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INVESTIGATION OF THE INDOOR AIR QUALITY, AIRTIGHTNESS, AND AIR INFILTRATION RATES OF A RANDOM SAMPLE OF 78 HOUSES IN WINNIPEG

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ABSTRACT

An investigation of the indoor air quality, airtightness, and air infiltration rates of 78 randomly selected houses in Winnipeg was conducted in the summer of 1987. Physical characteristics of each house were also recorded along with information on occupant behavior and attitude toward indoor air quality. Approximately 750 observations were made on each house.

The objective of the project was to obtain results that were representative of the Winnipeg housing stock. Therefore, a three-level sampling procedure was adopted, and every effort was made in gaining access to the houses selected by this procedure.

Indoor air quality was determined by measuring the pollutant levels at three locations in the home. The pollutants measured were carbon dioxide, carbon monoxide, formaldehyde, radon, ozone, and respirable suspended particulates. Airtightness was measured by the fan depressurization method; air infiltration was measured using the grab sample, tracer gas decay technique.

Indoor air quality was related to usage of exhaust fans in the home. Each fan was described in detail, recording its frequency of use, and measuring its sound pressure level.

INTRODUCTION

In recent years it has been realized that our greatest exposure to pollution is not outdoors, but in our homes and workplaces, where we spend the majority of our time. However, the magnitude of the problem has not yet been clearly defined. We do not know the health effects of most pollutants with certainty, nor do we know their concentration distributions. The purpose of this study was to learn more about the latter.

Among the factors that influence pollutant concentration in a house are its location and its physical characteristics including age, style, volume, envelope area, and detailed information about the heating, ventilating, and air-conditioning equipment. To study the influence of all these parameters will require that a large variety of houses be studied. Using a large enough random sample of housing should provide this variety and also provide results that are representative of the housing stock in the region sampled. Of course, in obtaining a sample of this nature, self-selection should be avoided since homeowners who are concerned about their indoor air quality or have noticeable indoor air quality problems would be the first to participate.

While the physical characteristics of the home may affect the indoor air quality, occupant behavior is also an important factor. For example, ventilation fans can help to maintain indoor air quality, but are frequently not used because homeowners object to the noise. Other examples of practices that may affect indoor air quality are the frequency with which windows are opened and closed, and hobbies such as wine making, painting, and ceramics.

This paper summarizes the results from an indoor air quality study of 78 randomly selected houses in Winnipeg. Indoor air quality, which was determined by directly measuring the various pollutant levels, was related to airtightness, air exchange rate, and occupant behavior. Noise levels of exhaust fans were measured and related to their frequency of use.

HOUSE SELECTION AND LEVEL OF RESPONSE

The objective of the house selection procedure was to ensure that the houses studied were representative of the Winnipeg housing stock. A three-level sampling procedure was used. First, 13 census tracts were selected at random from the 127 census tracts in the city of Winnipeg. Then a list of all the streets in each census tract was made, and three streets were selected at random. From each street, two houses were then selected at random.

To eliminate bias from a sample of households, it is necessary to eliminate self-selection. The selection technique used in the present study would eliminate self-selection if all householders selected by the random sampling technique agreed to participate. Every effort was made to come as close as possible to the objective of gaining access to houses selected by the random sampling technique.

A considerable amount of time was spent soliciting homeowners of the houses selected. To keep this time to a minimum, houses with no occupants at home when called upon were excluded from the study, provided that all calls were made in the evening. This time was chosen so that there would be no bias toward families where adult members are not at home during the day. When a call was made on a selected house and no one was home, it was replaced with the one next door having a higher street number than the one originally selected. While this procedure may have influenced the objective of random sampling, it was consistent throughout the entire study and always resulted in the selection of houses similar in age and appearance to the ones originally selected at random.

Every effort was made to ensure that the householders who were at home when called upon would agree to participate in the study. This was done by preparing a preliminary letter that was sent out to each householder before he/she was called on, arranging media publicity about the survey, arranging for the local Conservation and Renewable Energy Office of Energy, Mines and Resources Canada to act as a reference for the legitimacy of the project, and choosing personable and aggressive people to make the call on the householders.

