Title
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Publication Date
1983-03-01

LBL-15839 c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

Presented at the Air Pollution Control Association,
Inc. (APCA), 76th Annual Meeting, Atlanta, GA,
June 19-24, 1983

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March 1983

**ENERGY
AND ENVIRONMENT
DIVISION**

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

Presented at the Air Pollution Control
Association, Inc. (APCA), 76th Annual
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Paper 83-9.8

LBL-15839
EEB-Vent 83-14

CONTINUOUS MEASUREMENTS OF RADON ENTRY IN A SINGLE-FAMILY HOUSE

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This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Abstract

The body of information in this paper is directed to researchers and others interested in the field of indoor air quality. It is a progress report that describes detailed measurements during a six-month period of radon concentration, ventilation rate, and other environmental parameters that affect radon entry in a single-family house. Average radon concentrations in the house varied between 0.1 and 18.4 pCi/l during this period; the mean value observed was 3.1 pCi/l. Ventilation rates ranged from 0.03 to 1.00 ach; the mean value was 0.25 ach. The data show that the radon source strength varied substantially during the measurements; we continue to examine the environmental parameters measured to obtain a better understanding of the processes that influence radon entry into the house. The major radon entry site in this structure appears to be the basement sump. A portion of the time variation in the entry rate can be associated with changes in the water level in the sump that couples and decouples the sump with an exterior drain tile system.

Introduction

Controlling air quality within buildings requires understanding both the physical and chemical processes causing contaminant entry or production in the volume and also the mechanisms that remove these contaminants. This paper concentrates on the former; it provides detailed experimental data about the time variation of radon entry into a single-family residence and environmental parameters that may influence the entry rate.

Radon differs from many of the other indoor contaminants because it occurs naturally: its generation does not depend on a man-made process or activity. Radon-222 (radon) is the decay product of radium-226; both radionuclides are members of the decay chain of uranium-238. As a noble gas, radon is chemically inert and may be transported by diffusion or convection from material containing its radium parent into the surrounding air.

Radon has several chemically active short-lived daughters: Po-218, Pb-214, Bi-214, and Po-214. Because of their chemical activity, these radionuclides can be collected in the lungs, either directly or with airborne particles to which they have adhered. Each of these radionuclides quickly emits one or more alpha particles, a type of radiation that is highly effective, per unit of energy deposited, in damaging tissue. The effects of such radiation damage have been observed in the high incidence of lung cancer among miners exposed for long periods to high levels of radon and its daughters. Estimates of the presumed risk derived from linear dose-response models of cancer induction indicate that exposure to radon and its daughters contributes significantly to the total cancer risk associated with natural background radiation.

Several studies have reported measurements of radon concentrations in houses in the United States [1-5]. The available data indicate that radon concentrations indoors, particularly in houses, most often lie in the range of 0.5 to 2 pCi/l; however indoor levels an order of magnitude or more higher have also been observed. While suggestive of trends, these studies are an incomplete characterization of the indoor environment in this nation.

The measurements in the studies above were performed either using grab-sampling techniques to obtain an individual measurement of radon concentration or using a passive sampler to obtain an integrated long-term average value. Little information exists about the time variation of radon concentrations within a house. Two such studies are those of Spitz et al.[6] and Hess et al.[7] both indicating substantial time variations. Work examining the variability of radon concentrations is reviewed elsewhere [8]; this work has generally not included measurements of environmental parameters that may affect the concentrations of radon observed in the space.

Work of our group reported elsewhere has indicated that differences in radon input rate can account, in a large part, for the large differences in indoor concentrations from one house to another [3]. In a given house, both the radon input rate and the ventilation rate vary significantly and may even be correlated, presumably because of a common dependence on environmental parameters [9]. Considering the interest in understanding and controlling unacceptably high radon concentrations, these observations suggest the need for more comprehensive studies elucidating the ways in which various factors affect radon entry into homes. These same studies could serve to increase our understanding of the dependence of ventilation rates on environmental conditions.

Because of our interest in these questions we have undertaken a detailed study in a single house with the following objectives:

(a) to measure the radon concentration and ventilation rate as a function of time for an extended period.

(b) To calculate the radon input rate from the results of (a).

(c) To correlate the input rate of radon with coincident measurement results of environmental parameters, and

(d) to infer information about radon transport from these experimental results.

This paper presents some preliminary results from the study.

Experimental Details

House Description

The house chosen for this study, an occupied residence near Chicago, is a one-story structure with a finished basement. Floor plans of the basement and first floor are presented in Figures 1 and 2. The house, built in the 1950's, has a wood frame construction and a basement of poured concrete. The floor area of the basement and first floor, all conditioned area, is 2250 ft^2. The heating system is an oil furnace with a forced air distribution system.

The house was chosen for three reasons. First, the radon concentration in this house had been measured previously and was shown to be higher than the nominal (0.5 - 2) pCi/l concentration that appears to be typical of U.S. housing. The higher concentrations improve the measurement precision and also make the house more interesting from the point of view of understanding how to control high indoor radon concentrations. Second, the house was in reasonable proximity to another group that has done research on indoor radon — and the house owners were also interested in the radon question. This support considerably lessened the difficulty of maintaining a long-term field experiment.

Measured Experimental Parameters

Experimental parameters measured, the measurement techniques used, and the measurement intervals are reported in Table I. We measured the ventilation rate, the indoor radon concentration, two airborne alpha activities related to potential radon sources, and a range of environmental parameters that could affect the ventilation rate and the radon input rate. The measurements were begun in February 1982 and continued until mid-July of that year. The basic instrumentation system used, the AARDVARK, has been described in detail elsewhere [10] and will be described but briefly here.

