ventilation was only about 0.2 ach.

Possible causes for the lower-than-expected ventilation rates in the MCS homes are:

1) the occupants chose not to operate the AAHX as frequently as they should have or that the mandatory humidistat controls were not activating the AAHX on a regular basis;

2) the AAHX installations were deficient, either because of undersized AAHX or improper distribution installations (e.g., undersized ducting or leaky ducts).

3) PFT-measured ventilation rates were poor estimators of actual ventilation because of bad PFT tracer gas mixing.

The additional ventilation provided by the AAHX and it's impact on indoor air quality should be explicitly investigated. The above results and discussion strongly depend on the assumption that the PFT results are accurate. We will continue to investigate possible discrepancies between these measurements and values obtained from predictions of infiltration rates in these and other houses.

There is no single ventilation rate that will assure adequate indoor air quality in a house. The concentration of a pollutant in a building depends on the steady state balance of source strength and removal processes. Since source strengths are usually independent of the dominant removal process in a house, i.e., ventilation, the probability of having a high source term in a house with a low ventilation rate is not different from that in a house with a high ventilation rate, (except for the entry of radon that may be reduced by the same sealing that reduces ventilation). However, the consequences can be serious when a strong source is found in a low ventilation rate house. A widely recognized guideline of 0.5 ach has evolved from experience that has demonstrated problems with very tight new construction. For formaldehyde, a high source may, over time, diminish to a level where nominal ventilation rates are a satisfactory control technique. Mitigation of excessively high radon levels will likely require source control measures unless initial ventilation rates are very low, and could be practically increased. But, as we've seen in this study, it is difficult to demonstrate the *in situ* relationship of indoor pollutant concentrations to ventilation rates without either measuring or controlling other important variables (local environmental conditions, indoor temperatures, source characteristics).

Potential problems are present in this group of houses. *Average* radon concentrations greater than the BPA action level of 5 pCi/l (for weatherization of existing houses) were seen in 11% of the houses. Sixteen percent of all houses were above the EPA guideline of 4 pCi/l. A greater number would exceed both guidelines if it were necessary for only a *single* measurement location in each house to be higher than the guidelines levels. Formaldehyde concentrations greater than 100 ppb were observed in 30% of the houses tested. No substantial difference is seen between the MCS and Control samples in the number of houses having concentrations exceeding this level. Brief, hours-long periods of low-ventilation transients may result in brief, higher concentrations that could be a problem with sensitizing agents such as formaldehyde. The operation of the AAHX in the MCS homes should reduce peak concentrations that can occur during periods of low ventilation.

Vine (1987) mailed questionnaires to occupants in both MCS and Control homes participating in the larger RSDP sample to survey their subjective opinions of the house environment and AAHX operation. His tabulation of responses show more occupant complaints about mold and mildew in Control houses, perhaps because these growths had longer to develop in the older Control homes. Water vapor data from our study show no significant differences between the two house groups. However, Vine also indicates that bedrooms were the most frequently identified locations for mildew development for both groups of houses. Our water vapor data support these observations, with the poor spatial distribution more pronounced in the Control houses. Since ventilation rates are probably lower in bedrooms because doors are more frequently closed, it can be argued that the AAHX in each of the MCS homes provides better distribution of ventilation air. In addition to moisture accumulation and higher formaldehyde levels, bedrooms may have the potential for higher concentrations of other pollutants not monitored in this study.

A review of the incremental costs for the required energy conservation measures installed in 395 MCS homes of the larger RSDP study, shows that the average added floor area cost as built, was approximately \$3.00 ft^{-2} (Vine, 1986). Typical new home total construction costs range from \$35 to \$75 ft^{-2}. The average incremental cost for the air infiltration barrier in the MCS homes was approximately \$0.30 to \$0.40 ft^{-2}, while the incremental cost to include a central air-to-air heat exchanger was \$0.70 ft^{-2}. The total cost of house tightening and then adding supplemental ventilation with an AAHX was approximately \$1.00 ft^{-2}. This indicates that it is less expensive to reduce ventilation than to add it back with an AAHX. Therefore, it costs approximately \$1500 to \$1700 more for the MCS houses to have the same ventilation rate and indoor air quality as the Control houses. However, the mechanical ventilation system provides an assured minimum ventilation rate not affected by the changes in environmental conditions that reduce natural ventilation rates (assuming that the AAHX is used by the occupants). The AAHX also appears to provide slightly more uniform distribution of the ventilation air. And finally, the additional cost penalty may be quickly repaid by the energy savings from heat recovered by the AAHX. A separate study of the related energy data from the RSDP homes is not yet available.

V. SUMMARY

A comparison of ventilation and indoor air quality has been made in 29 energy-efficient MCS and 32 conventional construction new homes in the Pacific Northwest. The Model Conservation Standards resulted in 46% tighter air leakage construction. The addition of an AAHX in each MCS house boosted total ventilation (infiltration plus mechanical ventilation) in those homes equal to that of total ventilation (infiltration alone) in the Control homes. These rates for both housing groups were approximately 0.3 ach. Model predictions of ventilation rates, based on measured leakage areas, were higher than PFT-measured ventilation rates.

Indoor pollutant concentrations were very similar for the two house construction types. There are greater regional differences in indoor pollutant concentrations due primarily to variations in source strengths of pressed wood products (HCHO) and soils or geologic characteristics (Rn). Thirty percent of all houses exceed the 100 ppb formaldehyde guideline adopted by many organizations and 11% exceed the BPA mitigation action level for radon (16% exceed the EPA guideline).