This approach resulted in an overall acceptance rate of 56% (percentage of affirmative responses from houses originally selected). Close to 100% acceptance was frequently achieved in the higher-income census tracts, while on one street in a low-income area, the acceptance rate fell to about 4%. About one-third of these householders would not even answer their doors, and the majority of the rest simply slammed the door as soon as they realized the caller was not someone known to them. Thus, there was no possibility of achieving a high acceptance rate on this street or on some others where attitudes were similar.

Figure 1 shows the fraction of houses which were either the original house selected or the first house where occupants were home, starting from the originally selected house, to which access was gained. Figure 2 shows the overall success rate for each district. The response level is the number of houses tested divided by the number of houses contacted. Houses where occupants were not at home were not considered as negative responses.

To substantiate whether or not the selected houses were representative of the houses in each census district, Statistics Canada data on house age, number of occupants, and number of rooms were obtained. As would be expected in a randomly selected sample, the average age, number of rooms, and number of occupants for the houses of each census district was generally similar to the corresponding Statistics Canada data. The average age of all houses studied was 42 years; the average age of housing in the 13 census tracts based on Statistics Canada data was 41 years. Similarly, the average number of rooms in the houses studied was 6.9 as compared with 6.2 from the Statistics Canada data. The average number of occupants in the homes studied was 3.0; based on Statistics Canada data, the average number of occupants was 2.9.

TEST METHODOLOGY

Indoor air quality, air infiltration, airtightness, and exhaust fan noise level measurements were made in each house. Also, homeowner survey and technical survey report forms were completed to physically describe the house and to determine other information such as homeowner attitude toward indoor air quality, number of occupants, time that each occupant spends in the home, and practices within or outside the home that may affect the indoor air quality. The total time required to test each house was approximately 3.5 hours, and involved two visits. This amount of time was tolerated by most homeowners and was sufficient for gathering all of the relevant data.

Pollutant measurements were made to substantiate the indoor air quality in each house. Included in these measurements were carbon dioxide, carbon monoxide, radon, formaldehyde, respirable suspended particulates, and ozone. Air infiltration was measured using the tracer gas decay technique. Airtightness was measured using the blower door depressurization method.

Air Quality Measurements

Carbon Dioxide. The carbon dioxide (CO_2) concentration was measured at three locations in each house with a portable CO_2 monitor. These measurements were made immediately after the survey team arrived at the house to be tested. Thus, the carbon dioxide concentrations were measured before the presence of the survey team had any effect on the results. Because visits were made at various times of the day, at the householders' convenience, the carbon dioxide measurements were not necessarily representative of the levels attained by just the presence of the house occupants at the times of measurement. In some cases, one or more occupants of the house left for work or school just before the arrival of the survey team.

Carbon Monoxide. Carbon monoxide (CO) concentrations were measured with a CO instrument. The device could only measure carbon monoxide levels to the nearest part per million (ppm). Since carbon monoxide levels are generally low in residential housing, measurements made with this device only indicated the presence of carbon monoxide, and not precise levels that are required for comparison purposes.

Radon. Radon levels in the surveyed houses were measured by two methods. Instantaneous measurements in working levels (measurement of radon progeny) were made at three locations in each house using membrane filtration. Radon was also measured by placing a week-long passive sampler in the basement.

The membrane filtration technique involved the drawing of 30 liters of air through a .8 mm membrane filter. A sampler operating at 3 liters per minute for 10 minutes was used to perform this task. Counts from the filters were measured in the scintillation cell of a radon detector. Measured count rate, counting efficiency, sample volume, and an appropriate Kusnetz factor (a function of the time between testing and analysis) were used in the calculation of working levels.

