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RADON TRANSPORT INTO A DETACHED ONE-STORY HOUSE WITH A BASEMENT

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Abstract—We describe the results of a five-month study during which ^{222}Rn (radon) concentration, air-exchange (or ventilation) rate, and weather and radon source parameters were continuously monitored in a house near Chicago, with a view to accounting for the radon entry rate. The results suggest that the basement sump and perimeter drain-tile system played an important role in influencing the radon entry rate and that pressure-driven flow was more important than diffusion as a mechanism for radon entry.

For the first 15 weeks of the study period the mean indoor radon concentration and air-exchange rate were 2.6 pCi ℓ^{-1} (96 Bq m^{-3}) and 0.22 h^{-1}, respectively; both parameters varied over a wide range. Radon concentration measured at the sump cover varied bimodally between 0 and 10 pCi ℓ^{-1} (0–400 Bq m^{-3}) and 300–700 pCi ℓ^{-1} (10,000–30,000 Bq m^{-3}). These two modes corresponded well to periods of low and high indoor radon concentration; average indoor concentrations for these periods were 1.5 and 6.5 pCi ℓ^{-1} (55 and 240 Bq m^{-3}), respectively. For data sorted into two groups according to radon activity at the sump, the indoor radon concentration showed little dependence on air-exchange rate. This result is accounted for by a model in which the radon entry rate, determined by mass balance, has two components—one diffusive, the other a pressure-driven flow component which is presumed to be proportional to the air-exchange rate. In fitting this model to the data we found that (1) the flow component dominated the diffusive component for periods of both high and low activity at the sump and (2) the magnitude of the diffusive component agreed well with the expected contributions of radon emanating from concrete and soil and diffusing into the house. To account for the flow component, we hypothesize that pressure drives air carrying a high concentration of radon generated in the soil, either through the bulk of the soil or along the outside of the basement walls, then into the basement through cracks and openings.

During the final six weeks of the study, measurements were made with the water level in the sump maintained first below, then above the entrance of the pipe connected to the perimeter drain tile system. Average indoor radon concentrations during these two periods were 10.6 and 3.5 pCi ℓ^{-1} (390 and 130 Bq m^{-3}), respectively. The relatively high latter value compared with the mean for the first 15 weeks, combined with the observation of intervals of high airborne alpha activity at the sump during this period, suggest that the level of water in the sump does not, by itself, account for the variation in alpha activity at the sump that we had previously observed.

Fireplace operation substantially increased the air-exchange rate, but had only a small effect on indoor radon concentration, providing corroborative evidence that pressure-driven flow is an important mechanism for radon entry into this house.

Key word index: air-exchange, building materials, fireplace, indoor air quality, infiltration, pollution sources, radon, residential buildings, soil.

INTRODUCTION

Exposure in residences to the radioactive decay products of ^{222}Rn (radon) may constitute a serious public health problem. Extrapolating from studies of uranium miners, who, after exposure to high concentrations of radon progeny in mines, were observed to have a high incidence of lung cancer, Nero (1983) has estimated that among the U.S. population 1000–20,000 cases of lung cancer per year may result from exposure to radon progeny in residences. This estimate was based on an indoor radon concentration in the range of 0.5–1.0 pCi ℓ^{-1} (18–37 Bq m^{-3}), observed to be typical of indoor values, and thought to reflect a reasonable approximation of the average for U.S. housing.

Concern over public exposure to higher-than-average levels of radon progeny indoors has led to corrective measures being applied in Port Hope, Ontario (Eaton, 1982) and Grand Junction, Colorado (U.S. Department of Energy, 1979), where contaminated building materials and soils are thought to be the principal radon sources. Remedial action has also been taken in Bancroft and Elliot Lake, Ontario, and Uranium City, Saskatchewan, towns near uranium mines where local soils are thought to be high in radium content (Eaton, 1982). Corrective measures have been recommended for houses built on phosphate lands in Polk and Hillsborough Counties, Florida, where local soils are high in radium content (U.S. General Services Administration, 1979).

Several recent studies have shown that even in areas not associated with uranium or phosphate mining, and not contaminated by radioactive industrial byproducts, indoor radon levels are very broadly distributed (Hess *et al.*, 1982; Doyle *et al.*, 1984; Nero *et al.*, 1983; Sachs *et al.*, 1982; Rundo *et al.*, 1979). A small but significant number of houses in these studies, generally clustered yet broadly distributed across the United States, have indoor radon concentrations sufficiently high that occupants are exposed to radon progeny at an annual rate approaching or exceeding that permitted uranium miners.* The predominant source of radon in most of these houses is thought to be the soil beneath and adjacent to the building foundation. Recent experimental and theoretical studies suggest (as noted by Bruno, 1983) that the pressure-driven entry of soil gas bearing high concentrations of radon is potentially the largest indoor source and that the other sources (diffusion of radon from soil and building materials, and radon entering with tap water) cannot account for the high indoor concentrations observed. This postulate is supported by the Canadian remedial action efforts: control measures that either sealed penetrations between the foundation and the soil, or ventilated the soil around the structure were often successful (Eaton, 1982).

The transport mechanisms by which soil gas enters a building have not been well characterized. Some investigators have recently postulated that the same factors that drive infiltration, namely indoor–outdoor temperature difference ('stack effect') and wind, could drive soil gas into a house (Nazaroff *et al.*, 1981a; DSMA Atcon, 1983). Because of the high concentration of radon in the soil gas, hundreds to thousands of pCi ℓ^{-1}, only a small fraction of the infiltrating air need come through the soil to provide a large source of radon (Nero and Nazaroff, 1984). The pressure created by the stack effect and by wind is small, however, typically less than 5 Pa for low-rise buildings, and it is not clear whether this is sufficient to drive a significant flow through the soil.

A principal purpose of the current study was to examine radon entry into a single-family house, paying particular attention to mechanisms that might transport soil gas indoors. Our approach was to continuously measure air-exchange rate and indoor radon concentration, from which the rate of radon entry may be determined by mass balance, and at the same time to measure radon source parameters, such as the radon concentration in soil gas. Several environmental parameters were measured simultaneously to determine the effect of the various potential driving forces. Some preliminary observations on the results of these measurements were made by Grimsrud *et al.* (1983). The present paper discusses the results more fully, particularly in trying to account for the radon entry rate.

EXPERIMENTAL SITE

The study site was a conventional house located near Chicago. The house was monitored under normal living conditions from February to May 1982; additional measurements were conducted during the following six weeks with certain conditions of the house controlled to examine their impact on radon entry rate. We selected the house based on the following criteria: (1) moderately high indoor radon concentrations were previously observed; (2) the indoor space was fully conditioned with a central forced-air heating system (thereby allowing us to treat the house as a single chamber); (3) none of the occupants smoked (minimizing the risk of our instruments becoming fouled during the experiment) and (4) in every evident regard, the house was typical of a large class of U.S. dwellings. The house, shown in plan view in Fig. 1, has one main floor of wood frame construction and a full basement with poured concrete floor and walls. The floor of the basement is about 2 m below grade. Both the basement and the main floor are heated by an oil-fired forced-air furnace. Each floor has an area of 105 m^2 and the ceiling heights are 2.1 and 2.4 m for the basement and main floor, respectively, giving a total volume of 470 m^3. The house was built in the 1950s and, while some tightening measures have been applied, such as extensive caulking and weatherstripping, the energy consumption characteristics of the house are probably comparable to a typical suburban house built before the 1970s in a cold climate. Although the terrain is flat, the house is moderately shielded from the wind by other houses and deciduous trees. The house had two adult occupants, both of whom worked full-time outside the home so that occupancy is not thought to play a large role in ventilation of the house during the winter and early spring.

An important feature of the house with respect to indoor radon concentration is the presence of a sump in one corner of the basement. It is a concrete-lined hole, 60 cm in diameter by 75 cm deep, and is covered by a loosely fitting steel plate. Water from rain or melting snow and ice which drains through the soil adjacent to the house flows into the sump via a drain (or 'weeping') tile system that is emplaced around the perimeter of the house, near the level of the basement floor. As shown in Fig. 2, the operation of the sump pump is controlled by two floats that straddle the drain tile entrance. Thus, whenever the water level in the sump is low, a highly permeable pathway is present between the basement and the soil. However, as will be discussed later, the presence of water above the drain tile entrance in the sump is by itself not sufficient to prevent significant radon entry into the basement from the soil.

* The occupational limit for exposure to radon decay products is four working level months (WLM) per year, where one WLM results from exposure to decay products in equilibrium with a radon concentration of 100 pCi ℓ^{-1} (3700 Bq m^{-3}) for 173 h. In residences, assuming (1) that the ratio of the actual potential alpha energy concentration (PAEC) of decay products to the equilibrium PAEC is 0.5 and (2) that exposure is continuous, 4 WLM y^{-1} would result from a radon concentration of 16 pCi ℓ^{-1} (590 Bq m^{-3}). Conclusions about health risk must be made with some care, however: because of differences in breathing rates, physiology and airborne particle characteristics, the lung dose to a miner exposed at the occupational limit differs from the dose to a building occupant receiving the same exposure. Furthermore, other respiratory insults that may contribute to lung disease, including cancer, differ between mine and residential atmospheres.