Bedrooms were the location most frequently exhibiting elevated water vapor and formaldehyde levels, although the situation is improved in MCS homes, possibly due to better distribution of ventilating air by the AAHX.

As seen in other studies conducted in occupied residences, indoor pollutant levels generally correlate only weakly with ventilation rates, indicating that: 1) it is difficult to demonstrate the relationship between pollutant concentrations and ventilation where other important variables such as source description, occupant activities, local environmental factors, and indoor temperatures are not measured or controlled; and 2) elevated indoor levels are usually associated with a strong pollutant source. However, minimum ventilation, probably no less than 0.3 ach, is necessary so that minor pollutant problems are not exacerbated.

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VII. REFERENCES

Berk, J.V., Hollowell, C.D., Pepper, J.H., Young, R.A.(1980). "Indoor Air Quality Measurements in Energy-Efficient Residential Buildings," Lawrence Berkeley Laboratory Report No. LBL-8894 Rev.

DOE/EPA (1981). "Workshop on Indoor Air Quality Research Needs, Final Report of the Interagency Research Group on Indoor Air Quality," Leesburg, VA, April 1981.

Derochers, D. and Robertson, A. (1986). "The Effects of Occupancy and Furnace Operation on Residential Indoor Air Quality," *Indoor Air Quality in Cold Climates*, D.S. Walkinshaw, pp. 348-361.

Dietz, R.N., Cote, E.A. (1982). "Air Infiltration Measurements in a Home Using a Convenient Perfluorocarbon Tracer Technique," *Environ. Int.* 8: 419-435.

Dumont, R.S. (1986). "The effect of mechanical ventilation on Rn, NO_2, and CH_2O concentrations in low-leakage houses and a simple remedial measure for reducing Rn concentration", Walkinshaw, D.S. *Indoor Air Quality in Cold Climates*, Air Pollution Control Association, Publisher, Pittsburgh, PA pp.90-104.

Figley, D.A.(1985). "Indoor Formaldehyde Levels in Houses with Different Ventilation Strategies," *Proceeding of the Sixth Air Infiltration Centre Conference*, Sept. 1985, pp17.1-17.11.

Figley, D.A.(1986). "Radon Levels in Houses with Controlled Ventilation," Presented at the *79th Annual Meeting of the Air Pollution Control Assoc.*, Minneapolis, June 1986.

Fleischer, R.L., Mogro-Campero, A., Turner, L.G.(1982), "Indoor Radon Levels: Effects of Energy-Efficiency in Homes," *Environment International* 8:105-110.

Geisling, K.L., Tashima, M.K., Girman, J.R., Miksch, R.R., Rappaport, S.M.(1982). "A Passive Sampling Device for Determining Formaldehyde in Indoor Air," *Environment International* 8:153-158.

Girman, J.R., Allen, J.R., Lee, A.Y.(1986). "A Passive Sampler for Water Vapor," *Environment International* 12:461-465.

Grimsrud, D.T., Sherman, M.H., Sonderegger, R.C.(1983). "Calculating Infiltration: Implications for a Construction Quality Standard," *Proceedings of the ASHRAE/DOE Conference Thermal Performance of the Exterior Envelopes of Buildings II*, ASHRAE, Atlanta, pp 422-452.

Harris, J. (1986). "Comparison of Measured Air Leakage Rates and Indoor Air Pollutant Concentration with Design Standards for Energy Efficient Residential Buildings." Presented at the *Building Thermal Envelope Coordinating Council Symposium on Air Infiltration Ventilation, and Moisture Transfer.* Bonneville Power Administration, Portland, OR.

Harris, J. (1987). "Radon and Formaldehyde Concentrations as a Function of Ventilation Rates in New Residential Buildings in the Northwest." Presented at the *APCA 80th Annual Meeting*, New York, New York, No. 87-82A.3.

Hekmat, D. and Fisk, W.J. (1984). "Improving the Energy Performance of Residential Clothes Dryers." Lawrence Berkeley Laboratory Report No. 17501.

Hollowell, C.D., Berk, J.V., Boegel, M.L., Ingersoll, J.G., Krinkel, D.L., Nazaroff, W.W.(1980). "Radon in Energy-Efficient Residences," Lawrence Berkeley Laboratory Report # LBL-9560.

Kusuda, T. (1983). "Indoor Humidity Calculations," *ASHRAE Transactions 89* (IIB)

Leader, AB.P. (1986). "Chamber Studies of NO_2, SO_2, and RSP Deposition Rates Indoors." *Presented at the APCA 79th Annual Meeting,* Minneapolis, MN, Mo. 86-383.

Lipschutz, R.D., Girman, J.R., Dickinson, J.B., Allen, J.R., Traynor, G.W.(1981). "Infiltration and Indoor Air Quality in Energy-Efficient Houses in Eugene, Oregon," Lawrence Berkeley Laboratory Report No. LBL-12924.

Mathews, T.G., Fung, K.W., Tronberg, B.J., Hawthorne, A.R. (1986). "Impact of Indoor Environmental Parameters on Formaldehyde Concentrations in Unoccupied Research Homes." *Indoor Air Quality in Cold Climates,* D. Walkinshaw, pp. 389-401.