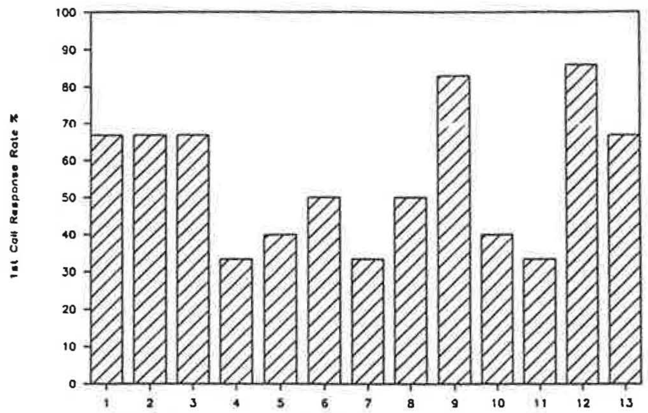

Figure 1 *Percentage of houses that were either 1) the house originally selected or 2) the first house in which occupants were home starting from the originally selected house to which access was gained*

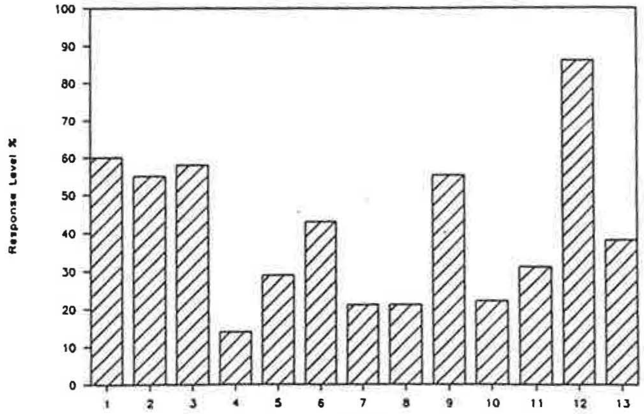

Figure 2 *Average number of houses called upon per house to which access was gained*

TABLE 1

Summary of Air Quality Measurements

	Average Concentration	Maximum	Minimum	Standard Deviation	Number of Measurements
Living Room					
CO (ppm)	0.7	4.0	0.0	1.0	76
CO_2 (ppm)	885	3100	350	431	76
RSP's (mg/m^3)	0.05	0.2	0.0	0.071	55
HCOH (ppm)	0.090	0.261	0.000	0.068	50
Rn (WL)	0.007	0.047	0.000	0.010	71
O_3 (ppb)	0.3	6.0	0.0	1.0	55
Basement					
CO (ppm)	0.7	4.0	0.0	0.9	69
CO_2 (ppm)	762	3000	330	374	68
HCOH (ppm)	0.088	0.235	0.000	0.064	45
Rn (WL)	0.012	0.062	0.000	0.014	71
Rn (pCi/L)	4.5	16.1	0.8	3.4	70
Bedroom					
CO (ppm)	0.4	3.0	0.0	0.7	73
CO_2 (ppm)	825	3000	290	430	70
HCOH (ppm)	0.092	0.285	0.000	0.073	49
Rn (WL)	0.007	0.049	0.000	0.010	59

Week-long radon measurements were made using the charcoal adsorption technique.

Formaldehyde. A formaldehyde monitoring kit was used for measuring the formaldehyde levels at three locations in each house. Passive bubblers were placed in each location for two hours and were subsequently analyzed by measuring the developed color in each sampler with a colorimeter. The color method used in this kit was the 3-methyl-2-benzothiazolone hydroazone hydrochloride (MBTH) method.

Respirable Suspended Particulates. Respirable suspended particulates (RSP) were measured at one location in each house with a respirable dust monitor. Because the instrument was designed for industrial applications, it could not give precise RSP measurements. However, the instrument was suitable for indicating high and low RSP levels.

Ozone. A multi-gas detector pump with long-range detector tubes was used to measure the ozone concentration at one location in each house. Each sample required 100 strokes of the detector pump and was too time-consuming to warrant measurements at two other locations (measurements were made in the living room on the main floor).

