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Comparison of Measured Air Leakage Rates and Indoor Air Pollutant Concentrations with Design Standards for Energy Efficient Residential Buildings

Jeff Harris
Division of Residential Programs
Bonneville Power Administration
Portland, OR 97208

ABSTRACT

The Residential Standards Demonstration Program (RSDP) was initiated by the Bonneville Power Administration (Bonneville) to collect field experience with a large number of homes built to the Northwest Power Planning Council's Model Conservation Standards. These standards included prescriptive construction specifications for air tightness levels and requirements for mechanical ventilation with heat recovery. A total of 423 homes were built to the standards and were measured for air leakage using a blower door. Estimates of heating season ventilation rates due to wind and temeperature differences were made using the blower door data and the LBL infiltration model. A subset of approximately 200 homes were also measured using perfluorocarbon tracer gas (PFT) methods. As a comparison, 411 "control" homes representative of conventional new construction practices were also measured for air leakage, modeled using the LBL procedures and a subset measured using PFT techniques. Both groups were measured for indoor concentrations of radon and formaldehyde. The paper discusses the results of these studies comparing the actual "natural" ventilation rates of the buildings to the designed rates. It also discusses the levels of pollutants found in the control homes with only "natural" ventilation to the concentrations found in the energy-efficient homes with "natural" and mechanical ventilation.

INTRODUCTION

In 1980, Congress passed the Northwest Regional Power Act (Act) which specified, among other things, that the four Northwest States were to pursue adoption of the Model Conservation Standards (MCS). The MCS were to capture all of the energy savings that were "cost-effective" to the region and "economically feasible" for the consumer.

The Northwest Power Planning Council (Council), set up by the Act, developed a set of standards in the form of building code requirements to accomplish the MCS goals. These standards were published in the 1983 plan to be adopted by the four Northwest States by 1986.

In order to demonstrate the feasibility of the standards and to collect data on various technical aspects of the MCS, Bonneville initiated the RSDP in 1983. The RSDP was designed to collect information on technical assistance incremental construction costs, energy savings, and potential indoor air quality (IAQ) impacts of the MCS.

Approximately 423 homes were built to the MCS throughout the four States. However, in order to determine the true effects of the MCS, a control sample of "current practice" homes was included in the energy and IAQ monitoring efforts. Data to be collected for IAQ purposes included fan door pressurization/depressurization tests, PFT measurements, 3- and 12-month integrated radon measurements, and first and second year formaldehyde measurement.

PHYSICAL CHARACTERISTICS OF THE RSDP BUILDINGS

Control Sample. The Control Group was intended to consist entirely of post 1980 construction homes representative of current building code construction techniques. However, because of recruitment difficulties some homes older than 1980 vintage were inadvertantly included. This deviation from the original design turned out to be a significant factor in the formaldehyde testing results. However, the majority of the houses appear to be fairly representative of the current construction practice.

The typical control home included no specific features to control air leakage beyond some very basic caulking and a requirement in Washington and Oregon for vapor retarders in the walls. No special provisions were made for mechanical ventilation in these homes. None of the current codes in effect at the time of construction required mechanical ventilation in residential buildings.

MCS Sample. The MCS houses were built to varying levels of efficiency depending on the severity of the climate. The MCS are specified by "climate zone" differentiated by degree days base 65. Typical levels of insulation are shown in Table 1. Almost all of the MCS houses were built with a "continuous air barrier" designed to limit the natural air leakage of the building to 0.1 air changes per hour (ACH). All of the MCS houses included whole-house mechanical ventilation in the form of an air-to-air heat exchanger (AAHX). Additional spot mechanical ventilation was required for baths and kitchens.

For most of the MCS builders this was their first attempt at this type of construction and their success, especially with the air barrier, varied considerably. Data from the fan door tests indicate that many of the "first time" builders did not achieve the level of performance that was originally expected. Unfortunately, the fan door test was conducted after the houses were completed and was not used during construction to help detect major leakage areas. Most builders followed a prescriptive approach to construction that included the features given in Table 2.

INFILTRATION MEASUREMENTS

Fan Door Tests. Fan door pressurization/depressurization tests were conducted on both the MCS and control groups in order to determine the relative "tightness" of the two groups. Seasonal average air change rates were computed using the infiltration model developed by Lawrenece Berkeley Laboratories (LBL) and data from the fan door tests. The results of these tests are provided in distribution form in Figures 1 and 2. Probably the most significant result from these tests were the wide-range of values observed in the control home groups. A significant amount of the control homes had natural air leakage rates as predicted by the blower door of less than 0.3 ACH. This result indicates that a large portion of the current building population may already be below what might be considered an "acceptable" air change rate.

The second most important observation is the failure of the majority of the MCS houses to meet their target for air tightness. Less than 15 percent actually achieved 0.1 ACH or less. This is probably largely due to the fact that most builders used a system of air leakage control that involved a polyethelyne air vapor barrier similar to that used in Canada and Sweden. Unfortunately, poly as a system is extremely sensitive to craftsmanship and quality control throughout the construction process.

The standard construction sequence in the Northwest involves up to 16 different subtrades, none of which have any responsibility or desire to protect or preserve the integrity of the air barrier. Where the subtrades were more used to working with poly (e.g., the colder Climate Zone 3) better results were generally achieved.

Several promising alternatives were developed during the course of the RSDP that significantly improved the success rate of the first time contractor in achieving an air-tight house. The "air-tight drywall approach" or ADA, provided a system that was dramatically less sensitive to the quality control of the subtrades and used existing structural materials in the house for the bulk of the air barrier. A second alternative involved the use of rigid insulating foam sheathing in an interior application as the primary air barrier. This system met with less success, but still showed some promise for applications where foam sheathing is being used for insulating purposes as well.

PFT tests. In order to get an understanding of what the true seasonal average ventilation rates were in the homes, a subset of the MCS and control homes was tested using the PFT measurement system developed by Brookhaven National Laboratories[1]. The PFT tests were conducted over a 3-month period during the heating season and included occupant and mechanical ventilation effects (AAHX, exhaust fans, etc.). The results from this analysis are represented in Figures 3 and 4.

Perhaps one of the most interesting observations from the test was that the control homes indicate a significantly lower ACH as measured by the PFT than measured by the blower door. Comparison of the PFT readings versus blower doors is included in Figure 5.

At first glance, this is counter-intuitive. Since the PFT includes occupant effects and mechanical ventilation, it should provide a "higher" reading than the blower door for the same house. However, part of the difference may be explained by the fact that the PFT is essentially measuring the "effective ventilation rate" (how much a pollutant concentration is reduced) where the blower door test is attempting to estimate the "total" ventilation rate of the building (how much air moves through the building)[2]. Unfortunately, given the degree of scatter in the data, there is no simple relationship between the two measures of air change rate. Research is currently underway to explain this difference[3].