Ventilation rates were measured using sulfur-hexafluoride tracer gas decays performed by an automated injection-decay system. Tracer gas was injected into the return air duct of the forced-air heating system until the concentration of tracer reached 5 ppm. Injection was then stopped and concentrations monitored for the next 90 minutes. Sampling occurred at six points in the space; the flow from each sampling point was adjusted to be proportional to the volume sampled and mixed in a manifold to yield concentrations characteristic of the entire volume. The slope of a linear fit of the natural log of the concentration versus time yields the ventilation rate.

Three radon-related measurements were made continuously over three-hour intervals. The first measured the average radon concentration of the entire house using a monitor based on a flow-through scintillation flask (as described by Thomas and Countess [11]). This measurement used the same sampling configuration as the ventilation rate measurements. Alpha activity monitors based on open scintillation flasks into which radon can diffuse were used for two source-related measurements. One such detector was placed over the sump in the basement, a suspected entry point for radon. A second diffusion detector was emplaced in the soil outside the building, with the detector opening at a depth of about 0.5 m, approximately 0.5 m from the basement wall.

Wind speeds were monitored using a Weather Measure anemometer mounted on a 10-m weather tower located adjacent to the house. Data were observed at 3-min intervals and stored as 30-min averages.

Temperatures were monitored at five locations using linearized thermistors. Shielded thermistors were used to measure the outdoor temperature and two indoor temperatures; a third indoor measurement was an effective temperature obtained using a globe thermometer. Soil temperatures were monitored using a thermistor buried alongside the soil alpha detector.

Temperatures were observed at 3-minute intervals and logged as 30-minute averages.

The differential pressure across each basement wall face was measured at locations 10 cm above the grade line using a Validyne pressure sensor. The reference pressure was measured in the basement at the same height as the pressure taps. Again, each pressure was sampled every 3 minutes; 30 minute averages of the pressures were stored.

Barometric pressure and precipitation data were obtained from the National Weather Service located at O'Hare International Airport (approximately 10 miles from the site).

Experimental Results

Weekly Summary

Table II gives a weekly summary of measured results covering the interval from 2.17.82 to 5.31.82. Data were obtained during 95% of this period. Individual entries in this table are weekly averages plus or minus one standard deviation. The radon source rate is a value calculated from the observed indoor concentration and the air exchange rate. The sump and soil observations of source radon are listed as counts per minute; an approximate calibration of these devices is that each 100 counts per minute corresponds to approximately 250 pCi/l in air under the sump cover or in the soil.

The temperature difference listed is the average indoor temperature minus the outside temperature. The pressure differences shown are average outside pressure on the four basement walls minus the inside pressure.

Radon Concentration

Figure 3 shows daily average radon concentration as a function of time for the main period of the experiment. The average concentration for this interval is 2.6 pCi/l. Ten percent of the three-hour measurements yielded concentrations larger than 6.0 pCi/l; the median value of all the results is 1.7 pCi/l. A major objective in analyzing these results is to explain the concentration peaks that are seen during the course of this work.

Ventilation Rate

The daily average air exchange rate, measured using the automated SF_6 decay system described above, is shown in Figure 4. The mean value for the entire study is 0.28 ach, the geometric mean is 0.23 ach. It is important to note that this measurement gives the total ventilation rate of the structure, including both infiltration and all other ventilation that is normally attributed to occupancy effects.

During the period from 6.10.82 to 6.30.82, a perfluorocarbon tracer (PFT) gas system developed at Brookhaven National Laboratory (BNL) [12] was installed to measure the ventilation rate. Two PFT sources and four diffusion tube samplers were used in the measurement. After analyzing the samples, the BNL research team calculated an average ventilation rate for this time interval of 0.31 ach. Our average based upon 306 SF_6 decay measurements during the same period is 0.33 ach.

The variations in the radon concentrations cannot be explained from the variation in ventilation rate. This can be seen most clearly if the radon source strength is calculated.

Radon Source Strength

For steady-state conditions, one can calculate the indoor radon concentration by equating radon entry rates and the radon removal rate.

$$F + I\ C_o = I\ C + \lambda\ C.$$

where:

C is the indoor radon concentration [pCi/l]

F is the radon source strength [pCi l^{-1} h^{-1}]

I is the ventilation rate [h^{-1}]

C_o is the outdoor radon concentration [pCi/l] and

λ is the radon decay constant [0.0075 h^{-1}].

Since $I\ C_o$ is usually small compared to F, and I is much larger than λ this equation yields a simple expression for the radon entry rate:

$$F = I\ C.$$

For time-varying conditions, the entry rate has a more complex dependence on ventilation rate and radon concentration, but the average entry rate may be approximated by a linear combination of ventilation rates and radon concentration values as discussed in Nazaroff et al.[10]. Using this approach with the data presented in Figures 3 and 4, we compute the daily average source strength shown in Figure 5.

Comparison of the variation of radon concentration, shown in Figure 3, and radon source strength in Figure 5 shows that some of the variation in radon concentration can be attributed to the ventilation. However, a larger fraction is caused by variations in the radon source strength itself. This leads to the major questions we anticipated, i.e., what is the source of the radon observed in the house and what environmental parameters govern the behavior of the radon source strength?