Relative Humidity. Relative humidity was measured using a sling psychrometer. Measurements were made on each floor of the house.

Airtightness and Air Infiltration Measurements

Airtightness. Airtightness was measured by the fan depressurization method. Testing was conducted according to the CGSB Standard, "Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method" (CAN/CGSB-149.10-M86) with the exception that intentional openings were not sealed. However, dampers on fireplaces were closed since they are normally closed when fireplaces are not utilized. While this practice increased the measured equivalent leakage area, it was consistent with the procedures carried out during the tracer gas tests.

Air Infiltration. One air infiltration measurement was made in each house using the tracer gas decay technique. In houses with forced-air heating systems, the tracer gas (sulphur hexaflouride) was injected into the return air plenum and samples were withdrawn from the same location. In houses with hydronic heating systems, the tracer gas was injected proportionately throughout the house, and samples were withdrawn from a central location. In either case, the mixing time was a half-hour.

Sound Level Measurements

A sound level meter (SLM) and an octave band filter set were used to perform the sound pressure level measurements. The SLM reference pressure was 2×10^{-5} Pa. Signals were processed by two different methods:

1. Weighting network, which corresponds to an inverted equal loudness contour at low pressure levels, and
2. Linear network, which enables the signal to pass through unmodified.

In addition to these measurements, a frequency analysis, which measures the sound levels at nine preferred frequencies, was also performed.

RESULTS FROM AIR QUALITY, AIRTIGHTNESS, AND AIR INFILTRATION TESTING

The random selection procedure resulted in a sample containing a wide variety of housing of which all were single detached dwellings. House construction dates ranged from 1902 to 1980, with the average house construction date being 1945. Of the 78 houses surveyed, 63 had forced-air heating systems, and 15 were heated hydronically. One of the houses that had forced-air heating had an electric furnace; the remainder used natural gas. Thirty-eight of the houses had central air-conditioning.

A summary that outlines the results from air quality measurements made in the 78 houses is contained in Table 1. Average levels for most of the pollutants are below generally accepted exposure guidelines. The levels of carbon dioxide, carbon monoxide, and ozone were found to be below the limits set by these guidelines in all the houses studied. However, it is important to note that this study was carried out during the warmer months of the year, when houses would be expected to be less tightly sealed than they would be in mid-winter.

The U.S. Environmental Protection Agency (EPA) recommends an action level of 4 pCi/L for radon. The average level found in the 70 houses surveyed in this study was slightly

TABLE 2

Summary of Airtightness and Air Infiltration Measurements

	Mean	Maximum	Minimum	Standard Deviation
Equivalent Leakage Area (cm^2)	1038	2594	293	507
Normalized Leakage Area (cm^2/m^2)	2.904	6.266	0.696	1.371
Air Change Rate at 50 Pa (ACH)	6.84	15.95	1.63	3.35
Air Infiltration Rate (ACH)	0.29	1.35	0.00	0.22

above this—at 4.5 pCi/L—and the highest level was 16.1 pCi/L, more than four times the EPA action level. Because air infiltration from below grade is generally much greater during winter months, when wind and stack effect come into play, it is expected that the radon levels measured in the 78 houses studied would be greater during the winter months of the year.

The exposure guidelines produced by the Federal Provincial Advisory Committee on Environmental and Occupational Health in April 1987 (the Guidelines) specify an action level of 0.1 ppm for formaldehyde. The average level found in this study was 0.09 ppm, and many of the houses tested were above the action level. Two of the houses were insulated with urea formaldehyde foam insulation (UFFI) and, interestingly, the formaldehyde levels in those living areas were found to be some of the lowest measured in this study. However, one of these houses did have a heat recovery ventilator unit.

The Guidelines specify an acceptable long-term exposure range (ALTER) of less than 0.04 mg/m³ for respirable suspended particulates (RSP) and a short-term range of less than 0.10 mg/m³. The instrument used in this study was not sensitive enough to detect RSP at 0.04 mg/m³, but it indicated eight living rooms at higher levels than the short-term exposure range out of 55 houses in which this measurement was made. In most of these houses with high RSP levels, there were smokers present.