Modera, M.P. and Sonderegger, R.C. (1980). "Determination of In-situ Performance of Fireplaces," Lawrence Berkeley Laboratory Report No. LBL-10701.

Meyer, B., and Hermanns, K. (1984). "Formaldehyde Release from Pressed Wood Products." *Formaldehyde Analytical Chemistry and Toxicology,* V. Turoski, American Chemical Society Chemistry Series, 210, pp. 101-116.

NAS (1981). *Indoor pollutants,* National Research Council, Washington, DC:National Academy Press.

Nero, A.V., Boegel, M.L., Hollowell, C.D., Ingersoll, J.G., Nazaroff, W.W.(1983). "Radon Concentrations and Infiltration Rates Measured in Conventional and Energy-Efficient Houses," *Health Physics* 45:401-406.

Palmes, E.D., Gunnison, A.F., DiMattio, J., Tomczyk, C.(1976). "Personal Sampler for Nitrogen Dioxide," *Am. Ind. Hyg. Assoc.* J. 37:570-577.

Reiland, P., McKinstry, M., and Thor, P. (1985). "Preliminary Radon Testing Results for the Residential Standards Demonstration Program," Bonneville Power Administration, Portland, OR., Report No. 3.

Reiland, P., McKinstry, M., and Thor, P. (1095). "Preliminary Formaldehyde Testing Results for the Residential Standards Demonstration Program," Bonneville Power Administration, Portland, OR., Report No. 1.

Reinhold, C. and Sonderegger, R. (1983). "Component Leakage Areas in Residential Buildings," *Proceedings of the 4th Air Infiltration Centre Conference,* Elm, Switzerland, September, 16.1-16.30.

Sextro, R.G., Harrison, J., Moed, B.A., Turk, B.H., Grimsrud, D.T., Nero, A.V., Sanchez, D.C., and Teichman, K.Y. (1987). "An Intensive Study of Radon and Remedial Measures in New Jersey Homes: Preliminary Results." *Presented at the*

4th International Conference on Indoor Air Quality and Climate, Berlin, Lawrence Berkeley Laboratory Report No. LBL-23128.

Shaw, C.Y.(1981). A Correlation Between Air Infiltration and Air Tightness for Houses in a Developed Residential Area, *ASHRAE Transactions* 87(II):333-341.

Sherman, M.H. (1987). "Analysis of Errors Associated with Passive Ventilation Measurement Techniques." Submitted to building and environment. Lawrence Berkeley Laboratory Report No. LBL-23088.

Sherman, M.H., Grimsrud, D.T. (1980). "Measurement of Infiltration Using Fan Pressurization and Weather Data," *Proceedings of the 1st Air Infiltration Centre Conference,* Windsor, England, Oct., 277-322.

Sokal, R.R. and Rohlf, F.J. (1981). *Biometry,* Second Edition, W.H. Freeman and Co.

Sonderegger, R.C., Condon, P.E., and Modera, M.P. (1980). "In-situ Measurements of Residential Energy Performance Using Electric Co-Heating," Lawrence Berkeley Laboratory Report No. LBL-10117.

Traynor, G.W., Apte, M.G., Dillworth, J.F., Hollowell, D.C., and Sterling, E.M., (1982). "The Effect of Ventilation on Residential Air Pollution Due to Emissions from a Gas-Fired Range." *Environment International* 8, p. 447.

Traynor, G.W, Apte, M.G., Carruthers, A.R., Dillworth, J.F., Grimsrud, D.T., and Gundel, L.A. (1985). "Indoor Air Pollution Due to Emissions from Wood-Burning Stoves," Lawrence Berkeley Laboratory Report No. LBL-17854.

Traynor, G.W., Nitschke, I.A., Clarke, W.A., Adams, G.P., Rizzuto, J.E.(1985). "A Detailed Study of Thirty Houses with Indoor Combustion Sources," Paper 85-30A.3 of the *78th Annual Meeting of the Air Pollution Control Association,* Detroit, June.

Turk, B.H., Grimsrud, D.T., Harrison, J., Prill, R.J., Revzan, K.L. (1987). "Pacific Northwest Existing Home Indoor Air Quality Survey and Weatherization Sensitivity Study," Lawrence Berkeley Laboratory Report No. LBL-23979.

Turk, B.H., Prill,R.J., Fisk, W.J., Grimsrud,D.T., Moed, B.A., Sextro, R.G.(1986). "Radon and Remedial Action in Spokane River Valley Residences: An Interim Report," *Presented at the 79th Annual meeting of the Air Pollution Control Association,* Minneapolis, June, LBL Report # LBL-21399.

Vine, E. (1986). "The Residential Standard Demonstration Program: Cost Analysis." Lawrence Berkeley Laboratory Report No. 21318.

Vine, E. (1987). "Air-to-Air Heat Exchangers and the Indoor Environment." *Presented at the Third International Congress on Building Energy Management.* Lausanne, Switzerland; Lawrence Berkeley Laboratory Report No. LBL-22908.