Comparison between the PFT and blower door results in Figure 6 indicate a greater amount of scatter than that shown by the same comparison for the control homes. This increase in scatter can probably be largely attributed to operation of the AAHX. Unfortunately, the data does not initially provide us with a good explanation of how much of the ventilation is due to the AAHX and how much is due to natural ventilation. At any rate, it appears that the MCS homes are providing basically the same level of ventilation as the control homes are on average.

INDOOR AIR QUALITY MEASUREMENTS

Formaldehyde. Formaldehyde measurements were taken on all homes using passive 1-week samplers during the heating season. Unfortunately, it was not possible to test all the homes during the first heating season resulting in slightly less than half the homes being measured a year later (winter 1985/86)[4]. However, this delay also provided an opportunity to retest a subset of houses for a second heating season. The grouping of these various samples is described in Table 3.

The median results for Group 1 are given in Figure 7 and the resulting statistical comparisons in Table 4. This table indicates that there is a statistically significant difference between the MCS and control groups with the MCS readings higher than the control. Results for Group 2, readings taken 1985/86, are given in Figure 8 and Table 5. Table 5 indicates that the MCS medians are lower than the controls although there is not a statistically significant difference between the MCS and controls. The difference in the Group 1 and Group 2 results can be explained by the two Group 3 results shown in Figures 9 and 10 and Tables 6 and 7. Results from Group 3a, houses less than 5 years old and tested during the winter of 1984/85, indicate a relatively high level of formaldehyde for both MCS and controls, but no statistically significant difference between the two of them. Group 3b indicates that the same Group, a year later, showed a significant drop in formaldehyde concentration after only a year for both MCS and controls. This analysis indicates that dwelling age is the primary factor in determining the formaldehyde concentration in both MCS and control dwellings. In fact, a plot of formaldehyde concentration versus the dwelling age at the time of measurement (Figure 11) indicates that there is a definite effect.

Other interesting results that are not necessarily explained by the dwelling age are the statistically significant low readings in Washington State versus the rest of the States and the statistically significant high reading in Oregon relative to the rest of the states. Several explanations are possible. A peculiar floor construction technique in Oregon requires that interior grade underlayment is required in almost all construction. Floor construction in Washington provides for the possibility of an exterior grade combination subfloor underlayment. The amount of formaldehyde in the subflooring has been shown to be one of the most significant sources of formalydehyde in homes[5]. At the time of the demonstration, interior grade underlayment typically used in Oregon was made with Urea-Resins with a much higher out-gas rate than the exterior grade Phenolic Resins used in typical Washington subfloor construction. Other possible explanations include the fact that many factories were converting to the Housing and Urban Development (HUD) standards during the period of RSDP construction. It is possible that the higher levels of construction activity in Washington introduced the HUD standard plywood into the field faster than in Oregon where activity was sluggish and supply houses were still getting rid of old stock.

Radon. Passive track-etch type detectors for radon progeny were included in all RSDP homes for both a 3-month period during the heating season. An additional set of detectors were placed in the homes for a 12-month test to determine the annual radon concentration. Both detectors were installed in the main living areas of the homes. The distributions shown in Figures 12 and 13 and the accompanying statistical analysis given in Tables 7 and 8 indicate that there were no statistically significant differences between the MCS and control groups. However, there were statistically significant differences between climate zones. This finding is similar to previous findings in the Bonneville service territory that there is a strong correlation between geographic location and radon concentration[6,7].

The logical explanation for this is that source strength is the overriding factor in determining indoor radon concentrations.

The distributions indicate that for the Bonneville region as a whole, the bulk of the measurements are below the Environmental Protection Agencies standard of 4 picoCurier per liter. However, there are a significant number of readings above this level that may require specific mitigation for both MCS and Control groups. The bulk of these high readings are associated with known high radon geographical areas in Northeastern Washington and Northern Idaho.

CONCLUSIONS

Based on a preliminary analysis of the ventilation, formaldehyde and radon measurements taken in the RSDP homes, the following general conclusions appear. First, the MCS homes did not achieve the level of tightness desired based on a prescriptive approach to air sealing. Second, there was no statistically significant difference between the MCS and control group formaldehyde concentrations when homes of the same age were compared. Third, there was no statistically significant difference in radon concentrations between the MCS and control groups for homes in the same state or climate zone. Fourth, there were significant differences in formaldehyde concentrations in both the MCS and control homes less than 5 years in age between readings taken 1 year apart. This indicates that at least for the first several years that the primary variable in formaldehyde concentration is age. Fifth, while there were no significant differences observed between the MCS and control group radon concentrations, there were significant differences in concentrations between different states or climate zones. This indicates that the primary variable in radon concentration is geographical location.

There is obviously a need for further detailed analysis of the data in order to more effectively sort out the differences due to house type, ventilation strategy, occupant effects, and other known variables. Bonneville is planning to continue this analysis and will report the data as it becomes available.

RECOMMENDATIONS FOR NEW HOME CONSTRUCTION

Based on the preliminary results, Bonneville is including the following recommendations in all of its new energy-efficient home construction programs.

First, all structural materials must meet the HUD standards for formaldehyde bearing products. This requirement is based on the theory that the best way to reduce indoor concentrations of formaldehyde is to reduce the amount out-gassed into the building in the first place. Given the rate of decay of formaldehyde concentrations shown by the data, this requirement should reduce the amount of time that the home will have concentrations greater than the ASHRAE recommended standard of 0.1 ppm.

Second, Bonneville is proposing to offer radon monitoring for all homes under the programs and to require certain preconstruction preparation for mitigation. This preparation consists of a requirement for an appropriate thickness of pea gravel under poured concrete slab floors along with sealed PVC pipe connections from the gravel to the interior through the slab. This system can easily be connected to a subslab pressurization or depressurization system if monitoring indicates the need. Other Bonneville-sponsored research indicates that the subslab ventilation strategy is one of the most effective for reducing radon concentrations.

Third, since there are still needs for ventilation based on occupant induced pollutants, Bonneville is requiring mechanical ventilation for spot removal of pollutants and general level of ventilation for the whole house. This whole-house ventilation may consist of dehumidistat controlled exhaust fans or a balanced AAHX.

Fourth, there is still a basic need for air sealing for protection against moisture, comfort, and energy savings. However, Bonneville is currently questioning the need for a fully continuous air barrier and is, therefore, recommending a minimum level of caulking and weather stripping combined with standards for window and door air leakage.

REFERENCES

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2. Relating Actual and Effective Ventilation in Determining Indoor Air Quality. Sherman, M. H. and Wilson, D. J.; Energy Performance of Buildings Group, Applied Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, August 7, 1986.

3. Infiltration Characteristics of Houses in the RSDP Program, Work Status Report; Parker, Danny; Northwest Power Planning Council, Helena, MT, November 1986.

4. Preliminary Formaldehyde Testing Results for the Residential Standards Demonstration Program. Reiland, P., McKinstry, M. and Thor, P.; Office of Conservation, Bonneville Power Administration, Portland, OR 97208; August 1985.

