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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

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Results of air quality measurements are presented for a group of low-leakage houses located in Saskatoon, Saskatchewan. Houses were tested for formaldehyde, nitrogen dioxide, radon, and humidity levels.

The median level of formaldehyde was 0.09 ppm, slightly lower than the guideline of 0.1 ppm. Elevated levels of formaldehyde (>0.1 ppm) were found in 18 of 46 houses. The median level of radon was 3.0 picocuries/litre, slightly lower than the guideline of 4 pCi/L. Elevated levels of radon (>4 pCi/L) were found in 12 out of 44 houses. The median level of nitrogen dioxide was 4.6 ppb, considerably lower than the guideline of 50 ppb. No houses were found with elevated nitrogen dioxide levels (>50 ppb). Those houses lacking a mechanical ventilation system had considerably higher incidences of elevated formaldehyde concentrations than those incorporating mechanical ventilation.

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Introduction

In recent years, a large number of houses have been constructed in the Canadian prairie region that have been sealed to a considerably higher degree than conventional housing. A 1981 report by Dumont and Orr[1] includes pressure test values for a group of 40 houses that were specially sealed. On average, these houses had equivalent leakage area values that were 53% of those in conventional houses. (See Table I).

As part of an ongoing research project, testing was done on the levels of selected pollutants in a group of these low-leakage houses. None of these were insulated with urea formaldehyde foam insulation (UFFI).

A number of guidelines exist for air pollutant levels. A frequently quoted standard is the document "Ventilation for Acceptable Air Quality" produced by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE).[2] Values for formaldehye, radon daughters, and nitrogen dioxide are presented in Table II.

In 1982 a preliminary air quality survey of 51 houses in the Saskatoon area was undertaken to determine levels of formaldehyde and radon daughters. The survey included houses of varying ages and airtightness levels.

As shown in Figure 1, a number of the houses exhibited higher levels of formaldehyde gas. Using the ASHRAE criterion of 0.1 ppm, 8 of the 51 Saskatoon houses had elevated formaldehyde gas levels. Of particular interest in this initial survey was the relationship between formaldehyde levels and the airtightness of the structure. Figure 2 presents the relationship between formaldehyde levels and the pressure test reading for each house. It shows that those houses with higher formaldehyde readings were generally among the more airtight of the sample. (It should be noted that the airtightness of the structure is not a direct measure of the air change rate, as many of the more airtight houses have controlled ventilation systems. These systems can substantially increase the amount of ventilation compared to natural ventilation from stack and wind effects.)

In the 1982 survey, radon daughter levels were also measured using the Terradex Track-Etch Detector. The results are presented in Figure 3. Using the ASHRAE level of 0.01 working levels as a cut off, 17 of 43 houses* had elevated radon daughter levels. A plot of the radon daughter levels as a function of the pressure test readings for the houses is presented in Figure 4.

1983 Study of Saskatoon Houses

As a follow-up to the 1982 study, a survey of formaldehyde, nitrogen dioxide and radon gas levels was conducted in 1983 in a sample of 46 houses in Saskatoon. The houses had all been built since 1978, and were chosen because they had a pressure test reading of less than 2.5 air changes per

*Due to equipment failure, not all of the tests were successfully completed. In this case, although 46 tests were conducted, only 43 were successful. Throughout this paper, reference is made only to successful tests.

hour (ac/h) at 50 Pa. The average pressure test reading for the 46 houses was 1.33 ac/h at 50 Pa. This is considerably tighter than the value of 3.6 ac/h at 50 Pa which was reported[1] as an average for conventional houses built during the period 1960-1980 in Saskatoon. The houses were of wood-frame construction and the majority had concrete cast-in-place basements.

For steady state conditions, the concentration of a pollutant within a well-mixed space may be expressed as:

$$C_s = C_o + \dot{N}/\dot{V}$$

where C_s = concentration of pollutant within the space (mass/volume)
C_o = concentration of pollutant at the source of the ventilation air, i.e., outside air (mass/volume)
$\dot{N}$ = net pollutant generation rate within the space (mass/time)
$\dot{V}$ = volume rate of air exchange (volume/time).

A high concentration of pollutant within the space may occur under any or all of three conditions:

- high outdoor concentration (C_o)
- high pollution generation rate ($\dot{N}$)
- low ventilation rate ($\dot{V}$).

Test Procedure for Air Quality Measurements in the 1983 Study

Formaldehyde

Formaldehyde tests were made in the houses using Dupont Pro-tek passive badges. Two badges, each of which was exposed for a one-week period, were placed in the living areas (generally the dining or living rooms) of each house. The badges were analyzed in a laboratory in Toronto. The measurements were taken from January 3 to January 21, 1983. During this time, the average outdoor temperature was -11°C, and the average wind speed was 13 km/h. A table presenting the test results in detail is contained in an earlier paper by Dumont.[3]

Radon Gas Tests

Radon gas level tests in the houses were made using Terradex Track-Etch passive detectors. The particular detector chosen has a filter which minimizes the contact of dust particles with the detector; hence only the radon gas and not the radon daughter concentration is measured. Measurements were made from January to April 1983.