The Guidelines do not specify an acceptable long-term exposure range for ozone since there are insufficient data to serve as a basis for establishing an ALTER. However, it is important to note that trace amounts of ozone were detected only in houses with electrostatic air cleaners.

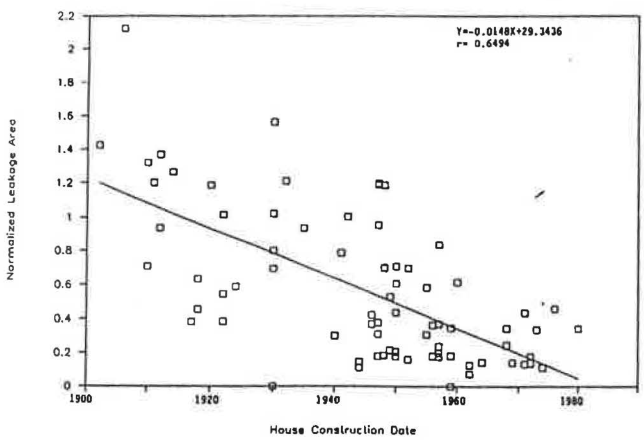

Figure 3 *House construction date vs. airtightness using normalized leakage area*

Table 2 summarizes the results from the airtightness measurements made on 76 of the 78 houses surveyed in terms of equivalent leakage area, normalized leakage area, and air exchange rate at 50 Pascals depressurization. In relative terms, the latter two are of greater importance when comparing and correlating data. Normalized leakage area relates buildings by floor area, and air exchange rate at 50 Pascals depressurization relates buildings by internal volume. The results from the air infiltration measurements made are also contained in this table. However, the results of these measurements were highly dependent on the weather conditions at the times of testing, and are only of importance when they are compared with predicted air infiltration (from airtightness information and local weather data). Figure 3 shows the relationship between house construction date and airtightness for 76 of the houses surveyed. Figures 4 and 5 show the relationships between measured and predicted air infiltration using the Sherman and Shaw models, respectively.

A homeowner survey report containing several data items was completed for each house. These included house identification; personal data about the occupants; energy conservation features of the house; several indoor air quality questions; questions about moisture problems; questions