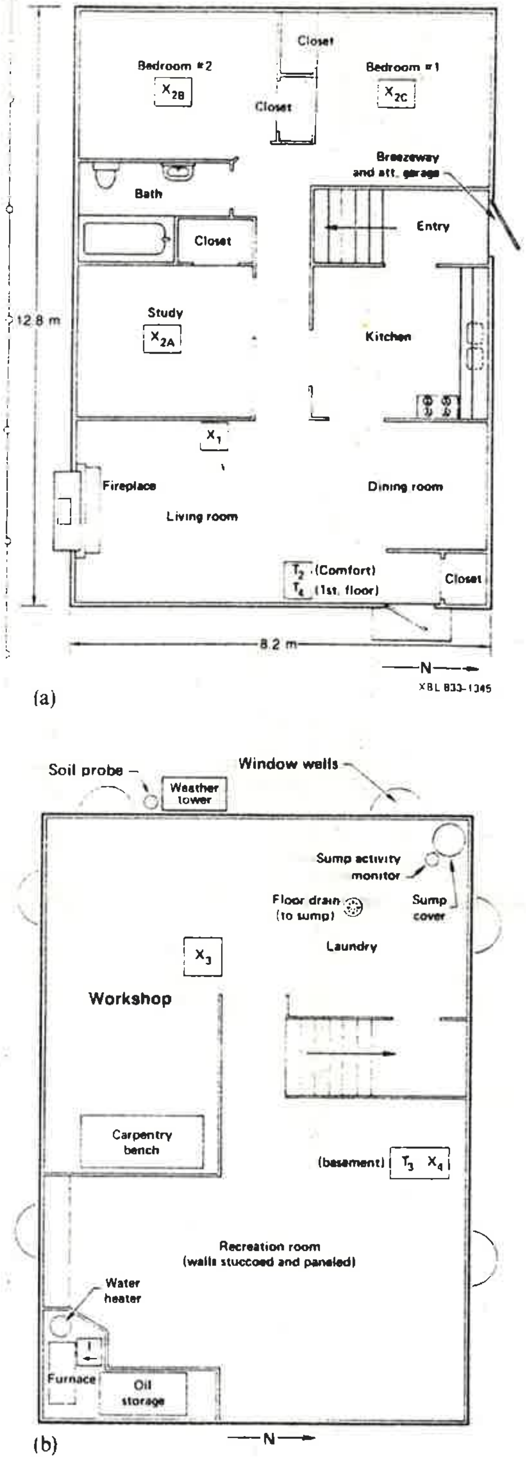

Fig. 1. Floor plans of (a) main floor and (b) basement of the house. Air was sampled from the six points labeled X_i, each in proportion to the volume served, and blended to determine indoor radon and sulfur hexafluoride (SF_6) concentrations. At the beginning of each air-exchange rate measurement, SF_6 was injected into the return-air duct of the furnace (point I) and the furnace fan was used to distribute the gas throughout the house. Temperatures were measured at the three points labeled T_i as well as on the weather tower and in the soil at the position of the soil probe.

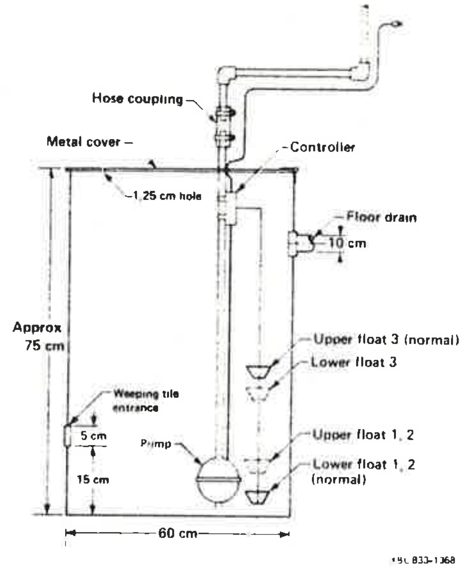

Fig. 2. Diagram of the sump. When the level of water which enters from the weeping tile, the floor drain, or the laundry (not shown), rises above the upper float, the pump is activated until the water level drops below the lower float position. With the floats in their 'normal' position, 70 ℓ of water is drained per cycle. The positions indicated by the numbers 1–3 correspond to the float locations during the three periods when the water level in the sump was controlled (see Table 5). The home-owner reports that the pump operates as frequently as every 10 min for a few days in the spring and for a day following a heavy rain (indicating that the soil may have a high permeability), and not at all for several weeks or longer during the winter.

INSTRUMENTATION

An automated instrumentation system was used to continuously monitor most of the parameters of interest, which are given (together with the sampling frequency) in Table 1. An earlier version of this sytem was described in detail by Nazaroff *et al.* (1983).

The air-exchange (or ventilation) rate was measured using tracer gas decay, with sulfur hexafluoride (SF_6) as the tracer gas. The house was treated as a single chamber with the average SF_6 concentration determined at 5-min intervals by mixing filtered air drawn from six points (labeled X_i in Fig. 1), each sampled at a rate roughly proportional to the volume served. At 90-min intervals, SF_6 was injected into the return-air duct of the furnace and the furnace fan turned on until the target concentration of 5 ppm was reached. The SF_6 analyzer was recalibrated automatically by sampling bottled gas containing 0 and 5 ppm of SF_6 every 6 h. Periods of furnace operation, which give information about the degree of mixing within the house, were detected by measuring the voltage across the thermostat switch. (Based on comparison of measurements of average radon concentration indoors and in the basement, mixing between floors appears to be rapid through April, while the furnace was still in use.)

Although it cannot be rigorously assessed in a straightforward manner, the uncertainty in the air-exchange rate measurement can be estimated based on the experimental data. The effect of analyzer drift, for example, accounts for an error of less than 5% in the measured concentration, based on examination of the calibration data from the entire monitoring period. The effect of imperfect mixing is estimated by the

Table 1. Measured parameters and measurement intervals

Parameter	Technique	Measurement interval (min)
Air-exchange rate	SF_6 Decay	90
Radon: indoor	Flow-through scint. flask	180
sump/basement	Diffusion scint. flask	30
soil	Diffusion scint. flask	30
Wind speed	Cup anemometer	3/30*
Temperatures: indoor, basement, outdoor, soil	Thermistor	3/30*
Pressure across basement walls	Variable reluctance pressure trans.	3/30*
Barometric pressure	NWS†	Hourly
Precipitation	NWS†	Daily

* Measured every 3 min, average for 30 min recorded.
† National Weather Service, O'Hare Airport.

goodness-of-fit of the decay data to an exponential curve (Bowker and Lieberman, 1972): the typical 90% confidence limit deviates from the best estimate of the air-exchange rate by 5–10%. Thus the overall measurement uncertainty, expressed as the coefficient of variation in measuring a constant air-exchange rate, is probably between 10 and 20%.

Radon concentrations in air were monitored at three sites: indoor (average), above the sump cover and in the soil adjacent to the house. The indoor concentration was determined by sampling the six-point blend of air using a flow-through scintillation cell. Using a three-hour averaging interval, the measurement uncertainties (one S.D. due to counting statistics) in a stable radon concentration were ± 0.2 and ± 0.3 pCi ℓ^{-1} (7 and 11 Bq m^{-3}) for concentrations of 1.0 and 5.0 pCi ℓ^{-1} (37 and 185 Bq m^{-3}), respectively. The corresponding uncertainties for measurements averaged over a week are ± 0.04 and ± 0.05 pCi ℓ^{-1} (1.5 and 1.9 Bq m^{-3}). Although the radon sampling was not designed to exclude contributions from ^{220}Rn, the data were treated with the assumption that this isotope, whose average indoor concentration is thought to be only 5% of that for ^{222}Rn (UNSCEAR, 1982), was not present.

Radon concentration in the soil air was measured by a scintillation cell–photomultiplier tube assembly placed adjacent to the house, 50 cm below the soil surface. In this detector radon must diffuse through 15 cm past four baffles before reaching the cell entrance. The time constant for responding to changing radon concentration was determined in indoor air to be about one hour. A similar device monitored radon at the sump via a hole in the cover. This instrument has a single baffle, and its time constant for response to an increasing radon concentration was found to be about 10 minutes. For either instrument, exposure to a ^{222}Rn concentration of 2.2 pCi ℓ^{-1} results in a net count rate of 1.0 min^{-1}.

The data from these devices must be interpreted with some care, however. Neither had filters to prevent entry of radon progeny, and the short path length of the monitor at the sump potentially allows thoron (^{220}Rn) to contribute to the observed count rate. Furthermore, the concentration of radon in the soil-air monitor varies not only with the radon concentration in the soil air but also with soil moisture. In saturated soil, for example, the radon diffusion length is only a few cm (Tanner, 1964), and consequently the radon concentration in the detector would be less than that in saturated soil pores. To highlight these limitations, data from these monitors are frequently reported in this manuscript as net count rate and referred to as measures of airborne alpha activity; the conversion to equivalent radon concentration is made as necessary to interpret the results, with the understanding that these caveats reduce the precision of the analysis.