Appendix A presents a discussion on the consistency of the formaldehyde and radon sensor readings.

Nitrogen Dioxide Tests

Nitrogen dioxide tests, one per house, were made during a week in early January using a passive detector. The test badges were processed by Health and Welfare Canada. In addition to these three tests, data were gathered for each house, as follows:

1. Pressure test result at a pressure difference of 50 Pa
2. Type of heating system
3. Type of ventilation system used
   a. None
   b. Fresh air duct into plenum
   c. Air-to-air heat exchanger
4. Type of air-to-air heat exchanger
5. Number of occupants during day and night periods
6. Inside temperature and relative humidity during formaldehyde tests
7. Area of particle board
8. Number of wood heating appliances (wood stoves or fireplaces)
9. Number of cigarette or cigar smokers.

Test Results

The formaldehyde levels for each house are presented in Figure 5. The values shown are the average of the two readings taken. The median value for the 46 house sample was 0.09 ppm, with 18 houses having values greater than 0.1 ppm. A plot of formaldehyde levels as a function of indoor relative humidity is shown in Figure 6. A plot of the formaldehyde levels as a function of the amount of particle board in each house is shown in Figure 7.

The results of the radon gas tests are shown in Figure 8. Of the 44 houses successfully tested, 12 houses had radon gas levels that exceeded 4 picocuries per litre, which is the USEPA remedial criterion. The median value for these 44 houses was 3.0 picocuries per litre.

The results of the nitrogen dioxide tests are shown in Figure 9. The median level for the 46 houses was 4.6 ppb. The houses were divided into four categories, depending on the presence or absence of wood appliances and smokers. The results were as follows:

Category	NO_2 (ppb)	Number of Houses
No wood appliances, no smokers	3.5	12
No wood appliances, smokers	5.3	4
Wood appliances, no smokers	5.1	21
Wood appliances, smokers	5.6	9

Discussion

Formaldehyde

The median formaldehyde level was 0.09 ppm, with values ranging between 0.033 and 0.24 ppm. The houses with higher formaldehyde readings tended to have higher relative humidities. Of the 8 houses with relative humidity (RH) values less than 30%, none had formaldehyde readings greater than 0.1 ppm. Of the 6 houses with RH values greater than 40%, 2 had formaldehyde readings greater than 0.1 ppm. A plot of the relationship between formaldehyde and interior relative humidity is shown in Figure 6. Assuming constant moisture generation rates in the various houses (on an equivalent volume basis), low relative humidity values are a result of higher air change rates. Thus the relationship between formaldehyde and relative humidity is not unexpected. There is a secondary effect, since the formaldehyde offgassing rate is known to increase with higher humidities.

Higher formaldehyde readings were also associated with the houses that did not have a mechanical ventilation system. Fifty percent of the houses with no mechanical ventilation system showed formaldehyde levels greater than 0.1 ppm. Only 27% of those that had mechanical ventilation showed levels greater than 0.1 ppm.

As part of the survey, measurements were made of the area of particle board contained within each house. The range of particle board areas varied from 0 to 311 m^2. In addition, there were other formaldehyde-emitting sources within the houses (some carpets, permanent press fabrics, hardwood plywoods) that were not quantified. As shown in Figure 7, there was weak positive correlation (correlation coefficient = 0.36) between the formaldehyde level and the amount of particle board in the houses. Observations or measurements were not made on other factors, such as the age and brand of the particle board, the type of covering on the particle board, tobacco smoke and other sources of formaldehyde.

A house can have a low formaldehyde reading by having either a low volume of formaldehyde-emitting sources or a high air change rate. Due to unavailability of equipment, air change measurements were not made during the period the formaldehyde readings were taken. It is possible to estimate the air change rate of those houses that did not have forced ventilation systems by using the pressure test data. Shaw[4] presented a correlation between the air change rate and the pressure test data, wind speed and outside air temperature. The correlation equation when the wind speed is greater than 3.5 m/s and the temperature difference is greater than 25 K, is as follows:

$$I = 4.53 \frac{C}{V}$$

where I = air change rate (h^{-1})
C = constant from pressure test ($L/(s\text{-}Pa^n)$)
V = volume of house (m^3).

Values for C, V, and I for the houses in the survey lacking forced ventilation systems are presented in Table III. As may be seen from the table, the calculated average infiltration rate for these houses was 0.21 air changes/h, and the corresponding average formaldehyde level was 0.106 ppm.