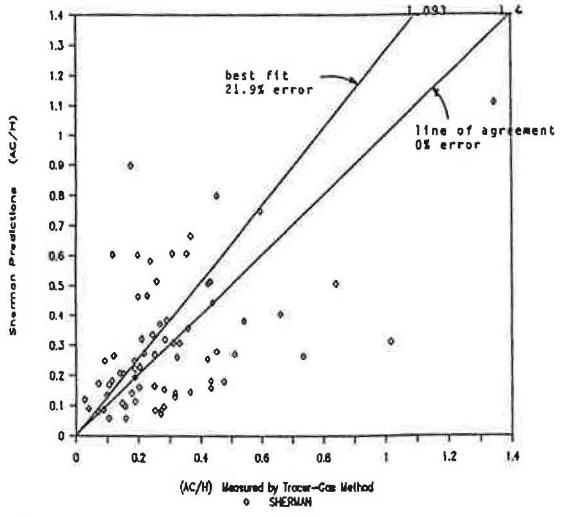

Figure 4 *Sherman model predictions vs. measured air exchange rates*

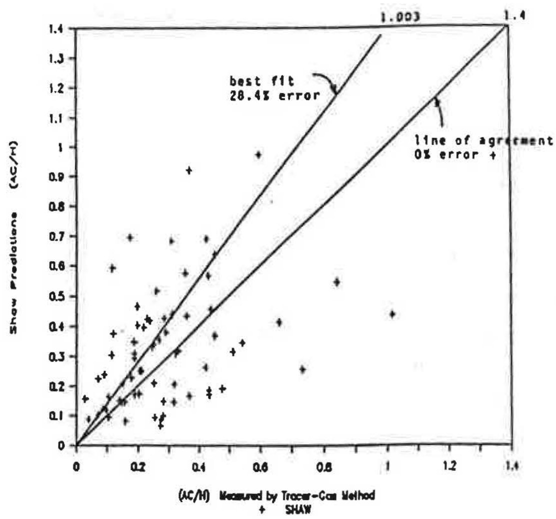

Figure 5 *Shaw model predictions vs. measured air exchange rates*

about heating, ventilating, and air-conditioning equipment; and questions about fan use. Information of greatest interest obtained from this survey was whether or not occupants were concerned about the air quality in their homes. Of the 78 houses surveyed, occupants of 32 of these houses—or 41%—were concerned about their indoor air quality. While there was no general correlation between census district and occupants' concern about indoor air quality, the highest income district expressed the greatest concern about indoor air quality. In this district, the occupants in five out of six houses surveyed were concerned about their indoor air quality.

Prior to the 78-house study, it was anticipated that exhaust fans in residential houses are frequently not used because occupants object to their noise. From information in the homeowner survey report and the measured sound pressure levels of exhaust fans in the surveyed houses, this was found not to be the case. No correlation was found between actual sound pressure level and perceived fan noise. Occupants who were concerned about their air quality were found to use their exhaust fans whether they perceived them to be noisy or not.

DISCUSSION AND CONCLUSIONS

The Winnipeg survey generated a set of approximately 750 observations and measurements of characteristics of a set of 78 randomly selected houses. As would be expected from such a large volume of data, many interesting ways of correlating pairs of variables develop. However, because many

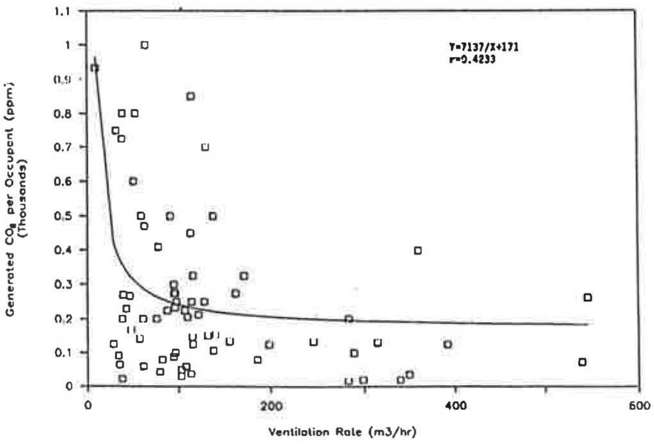

Figure 6 CO_2 per occupant vs. ventilation rate

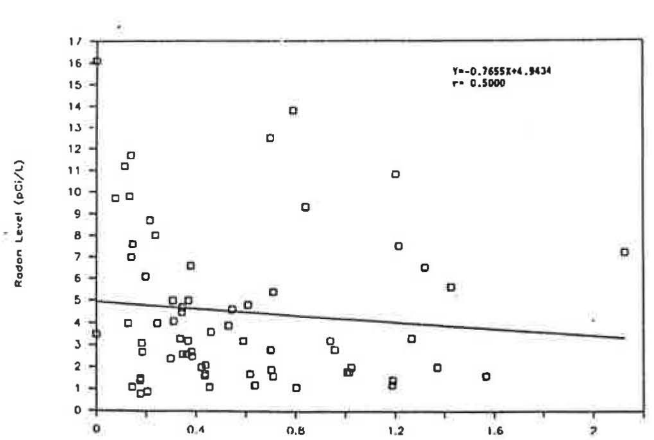

Figure 7 Radon level vs. normalized leakage area

of the correlations were weak, they have not been presented in this paper.