5. Formaldehyde: An Important Indoor Pollutant. Hawthorne, Alan R. and Mathews, Thomas G.; Measurement Applications Group, Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831; Proceedings: EPRI Indoor Air Quality Seminar - Implications for Electric Utility Conservation Programs January 1985.

6. BPA Radon Field Monitoring Study. Thor, Philip W.; Bonneville Power Administration, Portland, OR 97208.

7. Radon Monitoring Results from the BPA Residential Weatherization Program. Piper, M.; Division of Residential Programs, Bonneville Power Administration, Portland, OR 97208.

8. Preliminary Radon Testing Results for the Residential Standards Demonstration Program. Reiland, P., McKinstry, M. and Thor, P.; Office of Conservation, Bonneville Power Administration, Portland, OR 97208; August 1985.

Table 1

Model Conservation Standards for New Residential Buildings

		CLIMATE ZONE	
Component	HDD 6000	6000 HDD 8000	8000 HDD
Ceilings	R-38	R-38	R-38
Walls	R-19	R-25	R-38
Floors	R-19	R-30	R-30
Windows	Triple	Triple	Triple
Doors	Insulated	Insulated	Insulated
Infiltration	0.1 ACH	0.1 ACH	0.1 ACH
Space Heat kWh/Ft2/yr	2.0	3.2	3.2

Table 2

MCS Prescriptive Air Sealing Requirements

1. Window air leakage standards: 0.2 cfm/ft of crack

2. Door air leakage standards: 0.1 cfm/ft of crack

3. All service penetrations sealed

4. Continuous air barrier (Polyethylene, ADA, Interior Foam Board) sealing walls, floors, and ceilings together

5. Vapor Retarder of 1.0 perm or less on all surfaces

6. Sealed combustion appliances with direct supply connections only

7. Whole-house mechanical ventilation with heat recovery (AAHX)

    - Sized for 0.5 ACH
    - Two supplies, two returns
    - Controlled by dehumidistat or timers w/occupant override
    - Bath kitchen fan integration (optional)

8. Spot Ventilation for baths (50 cfm) and kitchens (100 cfm)

Table 3

Formaldehyde Test Sample Group Descriptions

Group 1: All readings taken during the winter of 1984/85

Group 2: All readings taken during the winter of 1985/86

Group 3a: All homes less than 5 years old tested winter 1984/85

Group 3b: All homes in group 3a tested during the winter 1985/86

Table 4

Formaldehyde Concentrations - Group 1 (winter 84/85)

Case	n	Median PPM		Z-score	Statistical significance at 99% conf.
	MCS/Control	MCS	Control		
All	207/370	0.102	0.083	4.58	yes
Zone 1	103/254	0.097	0.083	3.59	yes
Zone 2	41/ 47	0.099	0.079	1.61	no
Zone 3	63/ 69	0.116	0.097	1.85	no
Idaho	31/ 41	0.099	0.080	0.44	no
Montana	55/ 59	0.118	0.104	1.03	no
Oregon	38/ 85	0.108	0.105	1.48	no
Washington	83/185	0.094	0.067	4.04	yes

Table 5

Formaldehyde Concentrations - Group 2 (winter 85/86)

Case	n	Median PPM		Z-score	Statistical significance at 99% conf.
	MCS/Control	MCS	Control		
All	395/245	0.076	0.084	1.99	yes at 95%
Zone 1	262/173	0.077	0.084	1.31	no
Zone 2	72/ 34	0.060	0.084	2.91	yes
Zone 3	61/ 38	0.082	0.081	1.15	no
Idaho	35/ 25	0.079	0.088	0.09	no
Montana	54/ 34	0.082	0.082	0.78	no
Oregon	58/ 65	0.088	0.098	0.12	no
Washington	248/121	0.070	0.076	1.87	no

Table 6

Formaldehyde Concentrations - Group 3a (winter 84/85, age=5 yrs or less)

Case	n	Median PPM		Z-score	Statistical significance at 99% conf.
	MCS/Control	MCS	Control		
All	167/174	0.104	0.102	1.13	no
Zone 1	81/116	0.102	0.104	0.93	no
Zone 2	35/ 23	0.095	0.087	0.17	no
Zone 3	51/ 35	0.116	0.104	0.79	no
Idaho	27/ 20	0.099	0.114	0.06	no
Montana	44/ 31	0.118	0.125	0.55	no
Oregon	33/ 41	0.108	0.125	0.22	no
Washington	63/ 82	0.095	0.087	1.52	no

Table 7

Formaldehyde Concentrations - Group 3b (winter 85/86, group 3a)

Case	n	Median PPM		Z-score	Statistical significance at 99% conf.
	MCS/Control	MCS	Control		
All	167/174	0.079	0.084	0.25	no
Zone 1	81/116	0.087	0.086	1.05	no
Zone 2	35/ 23	0.066	0.084	1.86	no
Zone 3	51/ 35	0.080	0.079	1.52	no
Idaho	27/ 20	0.078	0.084	0.77	no
Montana	44/ 31	0.080	0.080	0.99	no
Oregon	33/ 41	0.088	0.108	0.98	no
Washington	63/ 82	0.076	0.075	0.38	no

Table 8

Radon Concentrations (3-month)

Case	n	Geometric Mean pCi/l		Z-score	Statistical significance at 99% conf.
	MCS/Control	MCS	Control		
All	416/400	0.71	0.82	0.85	no
Zone 1	270/275	0.44	0.52	0.74	no
Zone 2	78/ 53	1.28	1.47	0.18	no
Zone 3	68/ 72	2.64	2.54	1.06	no
Idaho	47/ 43	1.64	2.27	1.27	no
Montana	56/ 63	2.41	2.92	1.57	no
Oregon	60/101	0.59	0.64	0.14	no
Washington	253/193	0.49	0.49	1.20	no
Zone 1 vs Zone 2	545/131	0.48	1.35	5.04	yes
Zone 1 vs Zone 3	545/140	0.48	2.77	8.23	yes
Zone 2 vs Zone 3	131/140	1.35	2.77	2.66	yes

Table 9

Radon Concentrations (12-month)

Case	n	Geometric Mean pCi/l		Z-score	Statistical significance at 99% conf.
	MCS/Control	MCS	Control		
All	282/330	0.92	0.77	1.28	no
Zone 1	158/215	0.41	0.40	2.11	yes at 95%
Zone 2	60/ 44	2.17	2.17	0.00	no
Zone 3	64/ 71	2.92	2.94	0.49	no
Idaho	35/ 38	2.24	2.79	0.71	no
Montana	56/ 61	2.65	2.71	0.83	no
Oregon	46/ 67	0.58	0.51	1.78	no
Washington	145/164	0.57	0.43	2.63	yes
Zone 1 vs Zone 2	373/104	0.41	2.17	6.60	yes
Zone 1 vs Zone 3	373/134	0.41	2.93	8.82	yes
Zone 2 vs Zone 3	131/140	2.17	2.93	1.36	no
3-month vs 12 mo.	816/612	0.76	0.82	1.16	no