Radon

The median radon level for the houses was 3.0 picocuries per litre, with the values ranging between 0.82 and 9.44 pCi/L. The readings were all taken in the lowest levels of the houses, which were generally not occupied.

A number of houses in the study (12 out of 43) had radon gas concentrations exceeding 4 picocuries per litre. A possible source of the radon was the soil underlying the concrete floor. Work was carried out to determine the radon concentration in the floor drains, which are connected directly to the weeping tile in these houses. In addition, the effect of blocking the floor drain to limit radon gas entry into the basement was investigated.

The results of measurements of the radon concentration in the floor drain and in the basement air are presented in Table IV for a group of 7 houses. The radon gas measurements were taken using the Terradex Track-Etch detectors.

As may be seen from the table, the radon concentrations in the floor drains were very high, ranging from 52.1 to 413.3 pCi/L, with an average of 179 pCi/L. In each of the houses tested, the weeping tile was connected directly to the floor drain. Consequently the radon can migrate freely from the soil through the weeping tile and into it. If the floor drain is capped to prevent air flow from the floor drain into the basement, a substantial reduction in radon concentrations in the basement air would be expected. To determine if this reduction would in fact occur, tests were performed on 10 houses. The results of this remedial measure are presented in Table V.

As may be seen from Table V, in 8 of the 10 houses, the radon concentrations dropped. There was on average a reduction of 46% in the radon concentrations in the basement air after the floor drains had been sealed.

One major difference between the two sets of measurements was that the 1983 measurements were taken in the period from January to April, and the 1984 measurements were taken in the period from June to August. As the houses all had controlled ventilation systems which were intermittently operated, it is difficult to make firm conclusions as to whether the air change rates in the houses had increased or decreased from the first period to the second. In houses lacking forced ventilation systems, the air change rate in the summer is usually smaller, assuming that the windows are closed. This reduced air change occurs because the stack effect due to temperature difference between inside and outside is lower.

A followup study would be of interest to confirm that the perforated floor drain cap is a major radon entry path in those basements with the weeping tile connected directly to the floor drain.

Nitrogen Dioxide

The median value for the NO_2 readings was 4.6 ppb, with values ranging between 0.7 and 13.3 ppb, well below the ASHRAE guideline of 50 ppb. Three of the four houses with readings above 10ppb had either wood stoves or fireplaces. The fourth house, with a reading above 10 ppb, had 2 smokers with cigarette consumption levels of 1 pack (20 cigarettes) each per day. The houses with no wood appliances and no smokers averaged 3.5 ppb, and those with both wood appliances and smokers averaged 5.6 ppb.

Ventilation Systems

In this study three types of ventilation systems were used in the houses:

	%	No. of houses
a. no mechanical ventilation	10.9	5
b. fresh air duct into return air plenum of forced air furnace	23.9	11
c. air-to-air heat exchanger	65.2	30

As mentioned earlier in the paper, those houses lacking an air-to-air heat exchanger system had a considerably higher incidence of elevated formaldehyde readings than those houses with an air-to-air heat exchanger. Based on these data, it would appear that continuous mechanical ventilation would help to reduce air pollution levels.

Recommendations

The results of this study indicate a number of areas for further work:

1. Future studies of this type should include direct measurements of the air change rates in the houses using tracer gas or other appropriate means.
2. Remedial work on those houses exhibiting levels of pollutants higher than the standards should be undertaken.
3. Investigations should be undertaken to determine the source of the radon gas. An area that is likely to be a strong source is the floor drain, through which radon can leak into the house from the soil via the weeping tile system, particularly when it is connected to the drain above the trap.
4. Further work should be done on identifying formaldehyde sources in houses and in determining their strength.

Appendix A Consistency of the Radon and Formaldehyde Sensors

During the air quality measurements, a number of cross-checks were made with the radon and formaldehyde sensors, primarily to ensure that the companies supplying the sensors and doing the analyses were providing consistent readings.

Radon

During the course of the experiment, groups of 5 sensors were placed side-by-side in two locations. The first location for the side-by-side check was in a crawl space area that was known to have elevated radon levels. The results for the five sensors, all of which were placed side by side, were as follows, when read at the 1.0 pCi/L-month sensitivity level.

Sensor No.	Radon reading (pCi/L)
D91	5.48
D92	5.73
D93	6.43
D94	4.90
D95	5.40
average =	5.59
standard deviation =	0.56

A second check, again using 5 sensors placed side by side, was performed in a well-ventilated laboratory. The results for this comparison are shown below:

Sensor No.	Radon reading (pCi/L)
D96	0.27
D97	0.14
D98	0.22
D99	0.12
D100	0.17
	average = 0.18
	standard deviation = 0.06

Formaldehyde

A side-by-side check was performed on the DuPont sensors. A total of 4 sensors were placed side by side in one house for a one week period. The readings were as follows:

Sensor No.	Formaldehyde level (ppm)
1	0.071
2	0.076
3	0.078
4	0.088
	average = 0.078
	standard deviation = 0.007

References

1. Dumont, R.S. and Orr, H.W., "Airtightness Measurements of Detached Houses in the Saskatoon Area," National Research Council Canada, Division of Building Research, Building Research Note 178, Ottawa, 1981.