After the first four weeks of the study the sump pump failed and the basement flooded. Following repair of the pump, the sump monitor was placed atop the dryer, a few meters away from the sump and one m above the floor. It remained in this position until the end of the initial 15-week monitoring period; its count rate was used to determine the radon concentration in the basement. For the subsequent 6-week experimental period it was placed in its original position to permit monitoring of radon activity at the sump.

Each of the radon monitors was calibrated before the study against monitors which had themselves been calibrated using a National Bureau of Standards certified radium solution. We estimate the calibrations to be accurate within 10%.

The radon entry rate was determined from a mass balance based on three-hour average measurements of indoor radon concentration and air-exchange rate (Nazaroff *et al.*, 1983). The calculated entry rate includes radon entering via outdoor air infiltrating into the house, but because the indoor concentration was much greater than the average outdoor concentration (measured nine times during the study by grab sample, analyzed by scintillation cell) this contribution was presumed to be small.

Several weather parameters were measured on-site at 3-min intervals; in each case the average and standard deviation for 30-min periods was recorded. Wind speed was monitored 9 m above ground level (4 m above the roof ridge). Temperature was measured at five locations: two on the first floor, one in the basement, one outside and one in the soil at the location of the radon probe. The pressure difference across the basement walls was measured by a variable-reluctance pressure transducer (Validyne, model DP103) coupled to a switching manifold. Polyethylene sampling lines with an inside diameter of 0.4 cm and lengths of 10–20 m were used to transmit the pressure from points outside the house, located 0.3 m above ground at the center of each wall, to the manifold. The indoor pressure was measured at the same height in the center of the basement. Barometric pressure and precipitation data were obtained from the National Weather Service station at O'Hare Airport, about 20 km north of the house.

RESULTS AND ANALYSIS

Fifteen-week monitoring period

Weekly average values for each of the parameters measured by the automated system are given in Table 2 for the initial 15-week monitoring period. Overall, data were collected for 95% of this time. The weekly-average indoor radon concentration varied by a factor of five, while the weekly-average air-exchange rate varied only three-fold. In itself this is evidence of variability in the rate of radon entry. Greater evidence is provided by the failure of the radon concentration to vary in inverse proportion to the air-exchange rate: the calculated radon entry rate, averaged for weekly periods, varied by nearly a factor of ten.

Radon concentration in outdoor air was measured nine times during the study by analyzing grab samples collected between 1230 and 1500 h, roughly biweekly. The resulting average of 0.3 ± 0.3 pCi ℓ^{-1} (11 ± 11 Bq m^{-3}) is within the range of 0.1–0.4 pCi ℓ^{-1} (4–15 Bq m^{-3}) for continental air as cited by Gesell (1983) and it is only about 10% of the average indoor concentration.

Table 2. Mean values ± one S.D. for parameters measured during 15-week monitoring period

Dates (1982)	Time meas. (%)	Indoor radon (pCi ℓ^{-1})*	Basement radon (pCi ℓ^{-1})*	Radon entry rate (pCi ℓ^{-1} h^{-1})	Sump activity† (min^{-1})	Soil activity† (min^{-1})	Air-exchange rate (h^{-1})	Wind speed (m s^{-1})	ΔT‡ (°C)	ΔP§ (Pa)	Furnace operation (% on)
17–23 Feb.	82	5.2±3.5		1.49±1.45	141±99	10±3	0.29±0.14	2.1	17.6	3.3	11.3
24 Feb.–2 March	92	1.8±1.5		0.41±0.40	31±83	97±31	0.23±0.04	1.4	19.4	3.5	12.2
3–9 March	99	4.1±3.3		1.60±1.99	129±114	106±25	0.34±0.17	2.2	23.6	4.3	15.7
10–16 March	99	6.2±3.9		1.44±1.00	124±121	86±19	0.23±0.05	2.7	11.9	2.9	8.6
17–23 March	98	1.9±0.7	1.7±0.9	0.38±0.24		145±22	0.23±0.13	2.1	12.4	2.7	8.7
24–30 March	92	1.5±0.5	1.4±0.7	0.37±0.17		115±20	0.29±0.17	2.8	12.6	3.2	7.4
31 March–6 April	98	1.2±0.5	1.2±0.7	0.28±0.15		136±14	0.26±0.12	3.7	12.7	3.6	5.1
7–13 April	98	1.6±0.5	1.5±0.9	0.33±0.13		95±10	0.21±0.05	2.3	13.1	2.8	7.0
14–20 April	95	1.8±0.7	2.1±0.9	0.31±0.19		136±19	0.17±0.05	2.8	6.6	2.2	0.9
21–27 April	99	1.5±0.5	1.8±0.9	0.25±0.14		119±13	0.16±0.05	2.3	8.6	1.9	0.7
28 April–4 May	98	2.9±2.6	3.2±2.9	0.28±0.48		232±34	0.10±0.04	1.6	3.5	1.3	0.4
5–11 May	99	1.6±0.5	2.1±0.7	0.17±0.12		268±47	0.13±0.09	2.1	3.1	1.1	0
12–18 May	87	3.9±3.7	5.7±5.3	0.79±1.15		259±52	0.21±0.12	1.4	5.7	0.6	0
19–25 May	97	1.6±1.1	2.3±1.3	0.23±0.22		229±21	0.20±0.19	1.1	5.7	1.1	0
26 May–1 June	85	2.7±3.0	4.6±5.7	0.73±1.3		227±10	0.22±0.14	0.8	2.5	0.6	0
Entire period	95	2.6±2.6		0.60±0.97		151±76	0.22±0.13	2.1	10.6	2.3	5.2

* 1 pCi ℓ^{-1} = 37 Bq m^{-3}.
† Airborne alpha activity; 100 min^{-1} ≃ 220 pCi ℓ^{-1} of ^{222}Rn.
‡ Average of basement and first floor temperatures minus that outdoors.
§ Outdoor pressure minus indoor pressure, measured 0.3 m above ground, average for four walls.

Figure 3, plotted for the two-week period that had the highest average radon entry rate, shows that at least some of the variability in radon entry rate is related to the sump: we see a strong correlation between the airborne alpha activity at the sump and the indoor radon concentration. Furthermore, we see that on several occasions during this time the activity at the sump changed rapidly between a low count rate and roughly 200–300 min^{-1}, which corresponds to 440–660 $\text{pCi}\,\ell^{-1}$ (16,000–24,000 Bq m^{-3}) of ^{222}Rn. A possible explanation for this behavior, discussed in detail later, is that the level of water in the sump and drain-tile system determine whether or not a highly permeable pathway exists between the basement and the soil. Through this pathway soil gas, carrying a high concentration of radon, may enter the house, driven by the stack effect, and perhaps by other factors, such as wind.

Because the indoor radon concentration varied so greatly in correspondence to the sump activity, data were sorted into two groups for further analysis. Before sorting, all data were averaged over 3-h period that corresponded to intervals of indoor radon measurement. Then, for data from the first four weeks of monitoring (i.e. before the basement flooded), the sorting criterion was an alpha activity at the sump of 20 min^{-1}, which corresponds to about 44 $\text{pCi}\,\ell^{-1}$ (1630 Bq m^{-3}); 56% of the 190 measurements exceeded this value. For the last 11 weeks, the basement radon concentration was used to sort the data and a concentration of 3.3 $\text{pCi}\,\ell^{-1}$ (120 Bq m^{-3}) was used as the criterion; only 11% of the 591 measurements during that period exceeded this value. A summary of the sorted results appears in Table 3.

Examination of the frequency distributions of these two parameters suggests that the sorting criteria are comparable. In each case the distribution is bimodal with a low number of measurements in the vicinity of