APPENDIX A
BUILDING CHARACTERISTICS
MCS AND CONTROL HOMES

HOUSE ID	#STORIES	OCCUPIED AREA (FT2)	OCCUPIED VOLUME (FT3)	YEAR BUILT	HEATING SYSTEM DELIVERY	HEATING SYSTEM AUXILIARY	SUBSTRUCTURE TYPE(S) /AREA (FT2)
NCD076C	1	1679	13432	5/1984	BB E	WS	CRWL/1679
NCD077C	1	2029	17201	11/1984	FA NG		BSMT-UNOCC/679 CRWL/666
NCD078C	2	2341	19937	1979	FA E		CRWL/420 SLAB/644
NCD079C	SPLIT	2284	20781	8/1984	BB E	WS	CRWL/1804
NCD080C	SPLIT	1700	13935	12/1984	BB E	WS	BSMT-OCC/525 CRWL/564
NCD081C	1	912	7050	7/1984	BB E		BSMT-UNOCC/500
NCD082C	1	2200	17571	11/1983	FA E	WS	BSMT-OCC/1056
NCD084C	2	1760	14550	11/1983	BB E	WS	BSMT-OCC/880
NCD085C	SPLIT	1890	15762	1/1985	BB E	WS	BSMT-OCC/672 CRWL/588
NCD086C	2	2680	21500	1/1985	FA E	WS	BSMT-UNOCC/1350
NCD090C	2	1623	12926	5/1979	BB E	WS	DAY BSMT-OCC/950
NCD252	1	1954	16096	9/1984	BB E	WS	BSMT-OCC/957
NCD253	2	2030	16072	8/1984	BB E	PS	BSMT-UNOCC/946
NCD254	2	2096	17653	9/1984	BB E		BSMT-OCC/836
NCD255	1	2670	21900	12/1984	FA E (HP)		BSMT-OCC/1300
NPO569C	1	866	6792	2/1983	BB E		CRWL/1032 - STANDING WATER
NPO570C	1	896	7172	1/1984	BB E		CRWL/777
NPO572C	1	1027	7956	1981	FA E	WS	CRWL/1027
NPO573C	1	1080	8869	1983	BB E		CRWL/1080
NPO574C	1	934	7727	7/1984	SPACE E	WS	CRWL/934
NPO575C	1	938	7223	12/1983	BB E		CRWL/1140
NPO741	1	1164	12345	11/1984	SPACE E	PS	CRWL/1168
NPO742	2	742	8005	12/1984	SPACE E		CRWL/299 SLAB/630
NPO744	SPLIT	1539	12725	12/1984	SPACE E		CRWL/744
NPO745	2	1237	11698	12/1984	SPACE E		CRWL/800
NPO747	1	962	7256	8/1984	SPACE E		CRWL/551 SLAB-UNOCC/85
NSA582C	1	1560	12480	11/1983	FA E		CRWL/1560
NSA583C	1	874	6508	1980	SPACE E	WS	CRWL/874
NSA584C	1	1238	12417	6/1984	FA E	WS	CRWL/1238
NSA771	2	1311	9919	6/1984	SPACE E	WS & PS	CRWL/760
NSA772	2	2272	20381	8/1984	FA E		CRWL/1518
NSA773	2	1257	9772	9/1984	RAD E	PS	CRWL/718
NSA776	2	3055	24559	12/1984	BB E	PS	BSMT-OCC/1474
NSA778	2	2334	18676	1/1985	SPACE E	WS	DAY BSMT-UNOCC/624 CRWL/144 SLAB/324
NSA779	1	1244	11003	1/1985	FA E	WS	CRWL/1245
NSA781	1	1115	8684	2/1985	RAD E	WS	SLAB/1116

BUILDING CHARACTERISTICS - continued
MCS AND CONTROL HOMES

HOUSE ID	#STORIES	OCCUPIED AREA (FT2)	OCCUPIED VOLUME (FT3)	YEAR BUILT	HEATING SYSTEM DELIVERY	HEATING SYSTEM AUXILIARY	SUBSTRUCTURE TYPE(S) /AREA (FT2)
NSP052C	1	1718	13779	4/1981	FA E	WS	BSMT-OCC/828
NSP053C	1	1167	9780	5/1980	FA E		BSMT-UNOCC/1135
NSP054C	2	1422	12720	1981	BB E		SLAB/1267
NSP201	SPLIT	1358	12690	8/1984	BB E		BSMT-UNOCC/189 DAY BSMT-OCC/537
NSP202	1	1690	14140	10/1984	BB E		BSMT-OCC/840
NSP203	SPLIT	1745	16134	9/1984	FA E		BS,T-OCC/950 DAY BSMT-OCC/330
NSP204	SPLIT	1907	18673	9/1985	FA E		BSMT-OCC/765 CRWL/803
NSP207	1	1590	13430	1/1985	FA E		BSMT-UNOCC/1275 CRWL/294
NSP208	SPLIT	1598	12524	12/1984	FA E		BSMT-UNOCC/426
NSP209	2	2136	17088	1/1985	E		DAY BSMT-OCC/1068
NSP212	SPLIT	1724	14487	11/1984	BB & FA E		BSMT-OCC/858
NVA551C	2	2469	19333	1982	SPACE/RAD E		CRWL/1667
NVA553C	1	988	8636	1/1984	SPACE E	WS	CRWL/1196
NVA554C	1	1174	9525	12/1982	SPACE E		CRWL/1174
NVA555C	1	1467	12202	1981	SPACE E		BSMT-OCC/442
NVA556C	1	1428	10995	9/1984	SPACE E		CRWL/1388
NVA558C	1	853	6828	2/1983	SPACE NG		CRWL/854
NVA559C	1	1555	12737	1982	SPACE E	WS	BSMT-OCC/483
NVA562C	1	1618	15216	9/1984	FA E (HP)		CRWL/1618
NVA563C	1	2166	18712	7/1984	SPACE E	WS	CRWL/2166
NVA701	SPLIT	1350	10463	9/1984	FA E		BSMT-UNOCC/1307 CRWL/130
NVA702	2	3030	26171	12/1984	FA E	WS	BSMT-OCC/429 CRWL/1189
NVA703	2	2061	17529	12/1984	SPACE E		CRWL/1113
NVA704	2	1346	10876	9/1984	SPACE E		CRWL/716
NVA705	SPLIT	2734	25526	1/1985	SPACE E	WS	BMST-OCC/1220