Identification of the Radon Source

Description of the Sump

In addition to the measurements yielding the average concentration of radon gas within the house, one of the diffusion-based radon sampling probes allowed localized measurements of radon concentrations at sites suspected of being entry points. One such site, a sump located in the NE corner of the basement, is shown in cross-section in Figure 6.

This sump contains a submersible pump that removes any water collected by pumping the water into the city storm sewer line (located above the level of the sump). Of particular interest for this study was an opening in the side of the sump, about 15 cm above its bottom, connected to a weeping tile drainage system located adjacent to the foundation walls of the house. The limit switches for the submersible pump were located such that when the pump stopped after pumping water out of the sump, the weeping tile entrance was open to the air in the sump. Thus, depending on the level of the water in the sump, the drain tile system constitutes a highly permeable pathway between the soil and the house.

Radon Measurements at the Sump

The implications of this observation are indicated in Figure 7. This figure shows measured radon concentration, the calculated radon source strength, measured radon activity at the sump (marked sump monitor in the Figure), and measured radon activity in the soil for a one-week period early in our measurement program. The contrast between the radon activity in the soil and that observed at the sump is striking. While the activity in the soil varies slowly, the activity at the sump shows a step-function-like behavior. The radon concentration in the house follows the activity observed at the sump with some regularity. The cause of the peaks is unknown; however, the second (which has an extraordinarily high radon source strength) is coincident with the operation of the fireplace.

Proper operation of a fireplace requires a substantial amount of combustion and make-up air. When operated in a tight house such as this, exhausting a large volume of air through the chimney causes the pressure in the house to decrease. This, in turn, increases the air leakage through all leakage sites in the shell of the house and, in particular, through openings connected to soil gas bearing radon.

The example shown in Figure 7 is relatively transparent to analysis; other results show similar behavior but more complex patterns. An example is shown in Figure 8. Focusing our attention on the solid line (radon concentration) and the long dashed line (the radon probe at the sump) we observe changes similar to those shown in Figure 7. The concentration observed at the sump appears to be very high or very low; the radon concentration in the house tends to follow the concentration at the sump. The peak seen on 2.20.82 (marked S in the Figure) has a particularly large source strength (short-dashed line) and is related again to fireplace operation. Thus the two largest peaks in source magnitude seen in the first half of Figure 5 appear to arise from fireplace operation.

We should not leave the impression with the reader that all measurements showed such erratic behavior. Figure 9 shows a weekly data summary when the radon concentration and source strength are relatively constant. The radon probe at the sump had been removed during this period because of problems with the sump pump. Similar results were observed for the six-week period beginning 17 March even though the fireplace was operated three times during this period.

Sump Water Level Tests

Three sets of measurements were made in June and July, while controlling the sump to provide additional information about radon entry. The results of these measurements are listed in Table III. During the first measurement period, the sump was pumped out and the floats adjusted so that the weeping tile entrance remained open at all times. Radon concentration measurements of the radon activity at the sump are shown in Figure 10 (cf. the long dashed line marked "sniffer").

The radon concentration in the house is considerably higher during this period than typical values that are seen at other times; the activity at the sump no longer shows its dual-state behavior. Instead of extended periods when the activity is virtually zero (as in Figure 7 and 8), the activity changes slowly with a period of the order of one day superimposed on a larger constant background. Correspondingly, the indoor radon concentration shows something approaching a diurnal variation as seen by others [8].

During the second interval the sump was always open but an exhaust blower was installed in the basement and run continuously. The sump activity remained high but the indoor concentration dropped from an average of 10.6 pCi/l to 2.7 pCi/l.

During the third interval the floats in the sump were adjusted so that the weeping tile entrance was always occluded. The exhaust blower remained off during this period. Figure 11 shows sump radon activity and indoor concentration during this period. In this case, both the radon activity at the sump and the activity in the soil (as shown by soil probe counts) exhibit behavior that had not been seen previously. The activity at the sump shows sharp rises with approximately daily periodicity; the soil probe shows sharp drops in activity that occur a few hours before the spikes seen at the sump. We are continuing to analyze this behavior. It is clear, however, that the presence of water above the drain tile entrance is not sufficient to prevent high concentrations of radon at the sump. It seems likely either that radon is being transported into the sump with the ground water, or that an unidentified pathway from soil into the sump exists.

Conclusions

This paper is a progress report; analysis of these extensive data sets continues. Some implications, however, are clear even at this preliminary stage of analysis.

Measurements of the radon concentration and ventilation rate as a function of time show significant variation. This reinforces the position that single grab-sample measurements of either parameter are unreliable estimates of long-term average behavior. Rather, integrated sampling techniques should be employed for exposure estimation.

Calculations of the radon source strength from the concentration and ventilation measurements show a time-varying radon input rate. The radon concentration within a structure is not simply a function of the ventilation rate: variations in concentration appear to arise, in large part, from changes in the radon source strength. We are continuing analysis of the data (e.g., that of Figure 11) to identify possible correlations between radon source strength and environmental parameters. It seems clear that when radon levels are high the basement sump is the dominant pathway in this building. We are beginning more detailed analyses of the time variation of this pathway, at the same time considering how to characterize the behavior of less eccentric sources.

Acknowledgments We thank Mike Essling and Richard Toohey of Argonne National Laboratory for their assistance in maintaining the equipment while in the field. We also have relied on the technical expertise of Lloyd Davis, Helmut Feustel, and James Koonce of our staff during this project.