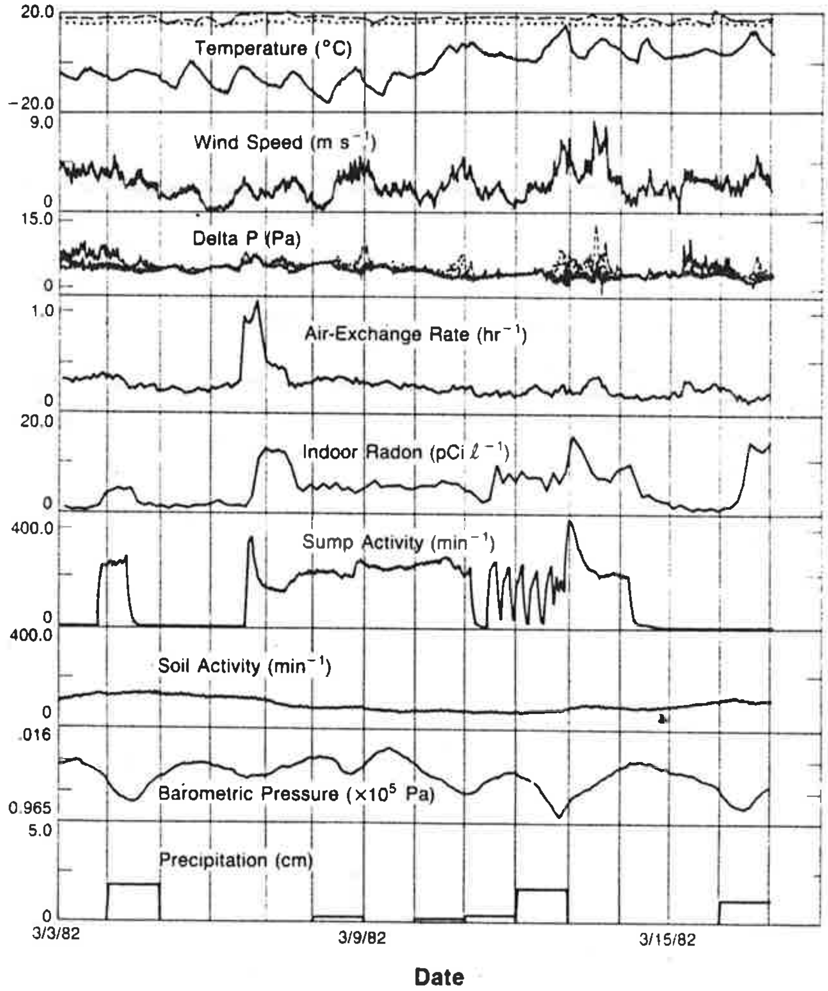

Fig. 3. Plot of most of the parameters measured vs time for a 2-week period. In the temperature plot, the solid, dashed and dotted lines represent the outdoor, first floor, and basement temperatures, respectively. The peak in the air-exchange rate plot results from the operation of the fireplace. Note the strong correlation between the airborne alpha activity at the sump ('sump activity') and indoor radon concentration. The vertical lines correspond to midnight.

Table 3. Summary of data sorted according to airborne alpha activity at the sump, giving mean values ± one S.D.

	Low (17 Feb.–14 March)	Low (15 March–31 May)	High (17 Feb.–14 March)	High (15 March–31 May)
Indoor radon (pCi ℓ^{-1})*	1.5 ± 0.8	1.5 ± 0.6	6.5 ± 2.9	6.4 ± 3.8
Basement radon (pCi ℓ^{-1})*	—	1.8 ± 0.6	—	8.6 ± 5.5
Air-exchange (h^{-1})	0.25 ± 0.10	0.20 ± 0.12	0.29 ± 0.14	0.19 ± 0.13
Radon entry (pCi ℓ^{-1} h^{-1})*	0.31 ± 0.21	0.27 ± 0.18	2.0 ± 1.6	1.3 ± 1.5
Soil activity (min^{-1})†	89 ± 43	170 ± 65	64 ± 41	223 ± 63
Sump activity (min^{-1})†	4 ± 3	—	203 ± 70	—
Wind speed (m s^{-1})	1.8 ± 1.1	2.2 ± 1.4	2.3 ± 1.3	1.3 ± 1.0
ΔT(°C)	19.4 ± 4.5	8.4 ± 6.4	18.3 ± 6.0	4.5 ± 5.5
ΔP (Pa)	3.6 ± 0.7	2.1 ± 1.2	3.5 ± 0.8	1.0 ± 0.7
Time measured (h)‡	252	1578	318	195

* 1 pCi ℓ^{-1} = 37 Bq m^{-3}.
† Airborne alpha activity; 100 min^{-1} ≃ 220 pCi ℓ^{-1} of ^{222}Rn.
‡ No. of measurement intervals for each parameter = time measured (h)/3.
During the period 17 February–14 March 1982 the criterion was an activity at the sump of 20 min^{-1}, or about 44 pCi ℓ^{-1} (1630 Bq m^{-3}). During the second period, 15–31 March 1982, basement radon concentration was monitored, rather than activity at the sump; here the sorting criterion was 3.3 pCi ℓ^{-1} (120 Bq m^{-3}). The agreement in mean indoor radon concentration for the sorted data from these two periods suggests that these are comparable criteria.

the selected criterion, which was chosen to lie between the two modes. Furthermore, despite the use of different sorting criteria, the average indoor radon concentrations for the first four weeks and the last 11weeks are comparable for periods associated both with low and high alpha activity at the sump. We therefore consider the data from all 15 weeks together. Overall, the alpha activity at the sump was observed or presumed to be high 22% of the time, and the corresponding average radon concentration of 6.5 pCi ℓ^{-1} (240 Bq m^{-3}) is more than four times as great as that when the activity at the sump was low.

Although the activity at the sump was high more than half of the time for the four weeks before the basement flooded, it was not high at any time during the subsequent four weeks. This sudden change may be related to the flooding: for example, cracks in the basement walls and floor may have become saturated, increasing the resistance of the substructure to pressure-driven flow of the soil gas.

The distributions of 3-h average measurements of indoor radon concentration and air-exchange rate, shown in Fig. 4, are roughly log-normal. There is only a small overlap in the distributions of radon concentration for periods of high and low alpha activity at the sump, in contrast to the air-exchange rate distributions for the sorted data, which are roughly comparable. It is noteworthy that the radon concentrations for both low and high activity at the sump are broadly distributed. Measurement uncertainty can account for only small and negligible portions of the geometric standard deviations (GSD) for the low and high distributions, respectively.

To test the hypothesis that the variability in radon concentration within periods of high and low activity at the sump is due to changes in the air-exchange rate, a scatter plot of radon concentration vs air-exchange rate was produced (Fig. 5). For low activity there appears to be a small dependence of radon concentration on air-exchange rate, but for high activity no dependence is apparent. As discussed below, this is in strong contrast to a situation where the entry rate is approximately constant and where, therefore, the radon concentration is inversely proportional to the air-exchange rate (as shown by the straight dashed lines in the figure).

The effects of indoor–outdoor temperature difference, wind speed and barometric pressure change on radon entry and indoor concentration were considered by grouping 3-h average data that had been sorted according to sump activity into eight bins, depending on whether each of the three weather parameters was higher or lower than the median value (see Table 4.) For periods of high sump activity, there are too few data and too much scatter to draw statistically sound conclusions about the effect of these parameters on radon concentration or entry rate. For low sump activity, however, indoor radon concentration is significantly lower (at the 99% confidence level) when both wind speed and temperature difference are high, but not when either factor is high independently. The radon entry rate is generally higher for higher temperature differences; the effect of wind speed, however, depends upon the temperature difference: higher entry rates are associated with high wind speeds when the temperature difference is small and with low wind speeds when the temperature difference is large. Barometric pressure has no significant effect on radon concentration or entry rate.

Radon activity in the soil adjacent to the house varies substantially with changes in indoor–outdoor temperature difference and wind speed, both for high and low alpha activity at the sump. Increased wind speed is associated with significantly decreased soil activity when the temperature difference is small, and increased temperature difference is generally as-

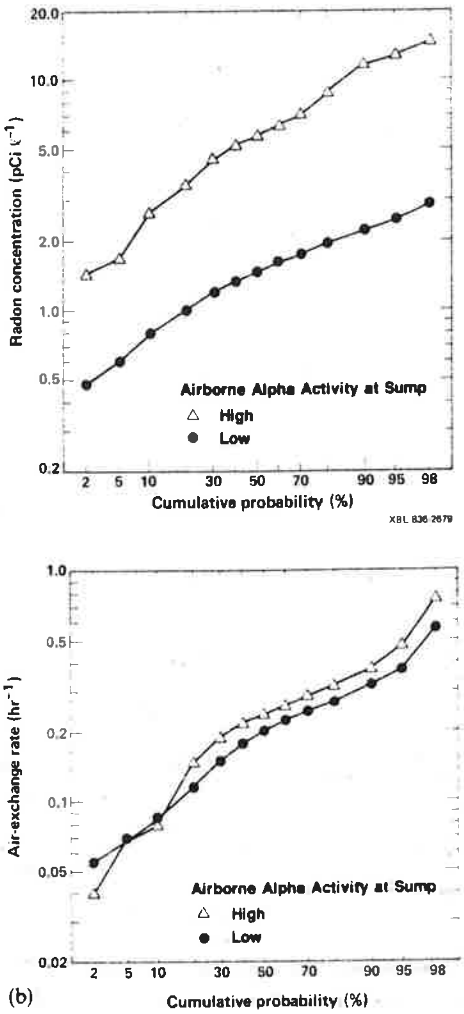

Fig. 4. Log-probability plots of (a) indoor radon concentration and (b) air-exchange rate for 3-h average measurements during the 15-week monitoring period. The geometric means and standard deviations for radon are 5.5 pCi ℓ^{-1} (204 Bq m^{-3}) and 1.75 for high alpha activity at the sump and 1.4 pCi ℓ^{-1} (52 Bq m^{-3}) and 1.55 for low activity. For air-exchange rate the corresponding numbers are 0.21 h^{-1} and 1.85 for high activity and 0.18 h^{-1} and 1.70 for low activity.