These weak correlations may be due to the total randomness of the study. There was no consistency in the types of heating, ventilating, and air-conditioning equipment in the houses surveyed. There was also no consistency in the times that tests were carried out, since visits to the houses were made at the homeowners' convenience. Occupants' attitudes toward air quality in their homes differed; therefore, some of their practices, such as opening and closing of windows and usage of exhaust fans, differed. Some stronger correlations did exist. However, most were related to tests that had specific procedures such as airtightness and air infiltration, and were therefore beyond the control of the occupants present.

Because instantaneous measurements were used to determine the air quality in the houses surveyed, the results are not necessarily representative of any of the houses in particular. They are meaningful, however, when using them to determine the overall averages of the pollutant levels in the 78 houses surveyed. Figure 6 shows the relationship between carbon dioxide generated per occupant vs. ventilation rate in terms of normalized leakage area (based on floor area). While there is a considerable scatter of the individual data points, the trend of lower CO_2 concentration with higher ventilation rates is clearly defined.

From the results of the air quality measurements made, it is clear that the city of Winnipeg has notably high radon levels. The average level recorded for 70 of the houses surveyed was 4.5 pCi/L, and the highest level recorded was 16.1 pCi/L. The relationship between radon level and normalized leakage area for 70 of the 78 houses surveyed is shown in Figure 7. Figure 8 is a histogram showing the distribution of the radon levels in the houses surveyed. No strong correlations existed between radon level and house age, style, or location in the city.

The random selection procedure produced a sample of houses from some of the lowest income districts, and from one of the wealthiest districts in the city of Winnipeg. Apart from obtaining generalized results about air quality in the Winnipeg housing stock, some interesting information about attitudes toward indoor air quality were obtained. Occupants of houses in the wealthier districts expressed greatest concern about the air quality in their homes and were the most willing to participate in the survey. Occupants of houses in the middle- and low-class districts were indifferent, with only 35% of the houses having occupants expressing concern. However, some of the occupants in these districts who were not con-

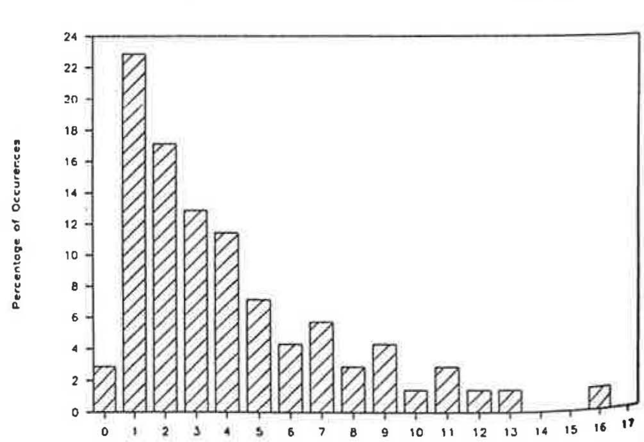

Figure 8 Distribution of radon levels

cerned were the most reluctant to allow the survey team to enter their home. There was an obvious correlation between willingness to participate in the survey and concern about indoor air quality, so the level of concern in the low-income districts might have been even lower if the number of refusals had been less. Their reluctance to participate may have been reflected in their negative responses in the homeowner questionnaire.

ACKNOWLEDGMENTS

This work was supported by the Canada Mortgage and Housing Corporation; National Research Council Canada; Manitoba Department of Energy and Mines; Public Works Canada; Energy, Mines and Resources Canada; and Manitoba Hydro.

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DISCUSSION

William Turner, Harriman Associates, Auburn, ME: What were typical noise levels and the minimum detectable level of the measurement instruments?

G.K. Yuill, G.K. Yuill & Associates Ltd., Winnipeg, Manitoba, Canada: The sound level measurement instrumentation had dynamic ranges of 36 to 140 dB for the linear weighting scale and 15 to 140 dB for the "A" weighting scale. The instrumentation was accurate to ±1 dB under specified reference conditions. Typical background readings were 30 dB and 56 dB for "A" weighting and linear weighting scales, respectively. Typical total noise levels were 60 dB and 68 dB for "A" weighting and linear weighting scales, respectively.