FIGURE 1

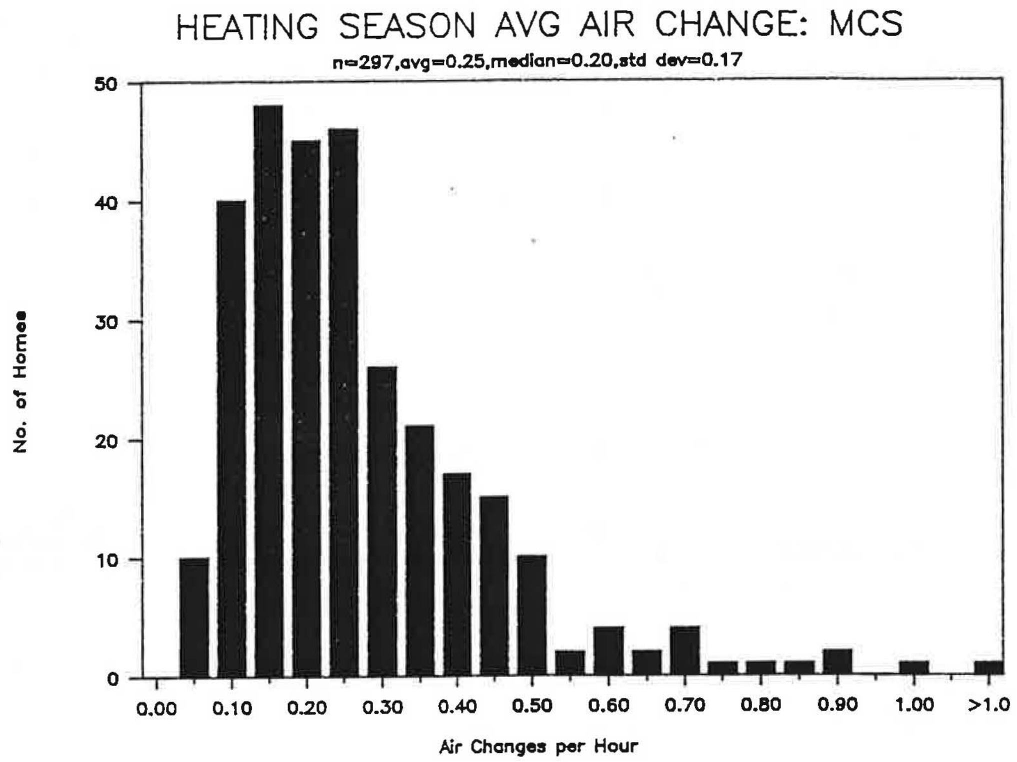


FIGURE 2

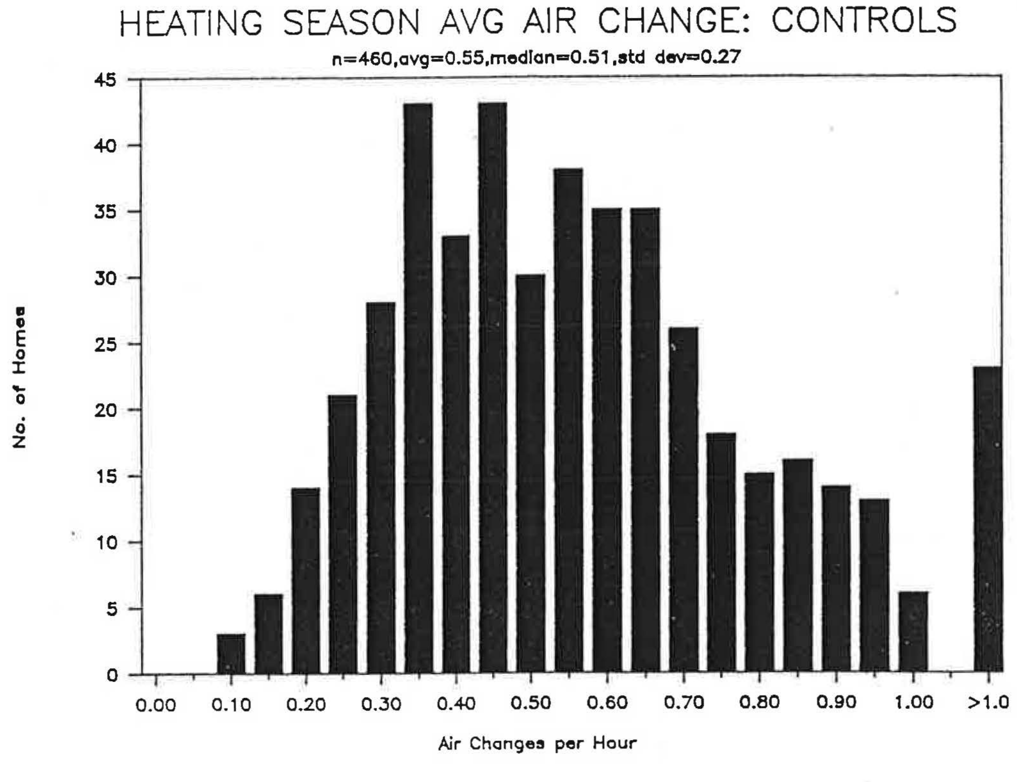
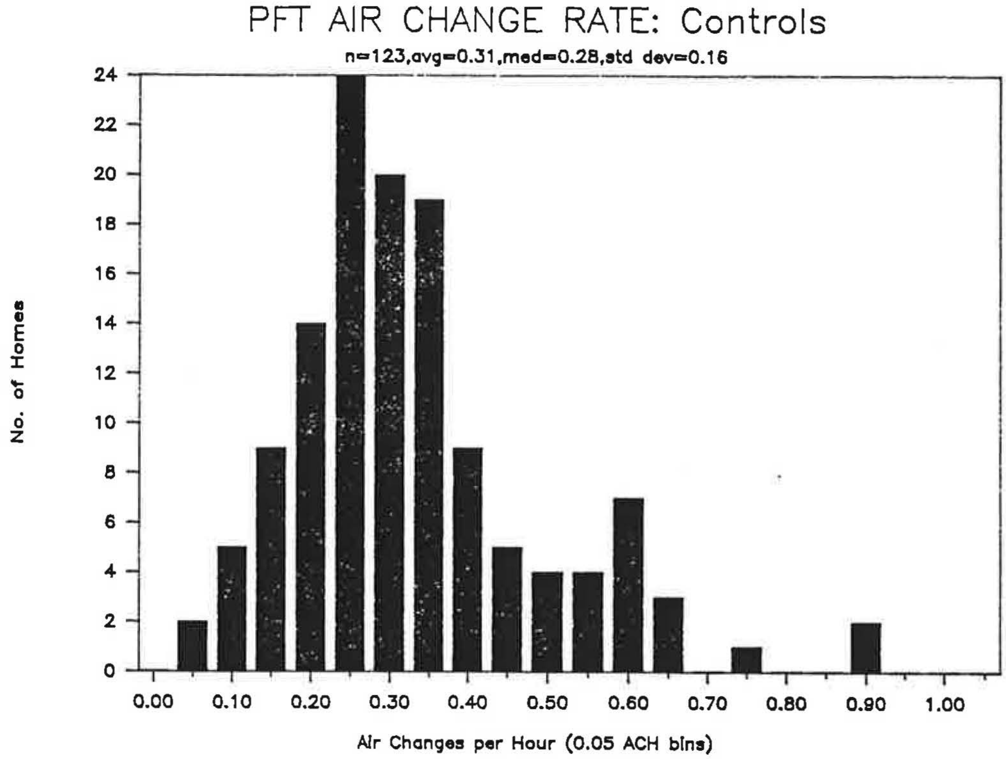