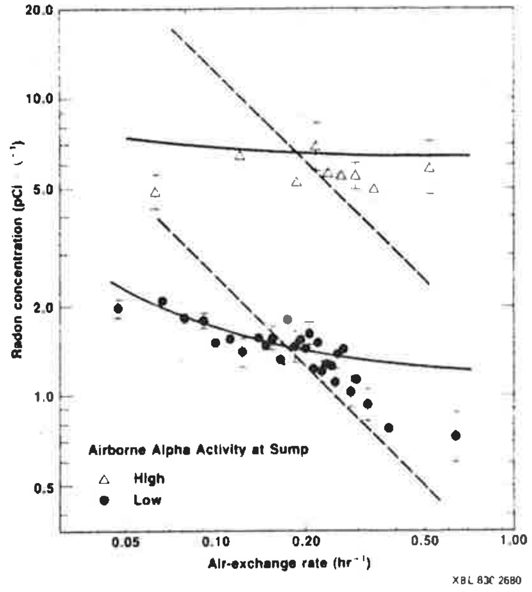

Fig. 5. Scatter plot of radon concentration vs air-exchange rate averaged over 3-h periods. Each point gives the geometric means of 19–21 pairs of measurements that have been sorted and grouped according to the air-exchange rate. The error bars represent one geometric standard deviation of the mean; for clarity only some are given. The dashed lines represent the expected relationship if the radon entry rate is independent of air-exchange rate. The solid lines reflect a model in which radon entry is presumed to have two components—one (diffusive) being constant, the other (flow) being proportional to the air-exchange rate.

sociated with significantly decreased soil activity independent of other factors. These results are consistent with a model of radon entry via pressure-driven flow, discussed in the following section. Within the framework of this model, however, it is puzzling that changes in soil activity are not associated with barometric pressure changes.

Effects of water level in the sump

Having observed the correspondence between airborne alpha activity at the sump and indoor radon concentration, we subsequently made measurements in three consecutive 2-week periods, during which the water level in the sump was controlled. During two periods, the sump floats were adjusted so that the water level never rose above the drain-tile entrance (position 1,2 in Fig. 2). In the first period, the basement was in its ordinary condition, and in the second a blower exhausted air from the workshop area of the basement to outside. During the third two-week period, the blower was turned off and the sump floats were adjusted so that the water level was maintained at least 10 cm above the drain-tile entrance (position 3 in Fig. 2).

Average measurement results for these three periods are given in Table 5; Figs 6 and 7 display detailed results vs time for the first and third periods. The results from the first two periods correspond to what one might predict based on the results of the 15-week monitoring period. The indoor radon concentration and alpha activity at the sump are high throughout these periods, compared with average concentrations for the 15-week period, and the radon entry rate is very high as well. With the exhaust blower operating, the average indoor concentration is lowered to a greater degree than predicted by the increase in air-exchange rate, consistent with the expectation that radon is entering the house in the basement and therefore a higher than average concentration of radon is being exhausted from the house.

The results from the third period are puzzling. Although we expected that occluding the drain-tile entrance to the sump would lead to an indoor radon concentration of 1–2 pCi ℓ^{-1} (40–70 Bq m^{-3}), we

Table 4. Arithmetic mean and range of standard errors for measurements sorted according to weather parameters

	$\Delta T\rightarrow$ WS$\rightarrow$ $\frac{dB}{dt}\rightarrow$	L L L	L L H	L H L	L H H	H L L	H L H	H H L	H H H	S.E. Range (%)
Low alpha activity at sump										
Indoor radon	(pCi ℓ^{-1})*	1.6	1.5	1.6	1.6	1.5	1.5	1.3	1.2	6–8
Rn entry rate	(pCi ℓ^{-1} h^{-1})*	0.21	0.21	0.23	0.29	0.33	0.35	0.33	0.27	6–10
Soil activity†	(min^{-1})	216	220	170	176	128	138	114	124	3–7
Ventilation rate	(h^{-1})	0.15	0.16	0.19	0.20	0.22	0.23	0.28	0.25	4–10
Press. across walls	(Pa)	0.9	1.1	1.8	2.0	2.7	2.8	3.5	3.7	3–6
Temperature diff.	(°C)	3.4	6.1	2.5	5.5	16.5	16.4	14.5	16.8	2–20
Wind speed	(m s^{-1})	1.2	0.9	3.4	3.1	1.1	1.0	3.1	3.3	3–11
Bar. press. change	(Pa h^{-1})	−21	26	−56	53	−29	32	−51	60	8–15
High alpha activity at sump										
Indoor radon	(pCi ℓ^{-1})*	8.1	6.5	6.6	9.6	6.8	7.1	5.3	8.6	6–12
Rn entry rate	(pCi ℓ^{-1} h^{-1})*	2.0	1.2	1.4	2.6	2.4	2.0	1.6	2.6	6–33
Soil activity†	(min^{-1})	236	243	152	105	73	70	77	64	3–25
Ventilation rate	(h^{-1})	0.25	0.17	0.19	0.28	0.29	0.28	0.31	0.29	3–18
Press. across walls	(Pa)	0.8	0.9	1.8	3.0	3.2	3.7	3.9	3.9	5–17
Temperature diff.	(°C)	3.8	6.1	3.8	9.4	19.4	22.7	20.2	20.5	5–39
Wind speed	(m s^{-1})	0.8	1.0	3.0	3.8	1.1	0.9	2.9	2.7	7–18
Bar. press. change	(Pa h^{-1})	−16	28	−69	82	−37	40	−82	85	16–31

* 1 pCi ℓ^{-1} = 37 Bq m^{-3}.

† Airborne alpha activity: 100 min^{-1} $\simeq$ 220 pCi ℓ^{-1} of ^{222}Rn.

The eight bins are obtained by determining whether the temperature difference (ΔT), wind speed (WS), and the rate of barometric pressure change (dB/dt) are higher (H) or lower (L) than the median value. For low alpha activity at the sump the medians were ΔT = 10.0°, WS = 2.0 m s^{-1}, and dB/dt = 0 Pa h^{-1}. For high activity the medians were ΔT = 13.6 C, WS = 2.0 m s^{-1}, and dB/dt = 3 Pa h^{-1}.

Table 5. Summary of results during three periods when the water level in the sump was controlled (mean ± one S.D.)

Dates (1982)	Time meas. (%)	Indoor radon (pCi ℓ^{-1})*	Radon entry rate (pCi ℓ^{-1} h^{-1})*	Sump activity† (min^{-1})	Soil activity† (min^{-1})	Air-exchange rate (h^{-1})	Wind speed (m s^{-1})	ΔT (°C)	ΔP (Pa)	Note
13–22 June	100	10.6 ± 4.2	1.94 ± 0.80	223 ± 48	93 ± 18	0.22 ± 0.14	1.3	4.0	1.0	1
24 June–6 July	98	2.7 ± 1.3	1.32 ± 0.49	215 ± 34	170 ± 31	0.54 ± 0.19	1.2	2.2	0.9	2
8–20 July	94	3.5 ± 1.3	1.49 ± 0.66	86 ± 68	202 ± 70	0.46 ± 0.21	1.3	1.1	0.7	3

* 1 pCi ℓ^{-1} = 37 Bq m^{-3}.

† Airborne alpha activity; 100 min^{-1} $\simeq$ 220 pCi ℓ^{-1} of ^{222}Rn.

Notes

(1) Sump-tile entrance always open, exhaust blower off.

(2) Sump-tile entrance always open, exhaust blower on.

(3) Sump-tile entrance occluded, exhaust blower off.

measured an average concentration of 3.5 pCi ℓ^{-1} (130 Bq m^{-3}), substantially greater than even the 2.6 pCi ℓ^{-1} (96 Bq m^{-3}) overall average for the first 15 weeks of the study (but less than the average for periods of high alpha activity at the sump). Furthermore, the activity at the sump was highly variable and seldom as low as the level observed previously during periods of low activity. It appears then that radon entry into the sump does not occur entirely through the drain-tile entrance, but also perhaps through cracks or through an undetected opening. The fluctuations in activity at the sump that were observed during the first 15 weeks thus may not have been caused, as we had first suspected, by changes in the level of water in the sump.

In fact, we cannot explain how the water level in the sump could change in a way that would account for the pattern of activity fluctuations we observed at the sump during the first 15 weeks. For example, it does not appear that pump operation can be triggered by water entering from the drain-tile system in such a way that the entrance remains open for more than a few minutes. Instead, on two isolated occasions, we observed that when the pump was triggered, either by rising water or manually, a rapid flow of water into the sump followed its emptying such that the drain-tile entrance was once again occluded. (One successive manual triggering did, however, leave the sump drained.) Thus the drain tile and surrounding gravel appear to constitute a water reservoir with sufficient