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Table I. Measured Parameters

Parameter	Technique	Interval
Air-Exchange Rate	SF_6	90 min
Radon: Indoor	Flow-through Scint. Flask	180 min
Sump Cover	Diffusion Scint. Flask	30 min
Soil	Diffusion Scint. Flask	30 min
Wind Speed	Anemometer	3/30 min
Temperatures: Indoor, Basement, Outdoor, Soil	Thermistor	3/30 min
Pressure Across Basement Walls (NESW)	Validyne Pressure Trans.	3/30 min
Barometric Pressure	National Weather Service	Hourly
Precipitation	National Weather Service	Daily

Table II. Weekly Summary of AARDVARK Chicago Data.

Dates	% Time Meas.	Indoor Conc. (pCi/l)	Radon Source Rate (pCi/l-hr)	100 c/min ≡ 250 pCi/l Sump (cpm)	Similar Calibration Soil (cpm)	Air-Exchange Rate (hr^{-1})	Wind Speed (mph)	ΔT °C	ΔP PA
2/17-2/23/82	81.8%	5.2 ± 3.5	1.49 ± 1.45	141 ± 99	10 ± 3	0.29 ± 0.14	4.7 ± 2.7	17.6	1.9
2/24-3/02/82	91.7%	1.8 ± 1.5	0.41 ± 0.40	31 ± 83	97 ± 31	0.23 ± 0.04	3.1 ± 2.8	19.4	2.0
3/03-3/09/82	99.4%	4.1 ± 3.3	1.60 ± 1.99	129 ± 114	106 ± 25	0.34 ± 0.17	5.0 ± 2.5	23.6	2.4
3/10-3/16/82	99.8%	6.2 ± 3.9	1.44 ± 1.00	124 ± 121	86 ± 19	0.23 ± 0.05	6.1 ± 3.0	11.9	1.9
3/17-3/23/82	97.9%	1.9 ± 0.7	0.38 ± 0.24		145 ± 22	0.23 ± 0.13	4.7 ± 2.6	12.4	1.7
3/24-3/30/82	92.0%	1.5 ± 0.5	0.37 ± 0.17		115 ± 20	0.29 ± 0.17	6.2 ± 3.3	12.6	2.0
3/31-4/06/82	97.9%	1.2 ± 0.5	0.28 ± 0.15		136 ± 14	0.26 ± 0.12	8.3 ± 4.0	12.7	2.3
4/07-4/13/82	97.6%	1.6 ± 0.5	0.33 ± 0.13		95 ± 10	0.21 ± 0.05	5.2 ± 2.7	13.1	1.7
4/14-4/20/82	94.6%	1.8 ± 0.7	0.31 ± 0.19		136 ± 19	0.17 ± 0.05	6.2 ± 3.2	6.6	1.4
4/21-4/27/82	99.1%	1.5 ± 0.5	0.25 ± 0.14		119 ± 13	0.16 ± 0.005	5.2 ± 2.7	8.6	1.3
4/28-5/04/82	97.9%	2.9 ± 2.6	0.28 ± 0.48		232 ± 34	0.10 ± 0.04	3.6 ± 2.6	3.5	0.9
5/05-5/11/82	99.4%	1.6 ± 0.5	0.17 ± 0.12		268 ± 47	0.13 ± 0.09	4.6 ± 2.7	3.1	0.9
5/12-5/18/82	86.6%	3.9 ± 3.7	0.79 ± 1.15		259 ± 52	0.21 ± 0.12	3.1 ± 2.1	5.7	0.5
5/19-5/25/82	97.3%	1.6 ± 1.1	0.23 ± 0.22		229 ± 21	0.20 ± 0.19	2.4 ± 1.6	5.7	0.7
5/26-6/01/82	84.5%	2.7 ± 3.0	0.73 ± 1.3		227 ± 10	0.22 ± 0.14	1.7 ± 1.3	2.5	0.4
Entire Period	95.4%	2.6 ± 2.6	0.60 ± 0.97		151 ± 76	0.22 ± 0.13	4.7 ± 3.2	10.6	1.5

Table III. Sump Water Level Experiments - AARDVARK Chicago Study.

Dates	% Time Meas.	Indoor Conc. (pCi/l)	Source Rate (pCi/l/hr)	Sump (cpm)	Soil (cpm)	Air-Exchange Rate (hr^{-1})	Wind Speed (mph)	ΔT °C	ΔP PA
6/13-6/22/82[1]	99.6%	10.6 ± 4.2	1.94 ± 0.80	223 ± 48	93 ± 18	0.22 ± 0.14	2.8 ± 1.8	4.0	0.7
6/24-7/06/82[2]	98.2%	2.7 ± 1.3	1.32 ± 0.49	215 ± 34	170 ± 31	0.54 ± 0.19	2.6 ± 2.0	2.2	0.7
7/08-7/20/82[3]	94.2%	3.5 ± 1.3	1.49 ± 0.66	86 ± 68	202 ± 70	0.46 ± 0.21	2.9 ±2.0	1.1	0.4

[1] Sump always open, exhaust blower off
[2] Sump always open, exhaust blower on
[3] Sump occluded, exhaust blower off