NOTATION:

BSMT = BASEMENT
DAY BSMT = DAYLIGHT BASEMENT
CRWL = CRAWLSPACE
SLAB = SLAB-ON-GRADE
OCC = OCCUPIED ZONE
UNOCC = UNOCCUPIED ZONE

FA = FORCED AIR FURNACE
BB = BASEBOARD
SPACE = WALL SPACE HEATER
RAD = RADIANT
HP = HEAT PUMP

E = ELECTRIC
NG = NATURAL GAS
WS = WOOD STOVE
PS = PASSIVE SOLAR

HOUSE ID:
CD = COEUR d'ALENE
PO = PORTLAND
SA = SALEM
SP = SPOKANE
VA = VANCOUVER
C = CONTROL

APPENDIX B
NEW HOME DATA SUMMARY

House ID	Ventilation and Leakage					Radon (pCi/L)		HCHO (PPB)		NO2 (PPB)		H2O (g/kg)	
	SLA+ (cm2/m2)		Predicted++ Short-term (ACH)	PFT* Short-term (ACH)	PFT** Long-term (ACH)								
	1st	2nd				Occupied	Unoccupied	In	Out	In	Out	In	Out
NCD076C	2.81	3.09	0.30	0.30	0.29	4.8	9.4	56.6	5.5	3.4	10.4	5.51	3.13
NCD077C	3.81	3.35	0.53	0.27	0.23	15.3	15.9	69.7	5.5	4.8	4.0	6.76	4.07
NCD078C	2.83	3.05	0.34	0.18	0.19	3.6	23.4	38.5	5.5	1.9	1.7	5.65	3.69
NCD079C	2.08	2.42	0.26	0.04	0.08	3.9	8.4	63.5	5.5	2.4	2.1	6.27	3.96
NCD080C	4.91	2.32	0.63	0.23	0.52	1.7	4.1	40.6	5.5	2.1	3.0	6.70	4.39
NCD081C	5.18	4.74	0.43	0.05	0.16	1.4	3.1	87.6	5.5	1.0	2.6	7.54	4.46
NCD082C	1.72	1.94	0.25	0.20	0.28	11.0	ND	23.7	5.5	1.0	3.0	6.68	5.12
NCD084C	2.22	2.44	0.28	0.11	0.14	9.7	ND	78.5	5.5	2.7	3.3	7.53	4.52
NCD085C	1.44	3.29	0.20	0.20	0.16	4.1	4.4	158.4	11.6	6.7	7.3	9.81	4.15
NCD086C	1.93	1.79	0.21	0.45	0.47	1.1	2.7	81.1	5.5	1.1	1.6	6.14	4.17
NCD090C	2.26	2.38	0.25	0.22	0.22	2.3	ND	60.1	5.5	1.0	1.0	5.44	3.34
NCD252	0.77	0.85	0.10	0.60	0.37	0.7	ND	38.8	5.5	2.9	1.0	5.17	3.17
NCD253	2.10	2.38	0.28	0.33	0.25	0.5	1.1	72.3	5.5	1.0	1.0	5.91	2.99
NCD254	1.23	1.48	0.23	0.42	0.54	0.2	ND	21.9	5.5	6.8	12.6	4.83	3.21
NCD255	1.51	1.58	0.23	0.25	0.31	1.2	1.5	81.9	5.5	5.1	8.2	6.34	3.80
NPO569C	4.07	4.68	0.28	0.28	0.50	0.4	0.4	140.6	11.3	2.5	12.4	8.49	6.47
NPO570C	4.46	4.91	0.39	0.26	ND	1.1	1.0	97.3	5.5	1.0	15.2	6.37	5.28
NPO572C	5.32	5.35	0.73	0.34	0.28	3.4	7.6	73.5	5.5	2.2	12.0	7.54	6.32
NPO573C	5.08	ND	0.34	0.28	0.28	1.0	0.7	144.1	5.5	2.6	9.9	8.20	6.48
NPO574C	5.69	7.12	0.75	0.24	0.62	0.5	1.7	87.8	5.5	1.0	9.9	7.02	6.11
NPO575C	3.62	3.87	0.25	0.19	0.19	0.1	0.1	228.5	5.5	2.1	11.1	7.56	6.83
NPO741	3.50	3.66	0.30	0.26	0.23	1.3	1.9	183.8	5.5	1.0	5.4	6.40	5.47
NPO742	14.99	13.12	1.63	0.18	0.28	0.7	0.5	88.0	5.5	2.3	4.3	5.44	5.10
NPO744	5.21	5.15	0.48	0.38	0.34	0.9	1.8	138.7	5.5	4.3	11.4	6.14	4.19
NPO745	1.68	1.72	0.08	0.13	0.13	1.1	1.8	343.3	5.5	1.0	1.0	9.32	6.65
NPO747	2.45	2.43	0.20	0.04	0.10	1.0	1.8	240.0	12.0	1.0	9.6	6.90	5.91
NSA582C	6.43	6.28	0.49	0.56	0.77	1.5	6.7	44.2	5.5	2.9	8.8	6.53	5.65
NSA583C	4.69	5.55	0.33	0.53	ND	1.7	3.2	74.7	5.5	2.2	19.3	5.80	4.42
NSA584C	7.63	8.50	0.54	0.55	0.47	0.7	1.0	62.3	5.5	1.0	4.2	6.12	5.12
NSA771	3.55	3.08	0.41	0.53	0.68	0.7	1.7	48.1	5.5	2.8	15.9	6.38	4.46
NSA772	4.27	5.01	0.48	0.39	0.37	1.2	1.0	97.7	5.5	1.0	4.0	6.58	4.92
NSA773	3.78	2.97	0.42	0.54	0.59	1.9	2.1	60.2	5.5	1.0	11.1	6.19	4.82
NSA776	2.60	2.95	0.34	0.35	0.40	7.6	ND	103.0	5.5	3.8	5.5	8.05	4.77
NSA778	3.25	4.21	0.36	0.18	0.19	1.2	1.9	115.7	5.5	1.0	2.2	7.26	5.61
NSA779	2.55	3.19	0.27	0.38	0.46	0.5	0.6	88.3	11.6	3.7	2.9	7.08	4.97
NSA781	2.80	2.99	0.20	0.35	0.29	4.8	ND	103.3	5.5	3.7	7.9	9.52	7.09