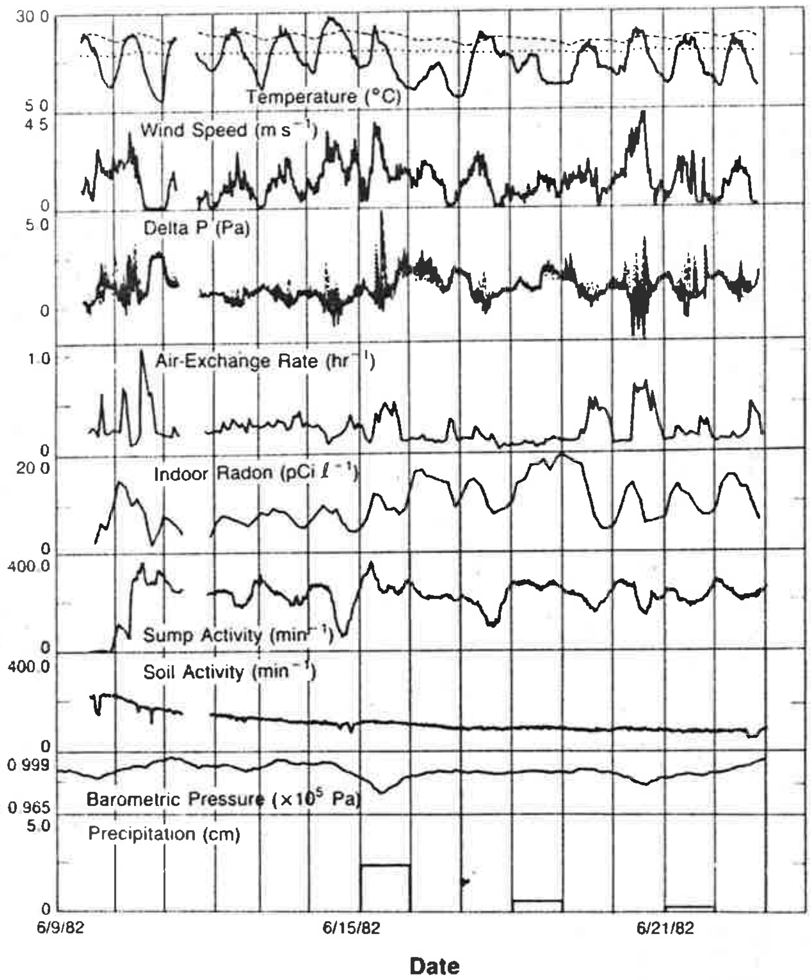

Fig. 6. Measurements during first control period when the level of water in the sump was maintained below the drain tile entrance. See caption to Fig. 3 for details; note that the scales for temperature, wind speed, ΔP, and barometric pressure differ from those in Fig. 3.

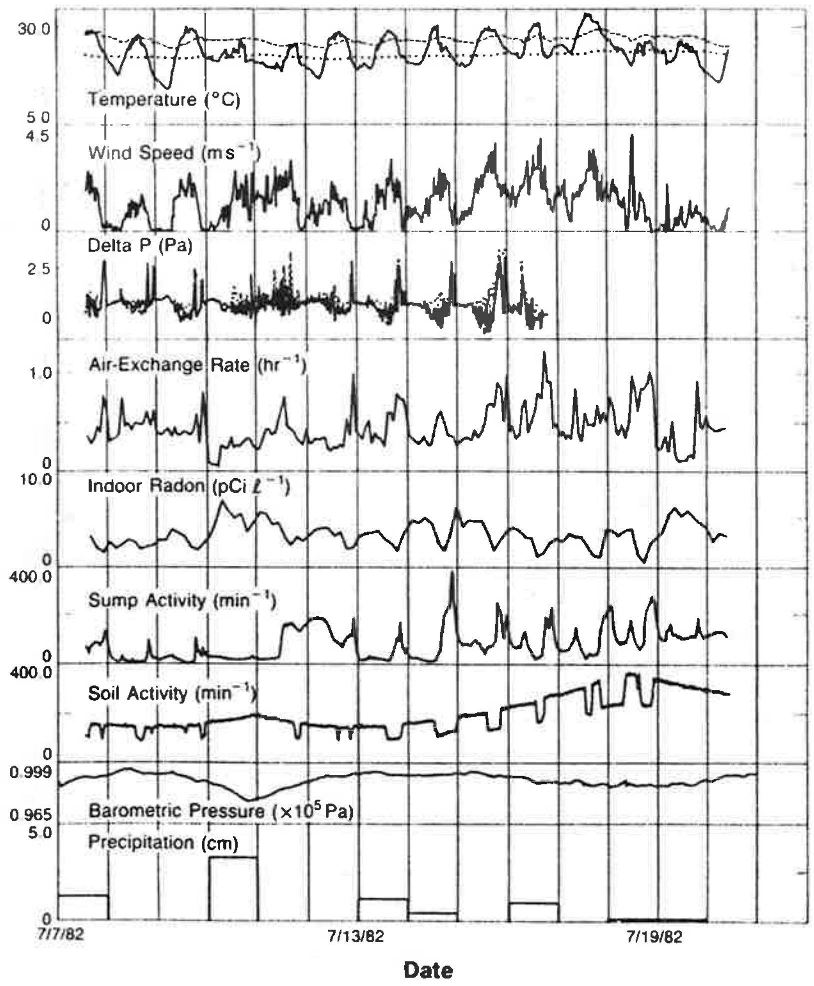

Fig. 7. Measurements during the third control period when the level of water in the sump was maintained above the drain tile entrance. See caption to Fig. 3 for details; note that the scale for indoor radon differs from that in Fig. 6.

capacity to partially refill the sump after pump operation concludes.

Two mechanisms (evaporation and washing machine operation) that could cause long periods with the water level below the drain-tile entrance are unlikely to have produced the observed pattern. Evaporation is a slow process and would not be expected to lead to the rapid fluctuations in activity that we observed. And although operation of the washing machine, which drained into the sump, could cause a rapid change in sump water level (a complete cycle triggers pump operation three times), the onsets of periods of high activity occur at broadly distributed times, including several instances in the middle of the night. This evidence suggests to us that the amount of water in the drain tile and gravel, rather than its level in the sump, may be the determining factor in whether the airborne alpha activity at the sump is high or low.

Striking patterns appear in the data presented in Fig. 7 and they merit mention even though we cannot fully explain their cause. In the plot of pressure differences across the basement walls, there is a sequence of rather sharp spikes which have the appearance of sudden depressurizations of the house for brief periods. These spikes occur on eight of the ten days in this plot for which there is pressure data, usually between late afternoon and late evening, and on several occasions double spikes are present. The same pattern, although less pronounced, can be seen in the air-exchange rate and sump activity plots. These results could be accounted for by the intermittent operation of a large exhaust fan used, for example, to cool the house. However the house is equipped only with small exhaust fans above the range and in the bathroom. For three reasons it seems unlikely that these could account for the observed patterns in the data: (1) such spikes were not observed until a few days prior to this final monitoring period; (2) the exhaust blower used during the experiments in which the sump water level was controlled did not increase the pressure difference (see Tabel 5) and (3) as evidenced by the relatively high average air-exchange rate during this period, windows and doors may have been open often, thereby reducing the pressure drop that a blower could generate.

The indoor radon concentration also shows a diurnal variation during this period with the maximum concentration, which occurs shortly after sunrise, being on average 65% greater than the minimum, which occurs close to sunset. This variation results, in part, from a difference in the air-exchange rate: the average rate in the late afternoon is about 30% greater than that in the morning. The remainder, though, must be ascribed to a difference in the radon entry rate. However, a potential explanation for the cause of this difference is complicated by the fact that both wind speed and temperature difference exhibit diurnal patterns that tend to offset one another as driving mechanisms.

Perhaps more puzzling is the pattern in the soil activity plot: on several occasions the count rate precipitously drops to 2/3 of its previous value, then, after a period of 30 min to a few hours, resumes its old value. These dips have a diurnal pattern: with one exception they occur between noon and midnight. Any explanation for these dips must allow (1) that only a portion of the response of the probe is due to radon, the rest being due to the short-lived daughters which are likely to be deposited on the cell walls and, thus, diminish in activity with a characteristic time of 30 min and (2) that the time constant of the probe in open air is about 1 h. Thus, reversals of direction of air flow in the soil, an attractive hypothesis because it could account for both the drop in soil probe activity and the increase in sump activity a short time later, would not be likely to produce dips as sharply defined as those observed. An instrumentation failure is also unlikely, although it cannot be ruled out.

DISCUSSION

The dependence of radon concentration on air-exchange rate

The air-exchange rate of a residence can be thought of as having several components: infiltration refers to the uncontrolled leakage of air through cracks and holes in the building shell driven by pressure differentials that arise from temperature differences and wind; natural ventilation refers to the air flow through open doors and windows; and mechanical ventilation results, for example, from the operation of an exhaust fan. In the two models of the dependence of radon concentration on air-exchange rate presented here, we assume that infiltration is the predominant component as is typical for U.S. houses during the heating season.

In the first model the radon entry rate is assumed to be constant, so that the radon concentration is given by

$$I = \sigma/\lambda_v, \tag{1}$$

where I is the radon concentration (pCi ℓ^{-1}), σ is the radon entry rate per unit house volume (pCi ℓ^{-1} h^{-1}), and λ_v is the air-exchange rate (h^{-1}). This model applies, for example, where radon enters the house primarily via molecular diffusion, or via tap water.

In the second model the radon entry rate has two components, a constant 'diffusive' component (σ_d), and a 'flow' component (σ_f), which is assumed to be proportional to the air-exchange rate. The resulting radon concentration is given by

$$I = \sigma_d/\lambda_v + k_f, \tag{2}$$

where $k_f = \sigma_f/\lambda_v$.

The flow component represents the entry of soil gas carrying a high concentration of radon into the house.