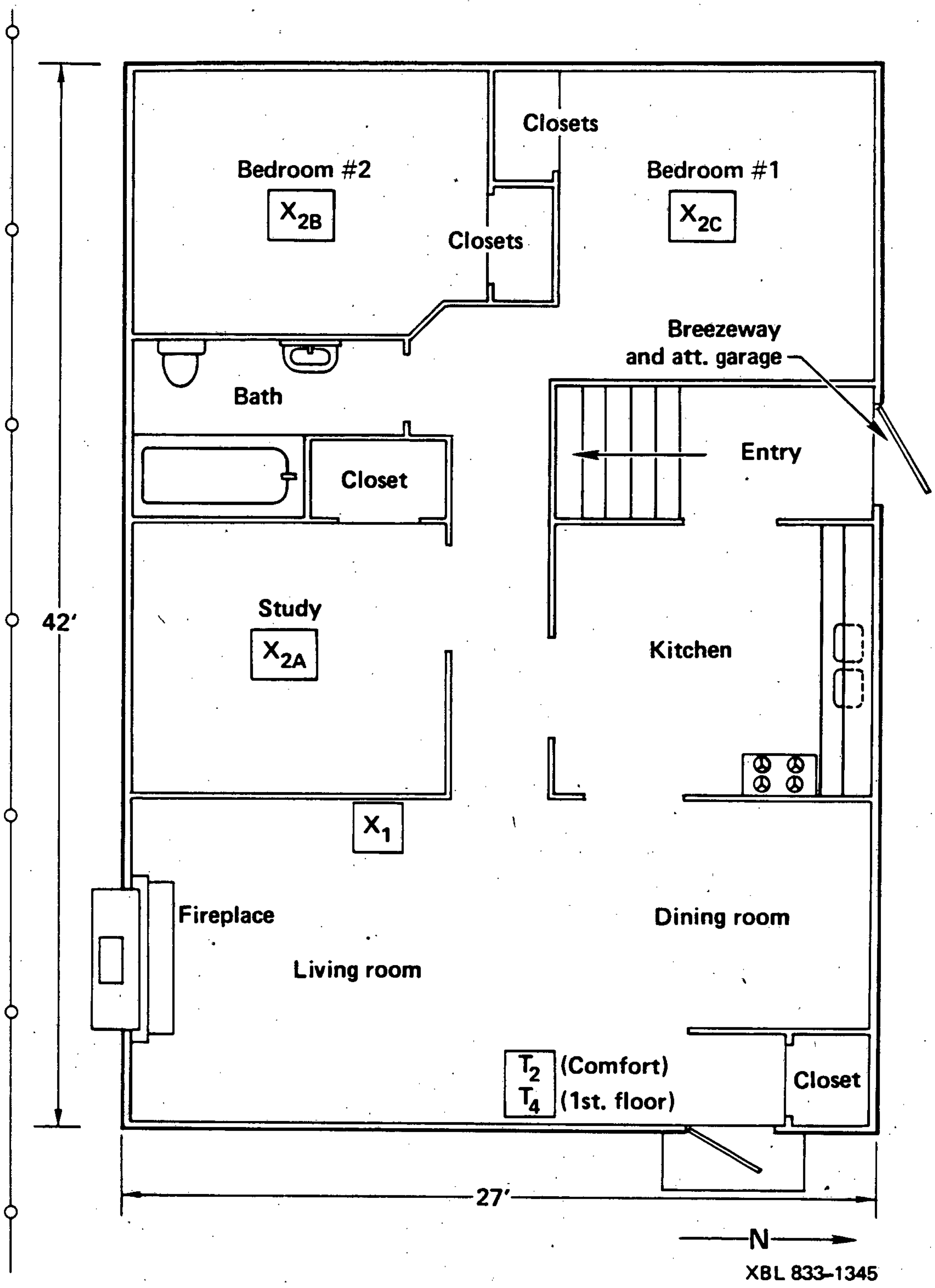


Figure 1 First-floor plan of the house. The points marked X_i are locations of the sampling points for radon and tracer gas; the points marked T_i indicate the temperature sampling locations.