2. ASHRAE, "Ventilation for Acceptable Indoor Air Quality" Standard 62-1981, 1791 Tullie Circle N.E., Atlanta, Georgia, 30329, U.S.A., 1981.

3. Dumont, R.S., "Air Quality Measurements in Low-Leakage Houses," National Research Council Canada, Division of Building Research, Building Research Note 218, Ottawa, 1984.

4. Shaw, C.Y., "A Correlation between Air Infiltration and Air Tightness for Houses in a Developed Residential Area," ASHRAE Transactions, Vol. 87, Pt. 2, 1981.

Table I. Comparison of air leakage characteristics for groups of Saskatoon houses

Type	Leakage area m^2	ac/h at 50 Pa	Number of houses
Pre-1945	0.1078	10.35	19
1946-1960	0.0709	4.55	20
1961-1980	0.0621	3.57	97
Special air-tight houses (1977-1980)	0.0330	1.49	40

Table II. Guidelines for generally acceptable levels of selected air contaminants

Contaminant	Level	Reference
Formaldehyde	0.12 mg/m^3 0.1 ppm at 25°C, 101.3 kPa	ASHRAE 62-1981
Radon	4 pCi/L	USEPA
Radon daughters	0.01 working levels	ASHRAE 62-1981
Nitrogen dioxide	100 ug/m^3 50 ppb at 25°C, 101.3 kPa	USEPA

Table III. Calculated air change rates for houses lacking forced ventilation

House Code	C $m^3/(s\text{-}Pa^n)$	n	V (m^3)	I ac/h	Formaldehyde ppm 2 wk average
B12	0.0327	0.668	832	0.178	0.1675
B11	0.0295	0.651	630.2	0.212	0.062
B13	0.0211	0.666	419	0.228	0.0905
FF5	0.0208	0.785	711.8	0.132	0.0415
E4	0.0498	0.543	704	0.320	0.139
F8	0.0341	0.617	490.5	0.314	0.1905
F9	0.0142	0.769	612	0.105	0.0835
F1	0.0273	0.698	733.6	0.168	0.136
L11	0.0238	0.771	552	0.195	0.1015
G3	0.023	0.665	618	0.168	0.0455
M9	0.0235	0.754	657	0.162	0.135
P2	0.0164	0.759	835.1	0.088	0.1605
P4	0.0199	0.792	607	0.148	0.12
S8	0.0461	0.518	428	0.487	0.0735
FF6	0.0351	0.693	758.3	0.209	0.0455
Average	0.02782	0.689	639.2	0.208	0.106

Table IV. Radon gas measurements in the floor drains and in the basement air of 7 houses

House No.	Radon concentration in floor drain (pCi/L)	Radon concentration in basement air (pCi/L)	Ratio drain/basement
1	169.3	2.51	67.5
2	98.4	2.24	43.9
3	91.4	1.43	63.9
4	413.3	1.87	221
5	255.4	3.95	64.7
6	173.4	3.02	57.4
7	52.1	9.63	5.4
Average	179.0	3.52	

Table V. Pre- and post-retrofit measurements of radon gas concentrations in Saskatoon houses

House code	Pre-retrofit 1983 (pCi/L)	Post-retrofit 1984 (pCi/L)	Ratio 1984/1983
D3	3.56	0.92	0.258
B3	6.81	3.4	0.499
Y1	5.2	1.2	0.231
L11	1.88	0.88	0.468
G7	2.17	0.51	0.235
B10	9.44	5.35	0.567
B15	3.67	2.86	0.779
C8	1.36	1.15	0.846
H7	0.82	1.3	1.59
P5	2.26	2.46	1.09
Averages	3.71	2.00	0.54