The two-component entry model has implicit simplifications. The term, k_f, is the product of two factors: the concentration of radon in the infiltrating soil gas and the fraction of infiltrating air that enters from the soil. For this term to be independent of the infiltration rate, either both of these factors must be independent of the infiltration rate, or they must vary in inverse proportion, conditions that will not be satisfied in general. For example, the radon concentration in the infiltrating soil gas may be subject to depletion if the infiltration rate is high. In addition, the fraction of infiltrating air entering the house through the soil depends on the wind speed relative to the temperature difference: for a given infiltration rate a high indoor–outdoor temperature difference leads to a greater average pressure difference across the soil than does a high wind speed. In spite of the simplifications in the model, however, it may adequately describe the average behavior of radon concentration as a function of infiltration rate.

In each of these models we have ignored the contribution of infiltrating outside air to the radon entry rate. This component would enter into (1) and (2) as a constant additive term equal to the outdoor concentration, which, in this case, averaged only 10% of the mean indoor concentration. We have also ignored the decay of radon as a removal process since its time constant ($0.0076\ h^{-1}$) is only 3% of the average air-exchange rate.

These models further assume that the house behaves as a single well-mixed chamber, i.e. that the average radon concentration in the air leaving the house is equivalent to the average indoor concentration. An indication of the degree of mixing is obtained by comparing the average indoor and basement radon concentration in Table 2. From 17 March to 4 May, while the forced-air furnace was still in use, there is good agreement between the basement and indoor radon concentration, indicating good mixing. During the last several weeks of the monitoring period, the basement concentration is seen to be somewhat higher than the average indoor concentration, consistent with our expectation that radon enters predominantly into the basement and that, with the furnace fan off, the mixing of air between the first floor and the basement is poorer.

These two models have been applied separately to the data for high and low airborne alpha activity at the sump and the resulting curves are plotted in Fig. 5. For low activity a least-squares fit to the three-hour data was used to determine the best estimate ± one standard error of σ_d and k_f to be 0.056 ± 0.005 pCi $\ell^{-1}\ h^{-1}$ (2.1 ± 0.2 Bq $m^{-3}\ h^{-1}$) and 1.15 ± 0.04 pCi ℓ^{-1} (43 ± 1 Bq m^{-3}), respectively. For the high activity data σ_d was assumed to be the same as for the low activity data; k_f was computed to be 6.0 ± 0.3 pCi ℓ^{-1} (220 ± 10 Bq m^{-3}). With the exception of a few points at high air-exchange rate for low activity, the second model is seen to fit the data much better than the first.

The diffusive and flow components of the radon entry rate model for this house are fairly stable with respect to changes in the data set. For example, to consider the effect of a bias that may result from applying a steady-state model to transient data, the low sump activity data were sorted into two groups according to whether the previous radon measurement had been higher or lower than the current one. The least-squares fit to these two groups yielded values of σ_d of 0.056 ± 0.009 and 0.051 ± 0.006 pCi $\ell^{-1}\ h^{-1}$ (2.1 ± 0.3 and 1.9 ± 0.2 Bq $m^{-3}\ h^{-1}$) and values of k_f of 1.0 ± 0.07 and 1.3 ± 0.06 pCi ℓ^{-1} (37 ± 3 and 48 ± 2 Bq m^{-3}. The entire data set for low sump activity was also analyzed with data for the month of May excluded, to eliminate the period when mixing between the floors was poorest. Here the two components were 0.066 ± 0.012 pCi $\ell^{-1}\ h^{-1}$ (2.4 ± 0.4 Bq $m^{-3}\ h^{-1}$) and 1.2 ± 0.07 pCi ℓ^{-1} (43 ± 3 Bq m^{-3}).

Despite this evidence that the radon entry rate increases with the infiltration rate, these results do not imply that mechanical ventilation is ineffective in reducing indoor radon concentrations. On the contrary, an earlier study by Nazaroff *et al.* (1981b) showed that a balanced mechanical ventilation system (i.e. one with equal intake and exhaust flows) was as effective as predicted by the first model in lowering indoor radon levels. However, an unbalanced ventilation system, such as an exhaust fan, may depressurize the house and therefore not produce desired results in controlling indoor radon levels.

Radon entry: the diffusive component

The fit to the diffusive component agrees well with our estimate of the contribution to radon entry of diffusion from concrete and from soil through the concrete. To estimate the concrete contribution, we assumed that the basement floors and walls were 15 cm thick, with a density of 2000 kg m^{-3} and that radon emanated from the concrete at a rate of 0.66 pCi $kg^{-1}\ h^{-1}$ (0.68×10^{-5} Bq $kg^{-1}\ s^{-1}$) [mean of 12 samples of concrete from Chicago, (Ingersoll, 1983)], half of which entered the house, resulting in 0.04 pCi $\ell^{-1}\ h^{-1}$ (1.5 Bq $m^{-3}\ h^{-1}$). To estimate the soil contribution, we assumed the average concentration of radon in the soil gas adjacent to the basement walls was 1000 pCi ℓ^{-1} (37,000 Bq m^{-3}), and that the 15 cm slab had a porosity of 0.068 and a radon diffusion length of 12.6 cm (Zapalac, 1983), resulting in 0.02 pCi $\ell^{-1}\ h^{-1}$ (0.7 Bq $m^{-3}\ h^{-1}$). Molecular diffusion into the sump through even an unoccluded drain tile entrance is negligible by comparison. Thus the total diffusive component is estimated to be 0.06 pCi $\ell^{-1}\ h^{-1}$ (2.2 Bq $m^{-3}\ h^{-1}$), in excellent agreement with our fit to the data.

Water flowing into the sump through the drain-tile system may contribute a small amount to the diffusive component of the radon entry rate. We estimate the average contribution to be an order of magnitude less than the maximum of 0.10 pCi $\ell^{-1}\ h^{-1}$ (3.7 Bq $m^{-3}\ h^{-1}$). This maximum rate was determined assuming that all of the precipitation (23.4 cm) that fell on or within 0.5 m of the house during the 15-week monitoring period flowed into the sump. The water is assumed to carry the equilibrium concentration of radon, 4100 pCi ℓ^{-1} (1.5×10^{5} Bq m^{-3}), which was determined based on the measured ^{226}Ra content of 1.9 pCi g^{-1} (70 Bq kg^{-1}), and assuming (1) that all of the radon produced in the soil enters the water and (2) that soil porosity and bulk density were 0.55 and 1.2 g cm^{-3}, respectively. Furthermore, all of the radon entering the sump with water is assumed to be released to the indoor air. This estimate clearly exaggerates the expected contribution in several respects: the flow of water into the sump, the concentration of radon in the water, and the transfer of radon from the water into the air.

Tap water also contributes to the diffusive component. Although the concentration of radon in tap water was not measured in this study, there are two compelling reasons to believe its contribution to the total entry rate to be small. First, the time pattern of indoor radon concentration does not show intermittent spikes corresponding to periods of heavy water use that are characteristic of houses which have tap water with high radon concentrations. Second, a recent study by Prichard and Gesell (1983) found relatively low concentrations of radon in the distribution systems of 174 municipal water supplies in the central United States. The expected contribution to the radon entry rate from the geometric mean concentration in that study, 115 pCi ℓ^{-1} (4250 Bq m^{-3}) is roughly 0.01 pCi ℓ^{-1} h^{-1} (0.4 Bq m^{-3} h^{-1}).

Radon entry: the flow component

The flow component, as determined above, cannot be as directly attributed to available transport mechanisms as the diffusive component. For illustrative purposes, we consider the data with high alpha activity at the sump during the first four weeks of monitoring. Table 3 shows that the average pressure measured across the basement walls was 3.5 Pa. During these times the radon entry rate was 2.0 pCi ℓ^{-1} h^{-1} (74 Bq m^{-3} h^{-1}), which is 1.7 pCi ℓ^{-1} h^{-1} (63 Bq m^{-3} h^{-1}) greater than the average entry rate for periods of low activity; we assume that this additional radon must enter with soil gas through relatively large openings in the basement floor or walls. If the average activity at the sump of 203 min^{-1}, corresponding to a radon concentration of 450 pCi ℓ^{-1} (16,700 Bq m^{-3}), reflects the average concentration of radon in the entering soil gas, then its flow rate into the house must be about 30 ℓ min^{-1}.

We can suggest two probable pathways for this flow. First, the pressure difference may drive a small flow of air through the bulk of the soil adjacent to the house. The second possibility is that the air flow is concentrated in small gaps that may exist between the basement walls and the soil, or in small cracks in the bulk of the soil, and that radon diffusing through the soil toward these gaps or cracks is swept along with the flow.

In assessing the first possibility we use Darcy's law for fluid flow per unit cross-sectional area through a porous medium

$$\mathbf{V} = -\frac{k}{\mu}\nabla P \qquad (3)$$

where k is the permeability, μ is the viscosity (18 $\times 10^{-6}$ nt sec m^{-2} for air at 10°C), and ∇P is the pressure gradient. The limited number of measurements of surface soils yield permeabilities in the range $(0.007\text{–}3) \times 10^{-10}$ m^2 (Buckingham, 1904; Corey, 1957; Evans and Kirkham, 1949), with the permeability of a given soil depending highly on the degree of compaction. Even though these data show a broad range, we expect still lower values for packed clay and higher values for gravel.