NEW HOME DATA SUMMARY - continued

House ID	Ventilation and Leakage					Radon (pCi/L)		HCHO (PPB)		NO2 (PPB)		H2O (g/kg)	
	SLA+ (cm2/m2) 1st	SLA+ (cm2/m2) 2nd	Predicted++ Short-term (ACH)	PFT* Short-term (ACH)	PFT** Long-term (ACH)	Occupied	Unoccupied	In	Out	In	Out	In	Out
NSP052C	4.89	5.33	0.70	0.38	0.58	3.4	ND	45.4	11.6	3.2	13.4	5.45	3.16
NSP053C	2.85	3.04	0.31	0.16	0.17	2.2	6.1	61.5	5.5	1.0	9.6	5.51	3.19
NSP054C	4.88	5.15	0.46	0.43	0.62	1.7	ND	45.5	13.0	5.9	18.4	4.41	3.85
NSP201	1.12	0.88	0.17	0.15	ND	5.8	5.9	61.0	18.6	2.7	22.0	7.59	3.17
NSP202	0.75	0.87	0.12	0.15	0.13	3.1	ND	63.2	12.1	1.5	18.9	7.53	3.91
NSP203	1.79	2.01	0.22	0.23	0.22	11.9	21.2	90.3	5.5	1.0	10.9	6.35	3.34
NSP204	1.48	1.83	0.19	0.13	0.13	19.2	26.4	65.2	11.4	1.0	10.8	7.45	3.18
NSP207	1.62	2.05	0.29	0.13	0.18	0.9	1.7	98.9	5.5	3.7	1.4	7.47	4.43
NSP208	1.40	2.02	0.20	0.70	0.53	2.9	5.4	66.4	11.7	2.1	11.3	5.51	3.37
NSP209	0.31	0.46	0.05	0.57	0.42	1.2	1.7	46.8	5.5	4.6	8.5	5.44	3.70
NSP212	1.10	1.25	0.18	0.16	0.30	1.6	2.5	63.1	5.5	2.1	17.7	5.86	3.27
NVA551C	2.90	3.02	0.30	0.50	0.35	3.0	21.8	48.1	5.5	7.4	17.0	6.62	5.79
NVA553C	6.15	5.40	0.59	0.36	0.34	1.4	2.5	101.6	5.5	3.2	13.6	6.19	4.64
NVA554C	3.74	3.90	0.41	0.18	0.14	1.1	1.2	135.8	5.5	1.0	4.0	6.96	4.87
NVA555C	4.76	5.19	0.68	0.34	0.34	1.9	ND	27.7	5.5	2.7	12.1	5.91	5.09
NVA556C	4.81	4.97	0.45	0.35	0.43	0.9	2.2	146.0	5.5	2.3	7.3	6.60	6.15
NVA558C	4.54	4.60	0.45	0.18	0.21	0.8	3.4	32.9	5.5	2.0	13.0	6.91	5.46
NVA559C	6.13	5.85	0.69	0.52	0.93	1.3	ND	41.2	5.5	4.1	13.3	7.07	6.34
NVA562C	5.20	ND	0.51	0.63	0.47	0.8	0.8	114.0	5.5	2.2	6.5	5.72	4.96
NVA563C	1.43	1.93	0.15	0.21	ND	0.9	0.5	167.4	5.5	1.0	9.0	6.52	4.93
NVA701	4.18	5.77	0.52	0.45	0.48	2.7	7.2	108.9	5.5	2.6	13.8	6.19	5.75
NVA702	1.81	4.00	0.30	0.80	ND	2.2	0.8	48.1	5.5	6.8	12.7	5.68	4.93
NVA703	1.60	1.83	0.18	0.65	0.30	0.6	0.8	141.7	11.4	2.4	9.7	6.15	5.12
NVA704	0.86	1.02	0.13	0.70	0.77	0.5	0.7	48.6	5.5	5.7	7.8	5.82	4.79
NVA705	2.14	ND	0.28	0.30	0.45	0.9	ND	85.4	5.5	1.0	2.4	6.63	4.97