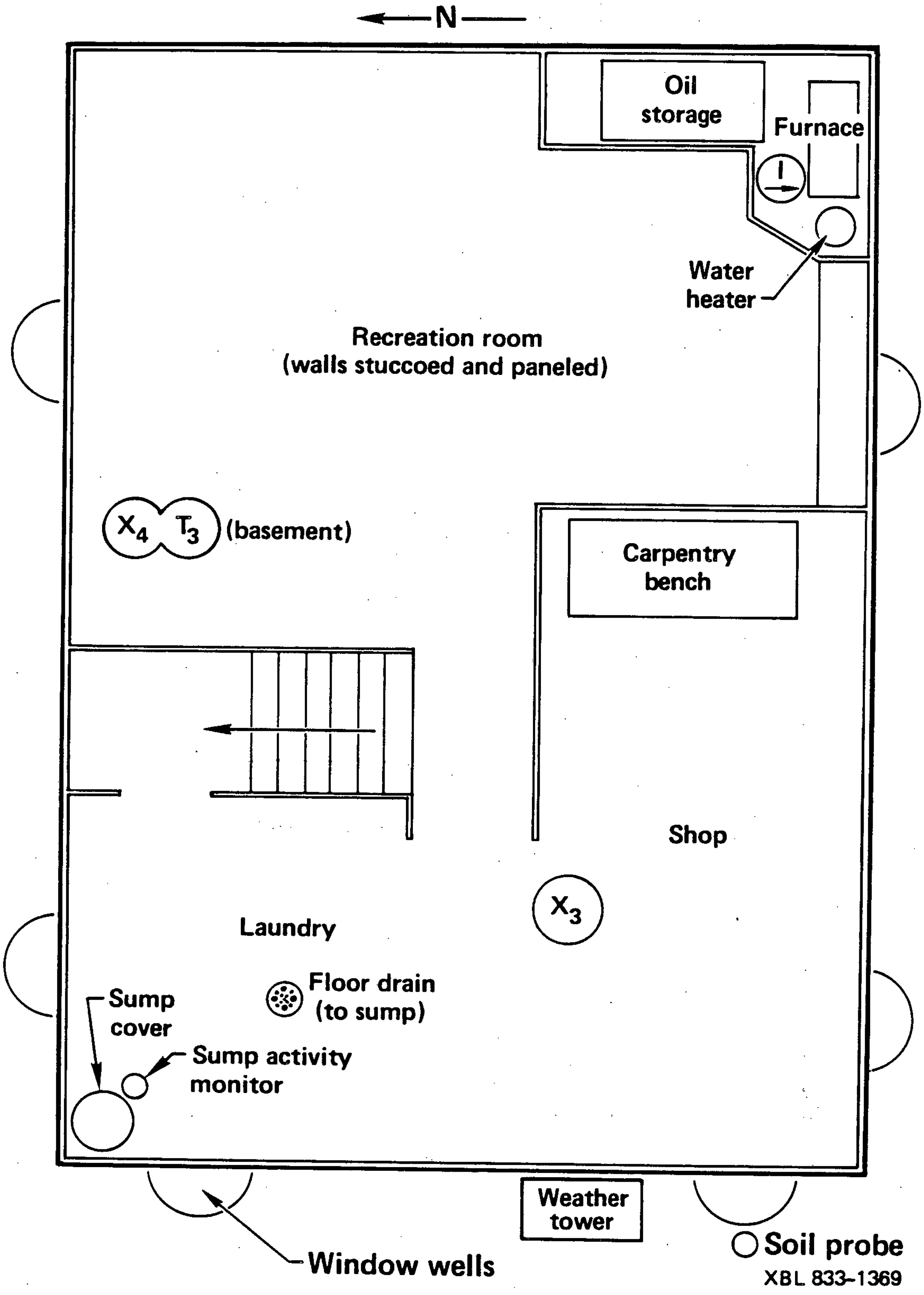
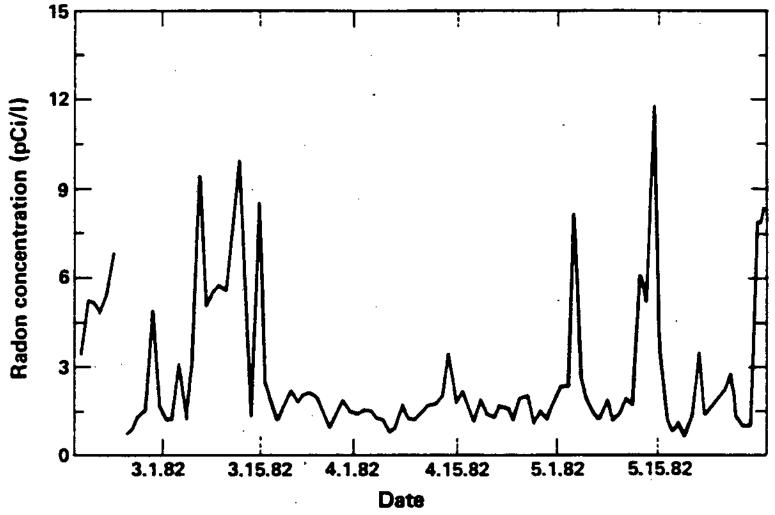


Figure 2 Basement plan of the house. The points marked X_i are locations of the sampling points for radon and tracer gas; the points marked T_i indicate the temperature sampling locations. The point marked I next to the furnace indicates the injection point for the tracer gas.



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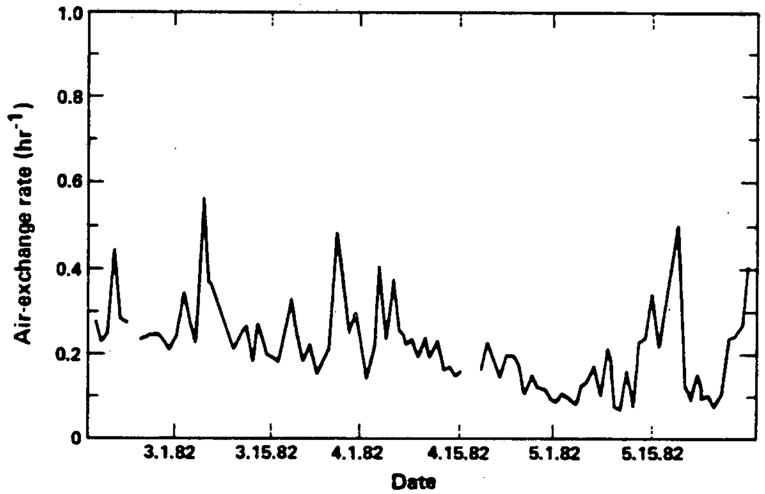

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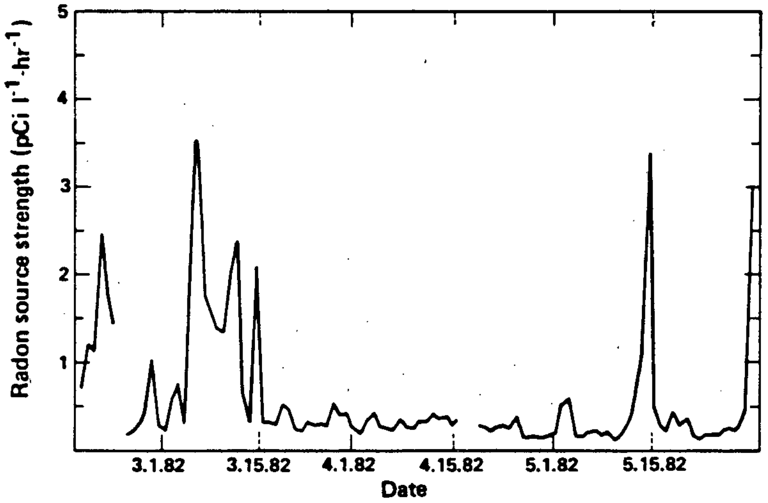

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Figures 3-5 Measured time variations of radon concentration, ventilation rate, and calculated values of radon source strength for the period from mid-February through May.