FIGURE 3


PFT AIR CHANGE RATE: Controls

n=123,avg=0.31,med=0.28,std dev=0.16

FIGURE 4

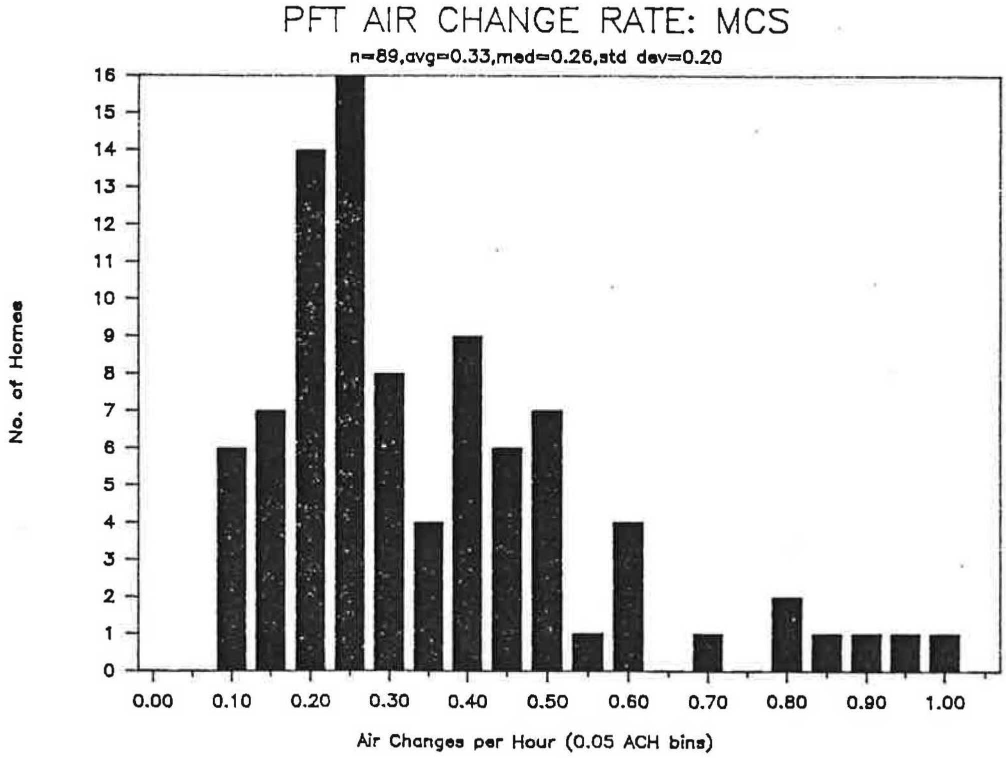

PFT AIR CHANGE RATE: MCS