+Air Leakage Area (cm2) / occupied floor area (m2)
++Model-predicted ventilation not including estimate for mechanical ventilation and occupancy
*Concurrent with NO2, HCHO, and H2O passive samples (6-10 days)
**Concurrent with radon detectors (55-70 days)

APPENDIX C

CALCULATION OF NO_2 REACTIVITY, K.

Figure C1 shows calculated reactivity, K, for NO_2 compared to indoor water vapor concentrations in each of the 61 homes. K was calculated from

$$K = \frac{I\,(C_o - C)}{C} \quad \text{where:}$$

K = Reactivity (hr^{-1})

I = Ventilation rate as measured by PFT (hr^{-1})

C_o = Outdoor concentration (ppb)

C = Indoor concentration (ppb)

The penetration factor was assumed to be one and the indoor source term was assumed to be zero. Researchers have shown a strong dependence of NO_2 decay on relative humidity in chamber studies (Leaderer, 1986).

This figure does not demonstrate that relationship, probably for several reasons. Indoor NO_2 concentrations were generally low, often near the detection limit of the sampling device and therefore more uncertain. As a result, the error in K when the uncertainty in the ventilation rate measurement is included is estimated to be approximately 60% to 100%. Traynor, et al., (1982) showed a reactivity of 1.3 ach for an unoccupied research house. The K for these data, on the other hand, range from less than zero to greater than 5. The other factor that may not be accounted for is the presence of unknown indoor combustion sources, including tobacco smoking.

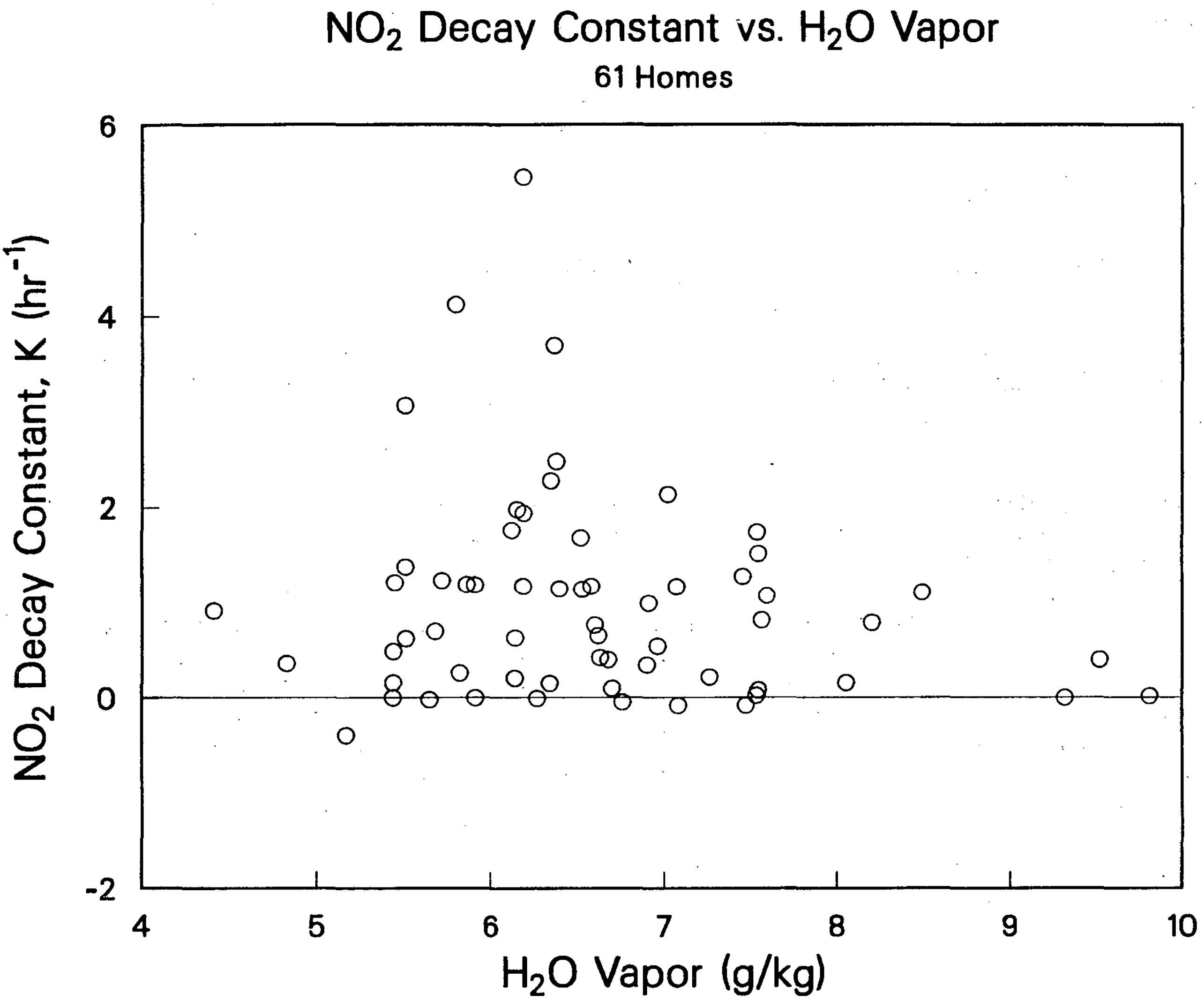

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Figure C1. Relationship between calculated NO$_2$ reactivity, K, and indoor water vapor concentrations in 61 homes. Uncertainty in K is approximately 60% to 100% due primarily to uncertainty in measurement of low indoor NO$_2$ concentrations.