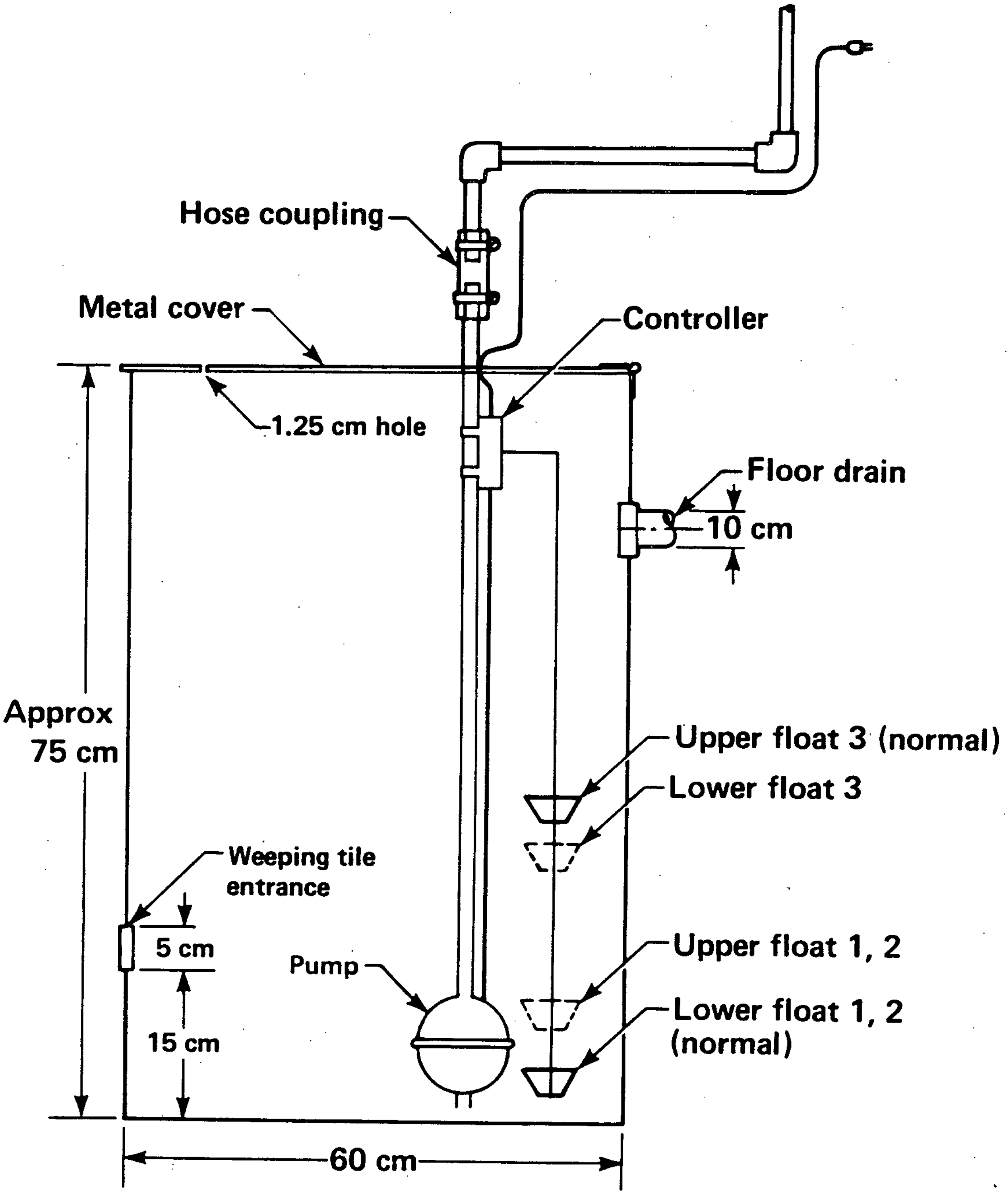

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Figure 6 A diagram of the sump in the basement. The limit-control switches that control the pump (marked upper float and lower float in the Figure) are normally in the positions shown with solid lines. The pump turns on when the water level reaches the upper float position; it turns off when the water drops below the lower float. During the water level tests we changed the float positions to the locations shown dashed in the Figure.