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FIGURE 5

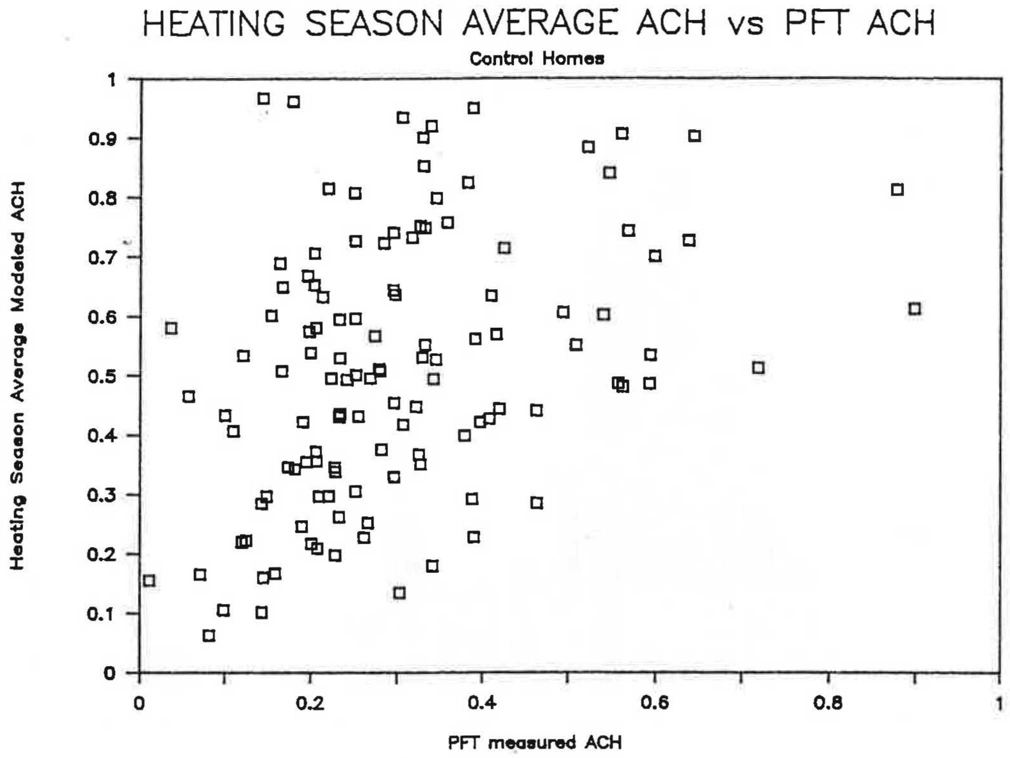


FIGURE 6

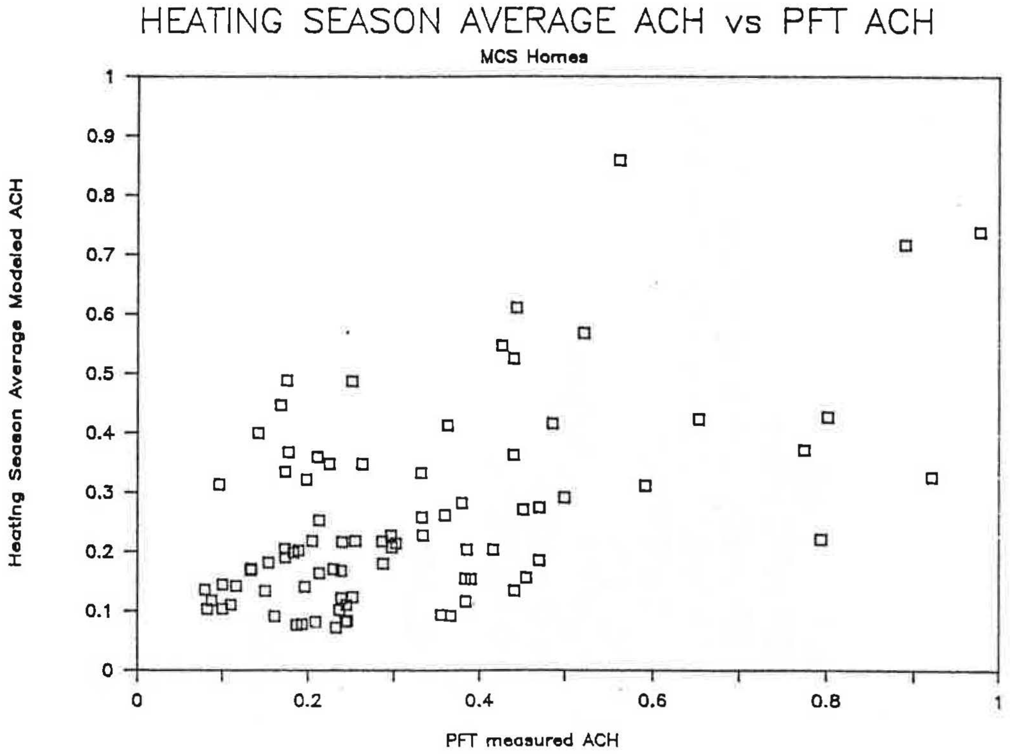


FIGURE 7