To model the flow through bulk soil we assume that the entire pressure difference is applied between the soil surface and the gravel that is presumed to surround the drain tile. Using an electrical analog with bipolar coordinates (Morse and Feshbach, 1953), we determine the flow into a pipe buried at depth d in an open field to be

$$Q = \frac{2\pi}{\sinh^{-1}(\sqrt{(d/a)^2 - 1})}\frac{\Delta p L k}{\mu}, \qquad (4)$$

where Δp is the total pressure drop across the soil, and a and L are the radius and length, respectively, of the drain pipe–gravel combination. Because of the presence of the basement wall, the true flow rate should lie in the range 0.5–1.0 Q. Estimating the values of a, L and d to be 0.15 m, 42 m (the perimeter of the house), and 2.0 m (the approximate depth of the basement floor below the soil surface), and assuming the soil permeability to be 10^{-10} m^2, a value at the high end of the range reported, the flow rate is then calculated to be in the range 45–95 ℓ min^{-1}, more than sufficient to account for the calculated entry rate of radon into this house. Although soil permeability may be much lower than the value assumed here, the concentration of radon in the soil gas may be several times greater than 450 pCi ℓ^{-1} (16,700 Bq m^{-3}), as discussed below.

The second possibility, that of air flow through gaps and cracks, is more difficult to assess quantitatively. In this case, provided the flow rate exceeds a minimum value, the rate of radon entry is limited by the diffusion of radon through the soil to the gap. We estimate the size of the gap by calculating the thickness of a channel, whose width equals the house perimeter and whose length equals the depth of the basement floor below grade, through which 30 ℓ min^{-1} would flow driven by 3.5 Pa. Using standard engineering formulae for flow through a channel, we determined the necessary thickness of the gap to be roughly 1 mm.

To determine how much soil must be contributing its radon to account for the observed indoor concentrations, we measured the radium concentration and radon emanation rate of soil samples taken adjacent to the house and in the yard. The results from these samples agreed with each other within a few per cent and showed a ^{226}Ra concentration of 1.88 pCi g^{-1} (69.6 Bq kg^{-1}) of which 41% produced radon that escaped from the soil grains. (The ^{228}Ra concentration was 0.7 pCi g^{-1}, or 25 Bq kg^{-1}.) A radon entry rate of 2.0 pCi ℓ^{-1} h^{-1} (74 Bq m^{-3} h^{-1}) could therefore be accounted for by 1.6×10^8 g of soil; based on our measurement of the density of this soil in the laboratory to be 1.2 g cm^{-3}, this mass corresponds to a shell of soil approximately 80 cm thick around the basement walls and floor. Since the diffusion length of radon in soil has been found to lie in the range 60–150 cm (Tanner, 1964; Colle *et al.*, 1981), the second flow possibility is not excluded by this result. Neither is the first, for if we assume that the required 30 ℓ min^{-1} of flow passes uniformly and entirely through the 80 cm shell, we find a velocity of 5 cm h^{-1}, five times greater than the diffusion velocity for a diffusion length of 100 cm; thus pressure driven flow downward could dominate diffusion upward as a means of removing radon from the soil.

The maximum concentration of radon in the soil gas is obtained by assuming that radioactive decay is the only removal process. Given a soil density ρ, emanating radium concentration e, and soil porosity ε, this concentration is (Nero and Nazaroff, 1984)

$$C_\infty = \frac{\rho e}{\varepsilon}. \quad (5)$$

A bulk soil density of 1.2 g cm^{-3} corresponds to a porosity for dry soil having no organic matter of 0.55 (Rawls, 1983), yielding C_∞ of 1700 pCi ℓ^{-1} (63,000 Bq m^{-3}) for the soil samples collected at this house, several times greater than the average concentration at the sump for high activity periods.

The effect of fireplace operation

There is another significant clue in the data supporting the hypothesis that radon entry into this house is predominantly driven by pressure differences across the basement walls. On five occasions during the monitoring period, the homeowner operated his fireplace. It has been previously observed that fireplace operation can, because of the large rate of air flow out of the chimney, depressurize a house and significantly increase the air-exchange rate (Modera and Sonderegger, 1980). Such behavior was observed in this study as well: the highest values of air-exchange rate during the 15-week monitoring period occurred during periods of fireplace operation.

In Fig. 8 are plotted air-exchange rates and radon concentrations for the five instances of fireplace operation. In each case three values of these parameters are plotted. The first and last are the average values for the twelve hours immediately preceding and following fireplace operation, respectively, and the middle value is the average during fireplace operation. The effect of the fireplace on air-exchange rate is consistent and clear, but the effect on radon concentration is irregular at best. In cases 3–5, the radon concentration is relatively low; for 3 and 4 the fireplace operation causes a much smaller decrease in concentration than might be expected based on the increase in air-exchange rate, and in case 5 there is no discernible effect. These cases therefore suggest that depressurization causes an increase in the radon entry rate. In the first two cases, the radon concentration is substantially higher and the concentration changes are irregular. In fact, during the times for which these data were plotted there were step changes in airborne alpha activity at the sump. In case 1, the activity was high until a few hours after fireplace operation ended, then became low; in case 2, it was low until a few hours after fireplace operation began, then became high. In these two cases, as in the rest of the study, the activity at the sump is an indicator of a factor that has a greater influence than the air-exchange rate on the indoor radon concentration.

CONCLUSIONS

In this study we found (1) that the airborne alpha activity at the sump varied significantly, in a bimodal

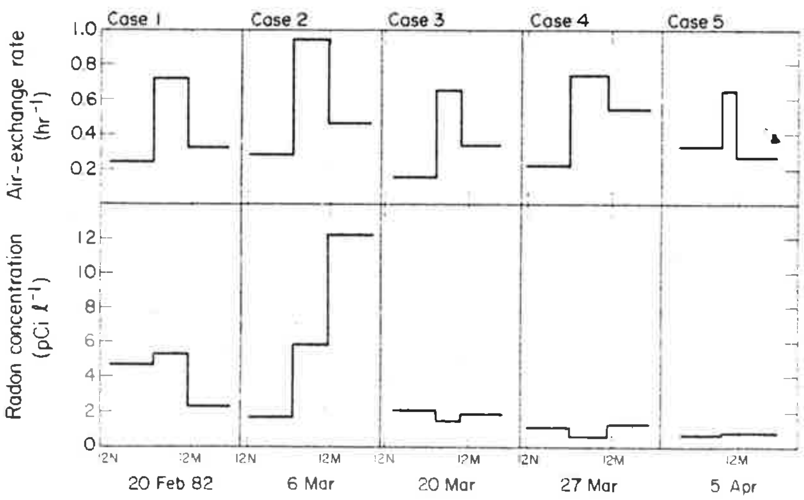

Fig. 8. Measurements of air-exchange rate and radon concentration for five periods during which the fireplace was operated. The three intervals plotted for each period are as follows: (1) 12 h prior to fireplace operation; (2) period of fireplace operation (variable duration); and (3) 12 h following fireplace operation.

fashion, and correlated well with indoor radon concentration and (2) that for either mode the radon concentration and the air-exchange rate, although both broadly distributed, did not vary in inverse proportion. The relationship between radon concentration and air-exchange rate can be understood in the context of a model in which radon entry has two components: diffusion and flow. In fitting this model to the data, we found that on average the flow component was 30 times as great as the diffusion component for periods of high activity at the sump and four times as great for periods of low activity. The diffusion component obtained by fitting the model to the data is well matched by the estimated diffusive entry from concrete and soil. The flow component could be accounted for either by flow along the basement walls or by flow through the bulk of the soil adjacent to the basement. In the latter case, assuming the average radon concentration of 450 pCi ℓ^{-1} (16,700 Bq m^{-3}) measured at the sump reflects the average in the entering soil gas, the soil permeability must be at the high end of the range of literature values found.

To the extent that our description of the radon entry into this house is accurate, and that the dominance of flow transport is not atypical, there are important implications. First, as was concluded in the Canadian remedial action program, among the most effective control strategies are likely to be those that seal the pathways by which soil gas enters a house, or those that ventilate the soil adjacent to and underneath the house (Eaton, 1982). Second, in evaluating the effect that a change in the air-exchange rate may have on the indoor radon concentration, one must consider not only its effect on the rate of removal of radon from indoor air, but also the change in radon entry rate that may result.

The predominance of pressure-driven transport would also affect potential means of identifying areas in the United States, and perhaps elsewhere, where high indoor radon levels are likely to occur. By itself the emanating radium content of the soil is probably an insufficient indicator of the radon entry rate. It is likely that the permeability of the soil is at least equally important, and the climate of the region and the building construction practices may also play important roles.

A number of questions remain for future investigation. We must determine whether soils adjacent to houses are sufficiently permeable to permit the necessary soil-gas flows; experiments should be conducted, perhaps using the controlled release of a tracer gas, to verify the soil-gas flow hypothesis and to determine whether the flow occurs through the bulk of the soil or along the basement walls; theoretical analyses could usefully be performed on the relative importance of the various driving forces such as wind speed, temperature difference and barometric pressure; and, ultimately, control techniques need to be refined and tested so that cost-effective corrective measures may be taken in houses with excessively high radon levels.

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