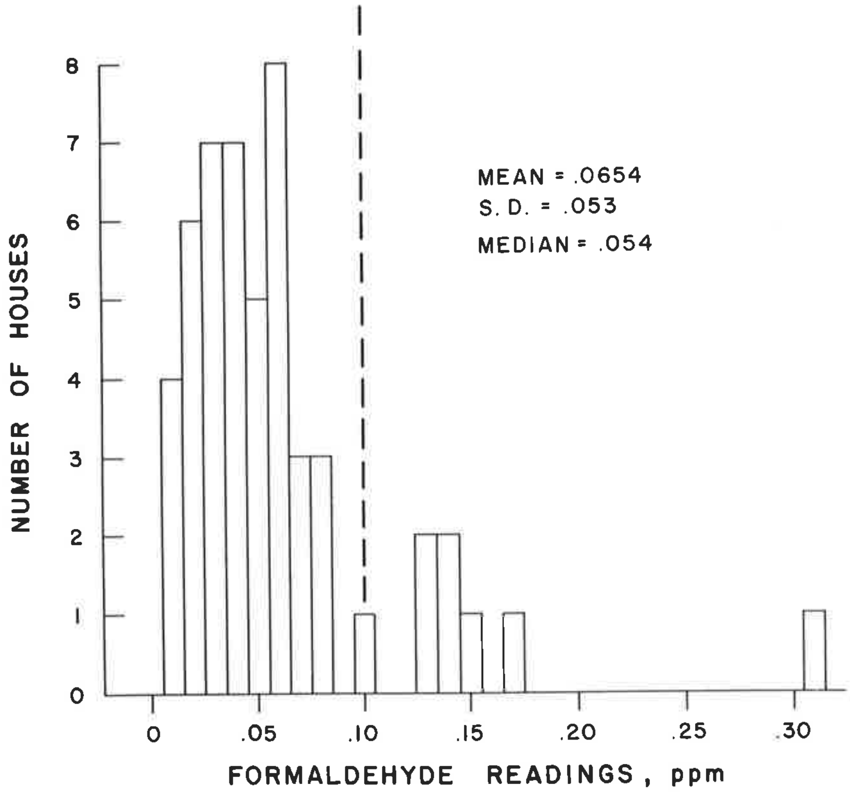

Figure 1. Formaldehyde readings, 1982 study.

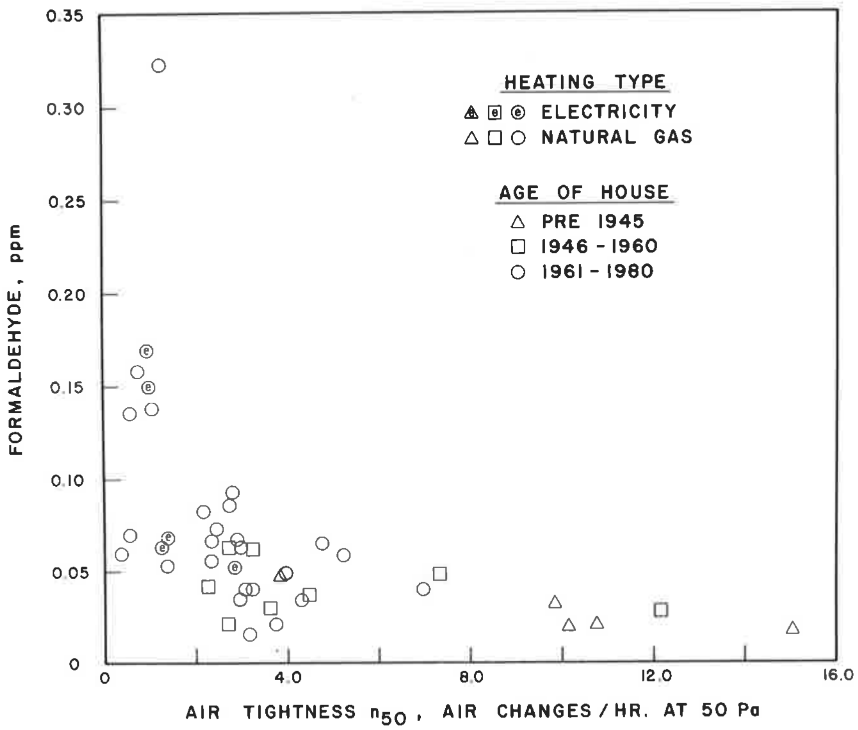

Figure 2. Formaldehyde readings as a function of air tightness, 1982 study.