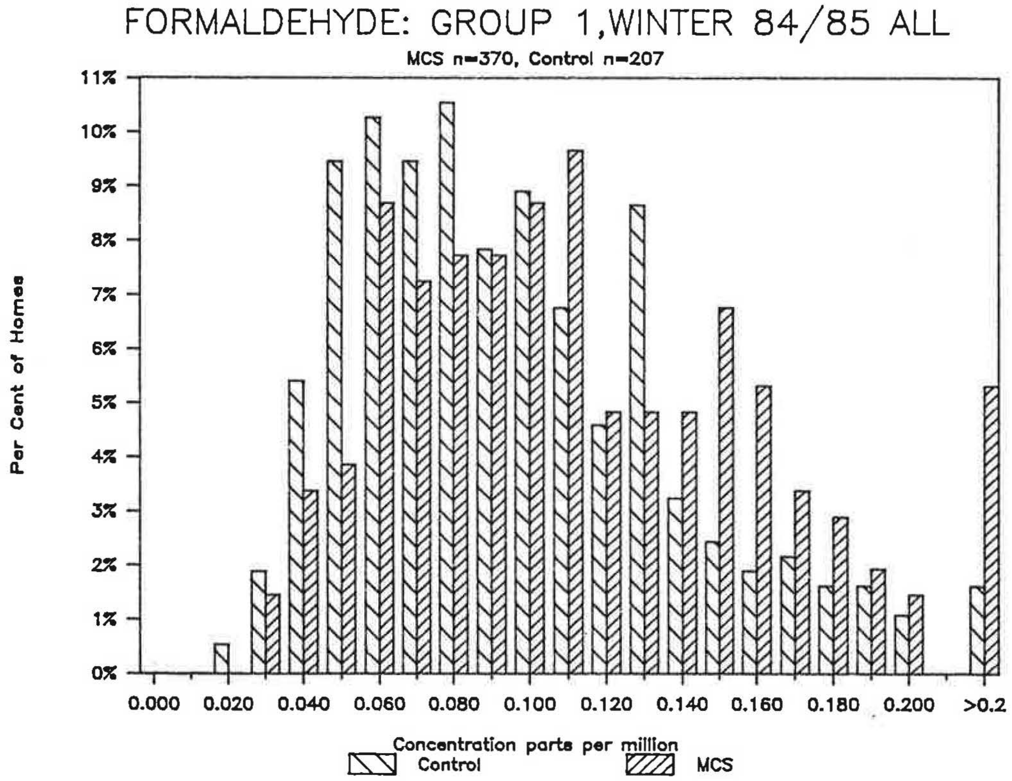


FIGURE 8

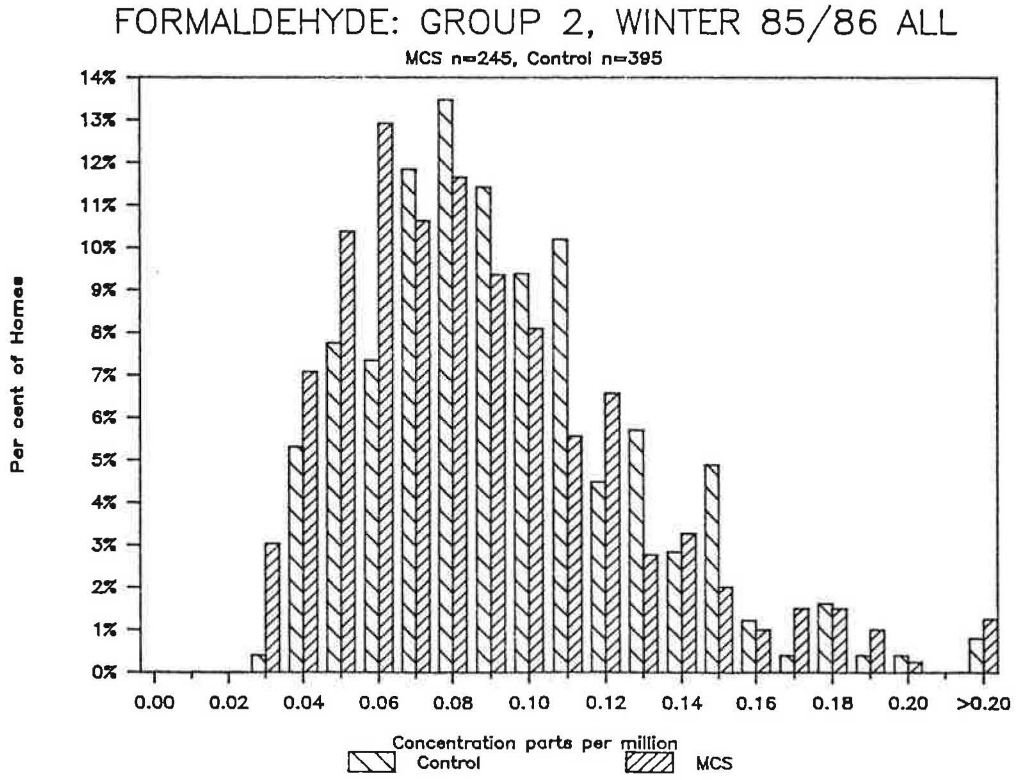
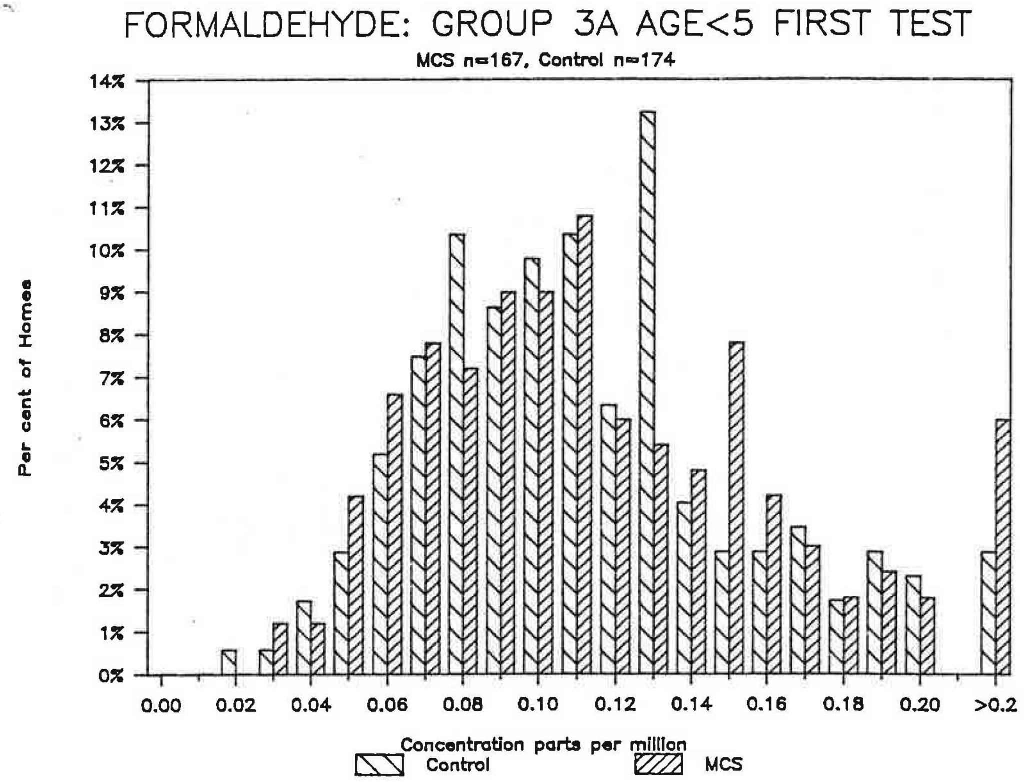
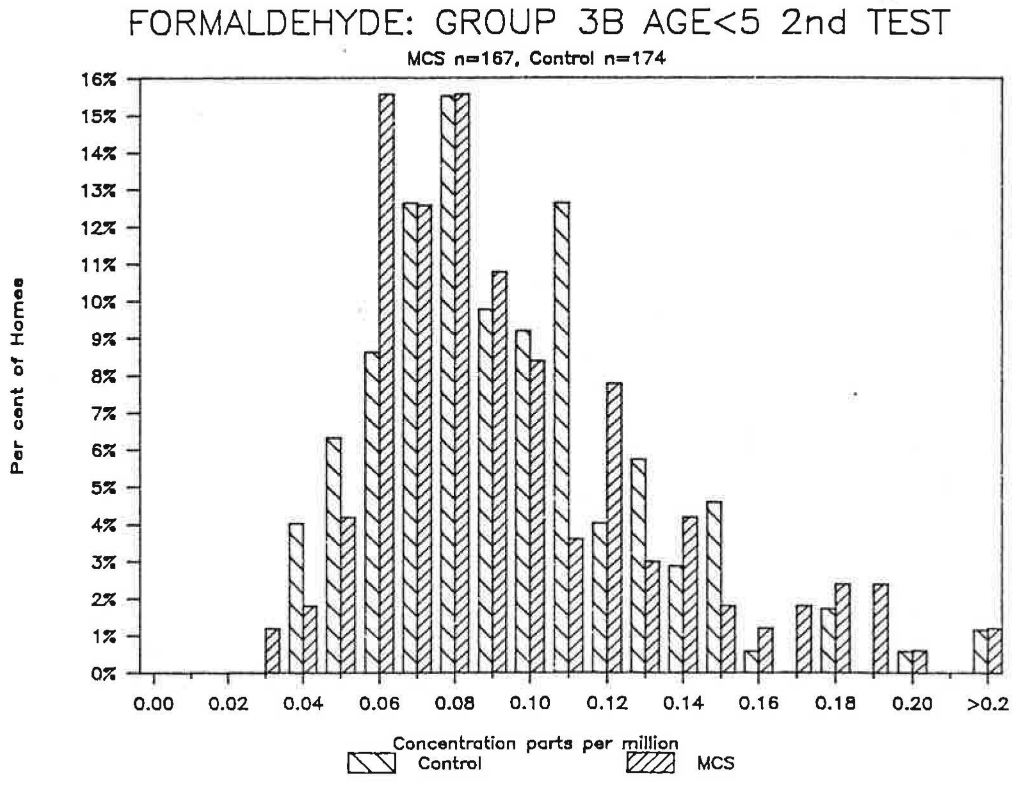