APPENDIX D

THE BPA DATABASE

The BPA database consists of data stored in disk files on a Digital VAX-11/8600 computer system. Data which is recorded by hand on the basis of laboratory analysis or questionaire is entered into individual files, each with a record structure designed for the particular application, using an entry program written locally; Datatrieve, the Digital data management program, is then used for calculations, selection, averaging, and report writing. Data which is recorded automatically by a locally produced data logger is written to a single file whose records consist of a code representing the collection location, a date and time, and a field for the output of each sensor. A separate file contains descriptive information keyed to the first field of the data file. A locally written program reads the data logger modules, transforms the output to usable data, analyzes the data, and produces graphic output. Data on tracer gas decay is handled by a distinct locally written program, which calculates air exchange rates and produces graphic output.

The following files contain the raw data:

BLDG	Basic information on commercial buildings
HOUSE	Basic information on residential buildings
HCHO, CHCHO	Residential and commercial formaldehyde
H2O, CH2O	Residential and commercial water vapor
NO2, CNO2	Residential and commercial nitrogen dioxide
RSP, CRSP	Residential and commercial respirable particles
CO	Carbon monoxide
CO2	Carbon dioxide
RADON	Radon, based on track-etch measurements
R_ORG, C_ORG	Residential and commercial organics
ACH	Commercial air exchange and circulation rates
EHS	All data collected by data logger
EHSHDR	Descriptive information keyed to EHS

All filenames use the extension ".DAT", e.g., radon data is stored in RADON.DAT. Data on tracer gas decay is stored in individual files for each building, with the building code as the filename and ".INF" as the extension. The file EHS.DAT characteristically contains data from a continuous radon monitor and, in many cases, a weather station.

Reports on data contained in a single file are produced by the use of Datatrieve or by locally produced programs, as described above. Each of the files other than thiose for organics, EHS, and infiltration includes a field "SITE", containing the building code, and, where appropriate, a field "LOCATION", containing a code for the sampling point within the building. The organics files are connected to the site and location by the lot and sample numbers common to this data and the respirable particle data. The codes used in the EHS data file are connected to the site and location by a table. Hence, a set of procedures written in the language of the Datatrieve interpreter allows the analyst to find data of any type for a given site and location. The results of these procedures may then be used for additional statistical analysis and tabular and graphic output.

APPENDIX E

DETECTION LIMITS FOR LBL PASSIVE SAMPLERS USED IN BPA FIELD STUDIES

Passive sampler detection limits are obtained by finding analytical absorbances (HCHO, NO_2) or weight differences (H_2O) which are significantly different from those obtained from representative unexposed sampler blanks. From these values the detection limit for a given exposure duration can be calculated using the sampling rate and correction factors established for each sampler type.

After completion of testing in 1984 and 1985, theoretical detection limits were determined using analysis data from BPA field samples. These detection limits have been selected as the criterion for evaluating and reporting all BPA field study passive sampler results.

The detection limits represent single variates which are significantly different ($P \leq 0.05$) from given populations of field blanks by application of a one-tailed student's t-test (Sokal and Rohlf, 1981).

Formaldehyde Detection Limits:

DETECTION LIMIT (ppb) 168 Hr	DETECTION LIMIT (ppb) 90 Hr	MEAN BLANK ABSORBANCE	MEAN INVERSE SLOPE	MEAN INTERCEPT
11	20	0.0136	4.3099	-.0008

These figures were calculated from the absorbances of 337 field blanks and 65 formaldehyde analyses performed in 1984 and 1985. The limits correspond to a sample concentration of 0.15 μg/cc, an absorbance of 0.036, and a sampling rate of 240 cc/hr.

Nitrogen Dioxide Detection Limits:

DETECTION LIMIT (ppb) 168 Hr	DETECTION LIMIT (ppb) 90 Hr	MEAN BLANK ABSORBANCE	MEAN INVERSE SLOPE	MEAN INTERCEPT
2	4	0.0166	44.159	-0.0024

These figures were calculated from the absorbances of 303 field blanks and 47 nitrogen dioxide analyses performed in 1984 and 1985. The limits correspond to a sample concentration of 1.33 mm NO_2, an absorbance of 0.030, and a sampling rate of 60 cc/hr.

Water Vapor Detection Limits:

DETECTION LIMIT (gH_2O/kg AIR) 160 Hr.	DETECTION LIMIT (gH_2O/kg AIR) 90 Hr.	MEAN BLANK
0.3	0.5	0.031g

These figures were calculated using the net weight increases of 275 field blanks weighed as part of water vapor analyses during 1984 and 1985. The limits correspond to a sampling rate of 102 cc/hr.

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