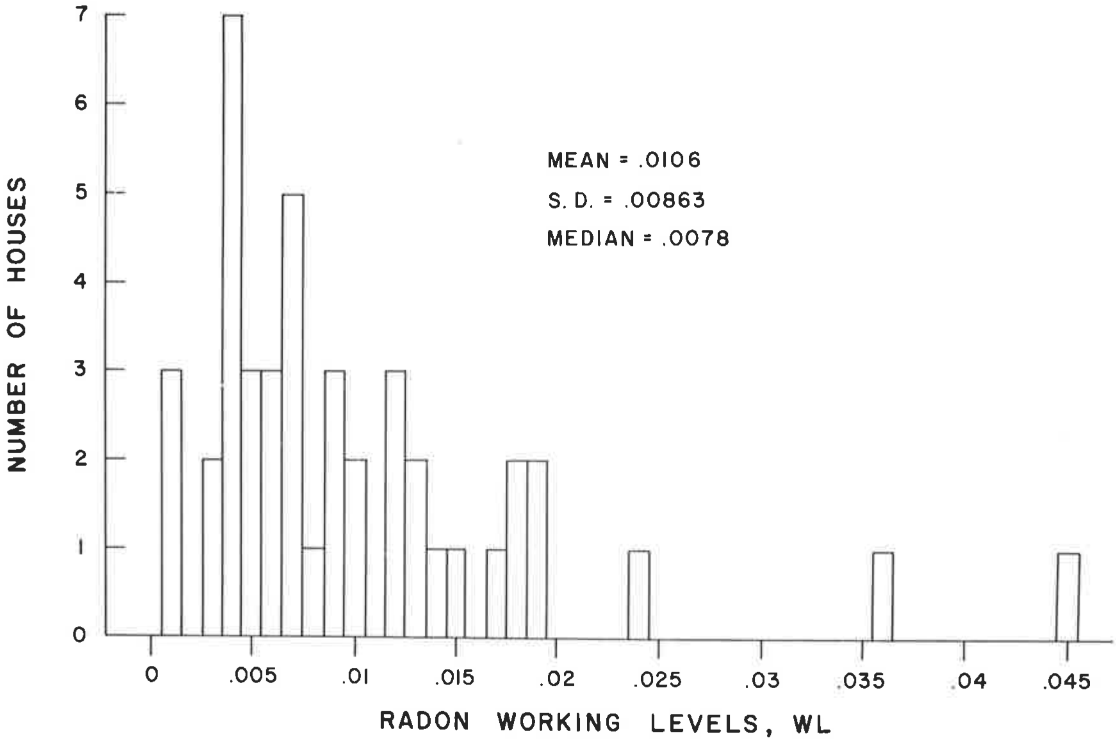

Figure 3. Radon readings, 1982 study.

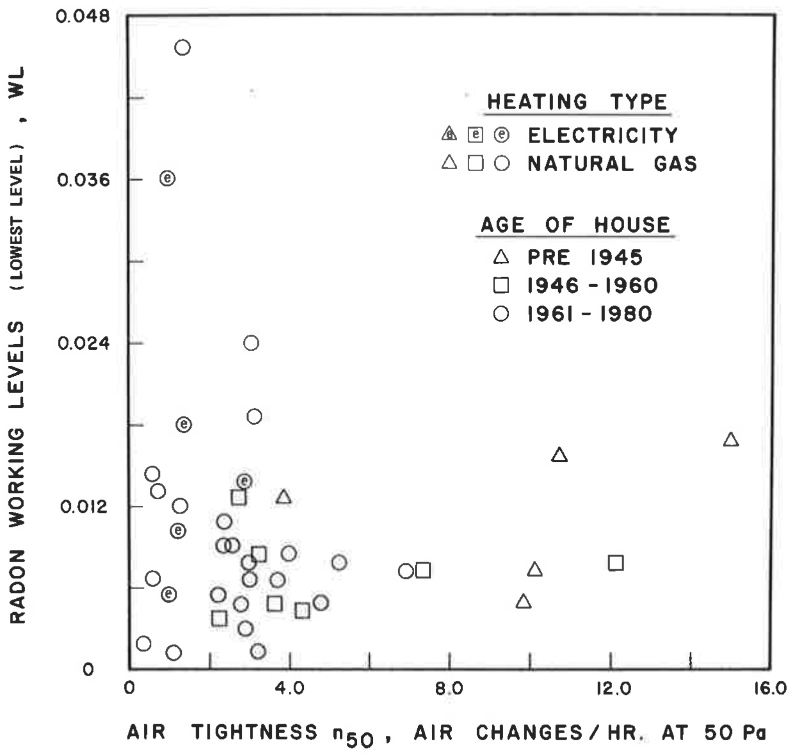

Figure 4. Radon readings as a function of air tightness, 1982 study.