FIGURE 9


FORMALDEHYDE: GROUP 3A AGE<5 FIRST TEST

MCS n=167, Control n=174

FIGURE 10


FORMALDEHYDE: GROUP 3B AGE<5 2nd TEST

MCS n=167, Control n=174

FIGURE 11

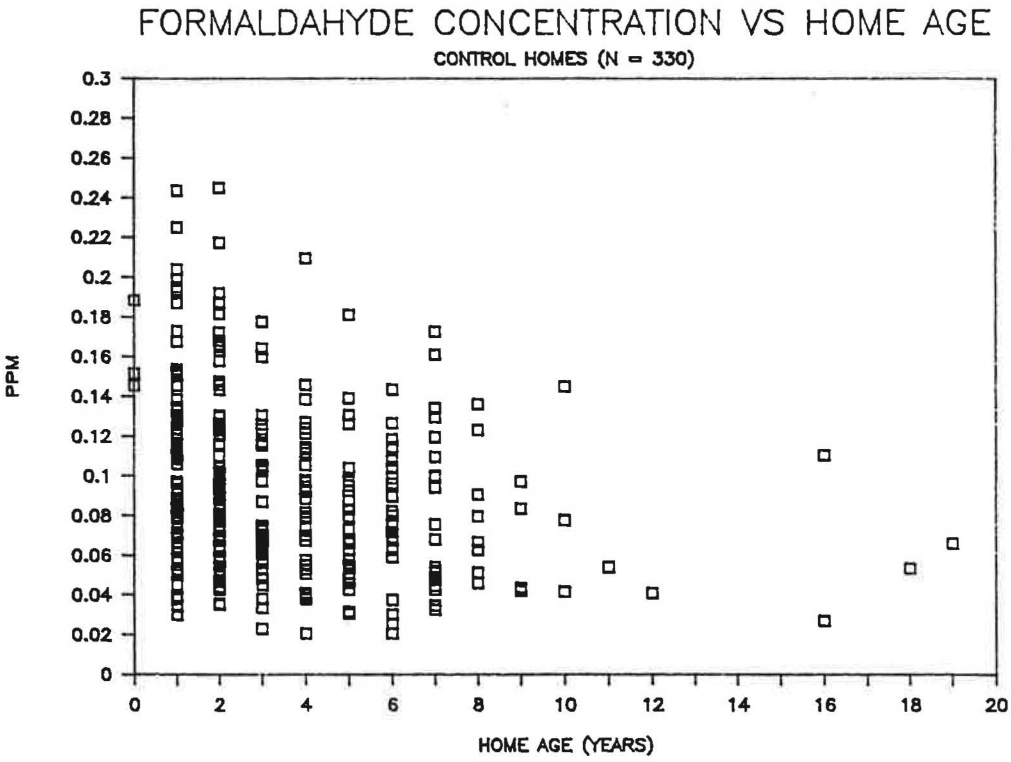


FIGURE 12

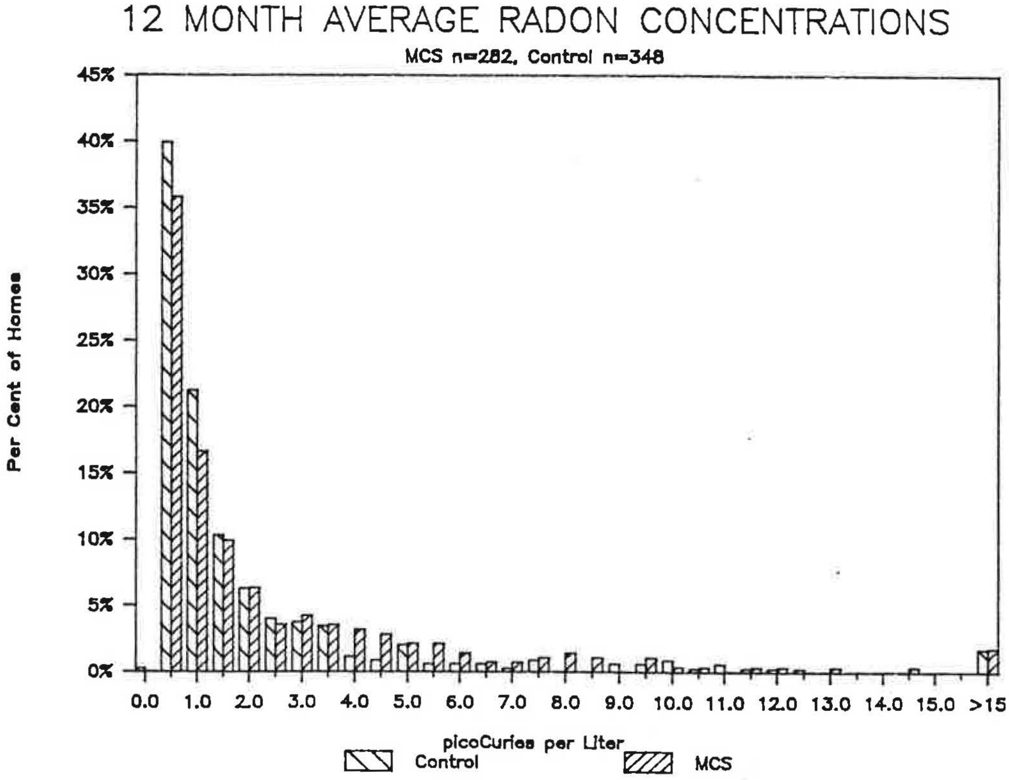
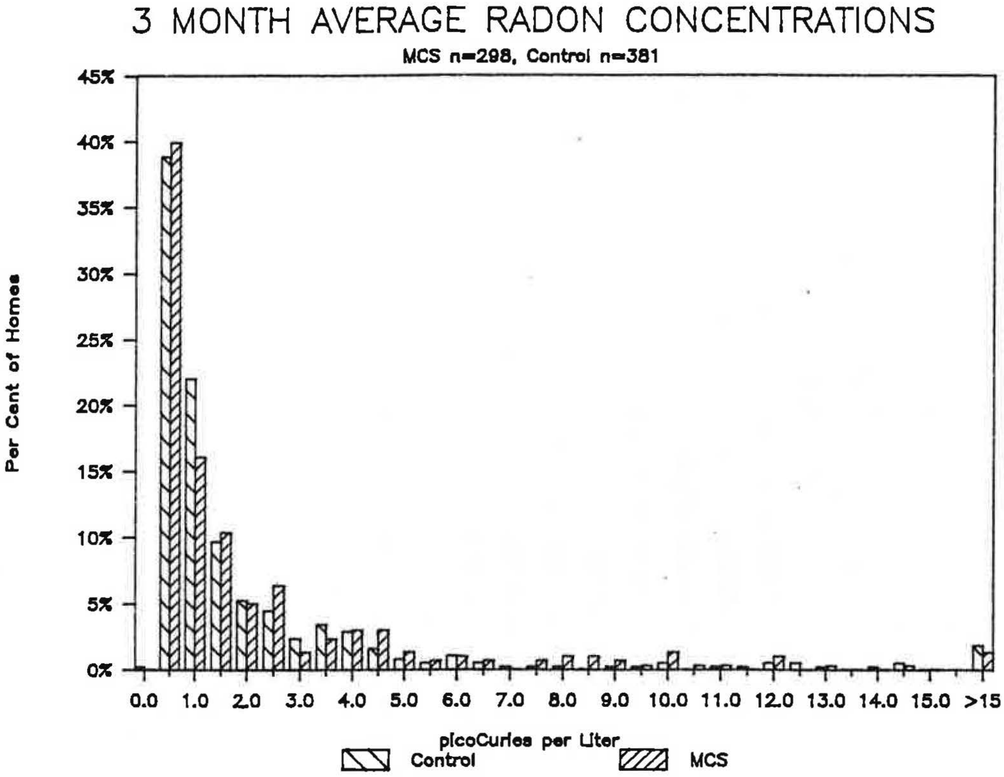


FIGURE 13


3 MONTH AVERAGE RADON CONCENTRATIONS
MCS n=298, Control n=381
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Per Cent of Homes
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
>15
picoCuries per Liter
Control
MCS