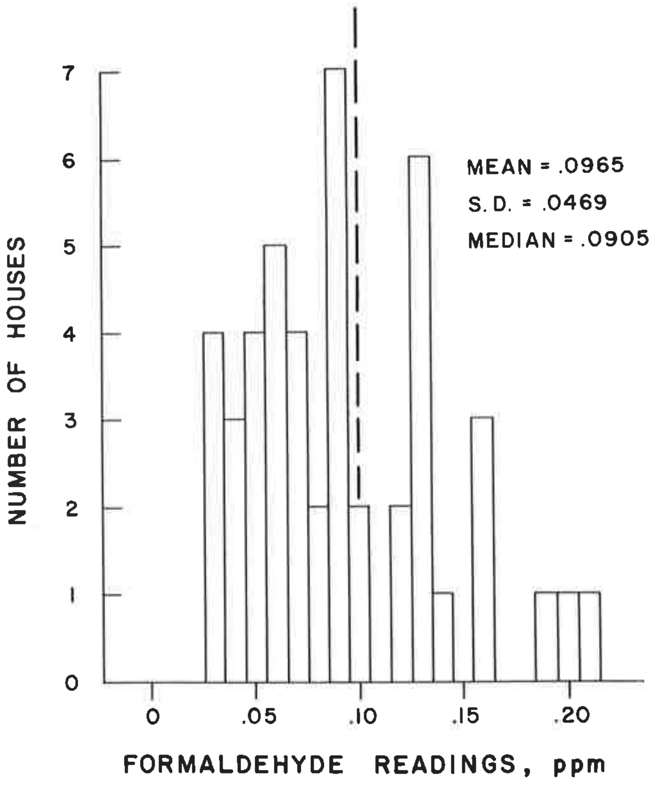

Figure 5. Formaldehyde readings, 1983 study.

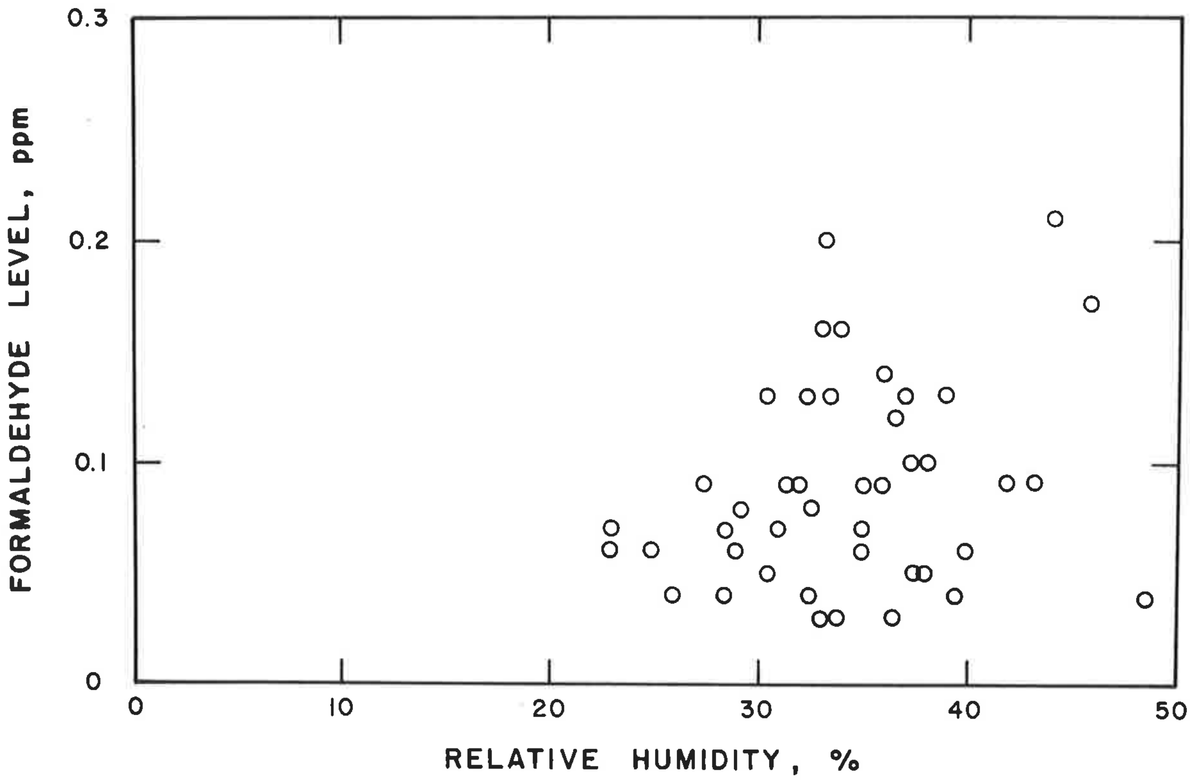

Figure 6. Formaldehyde readings as a function of indoor relative humidity, 1983 study.

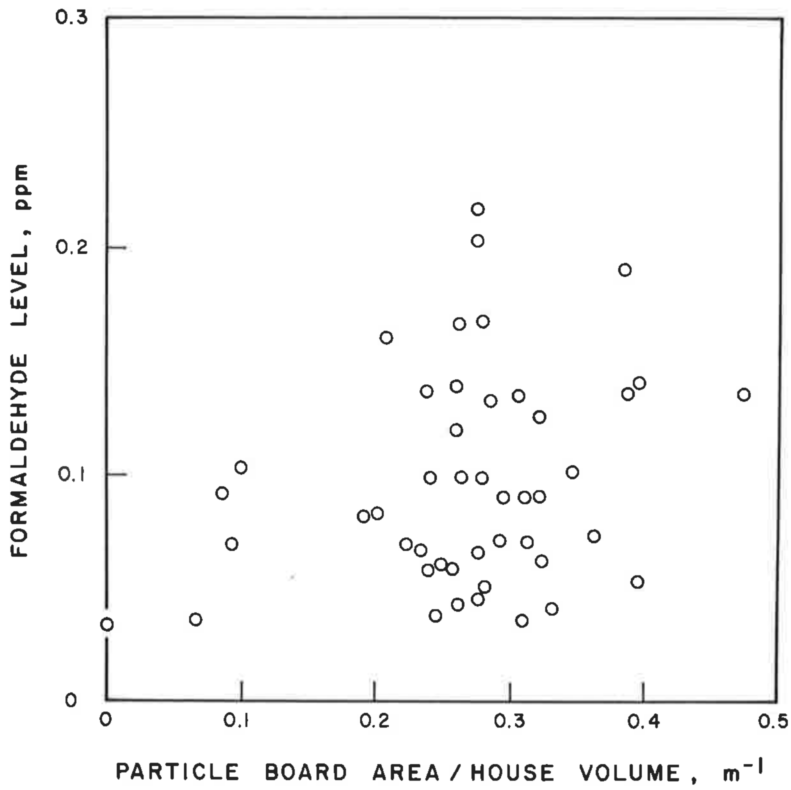

Figure 7. Formaldehyde readings as a function of the amount of particle board, 1983 study.

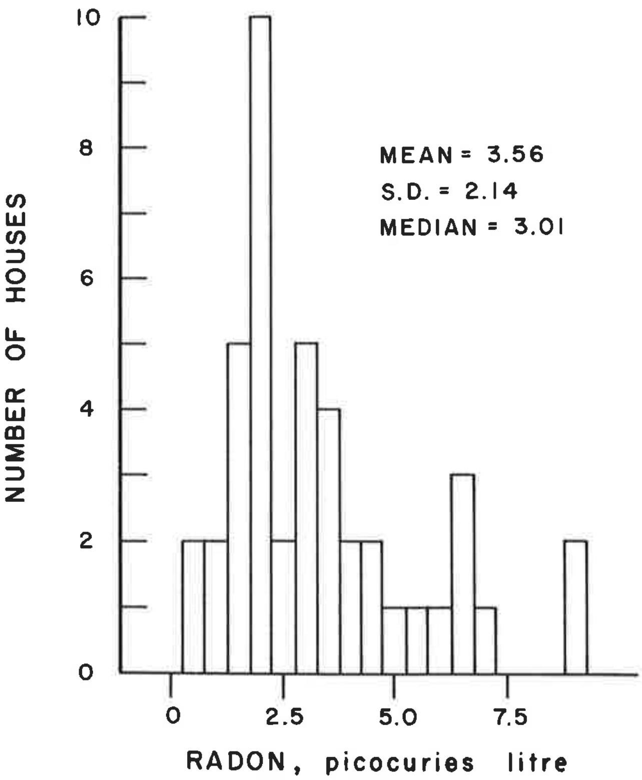

Figure 8. Radon readings, 1983 study.

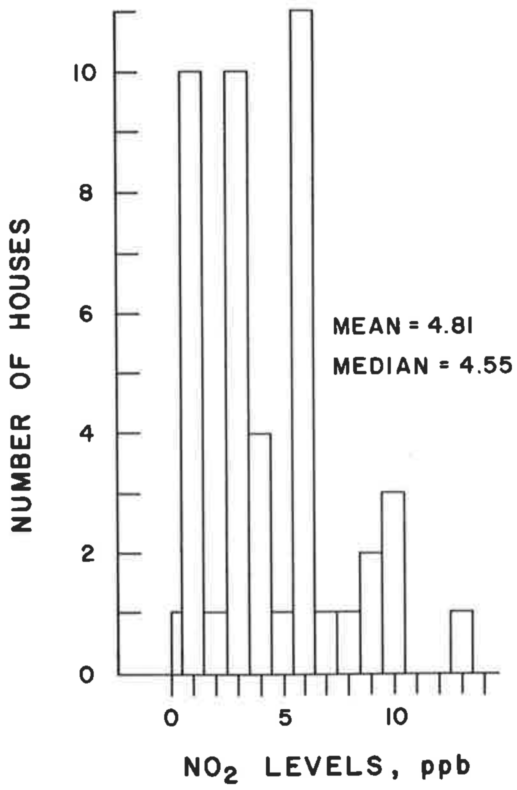

Figure 9. Nitrogen dioxide readings, 1983 study.

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