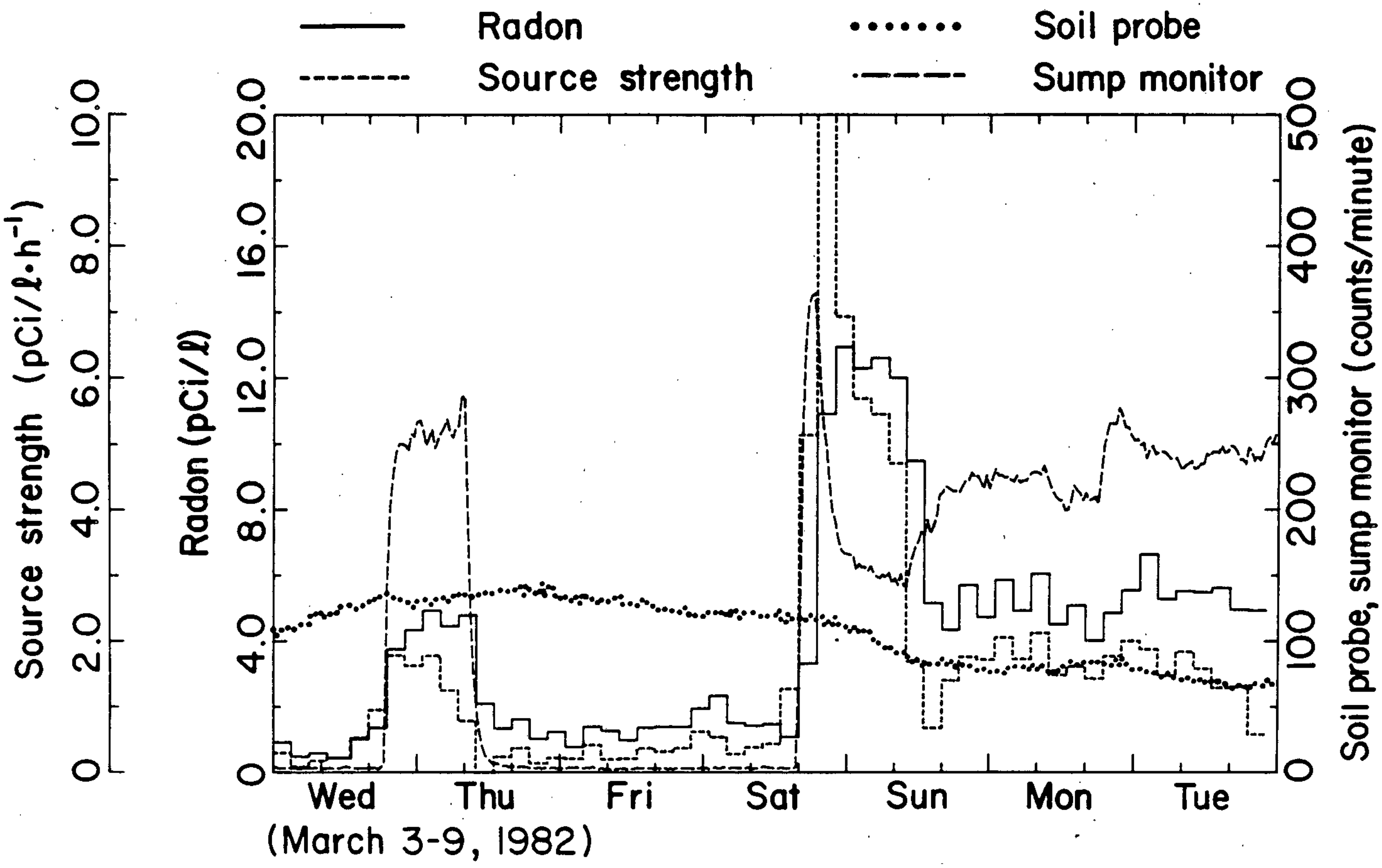

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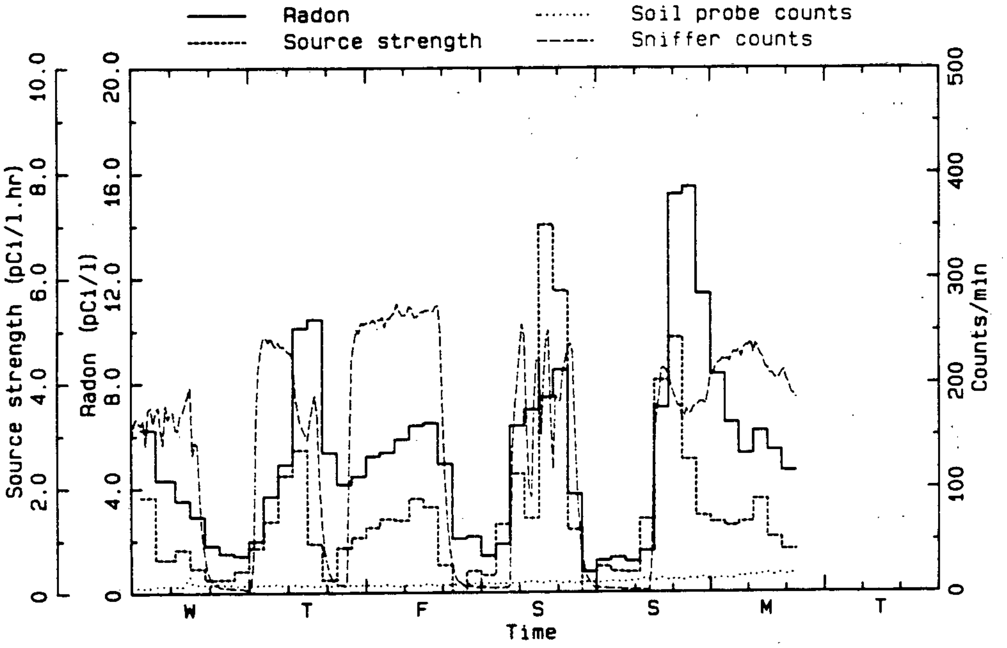
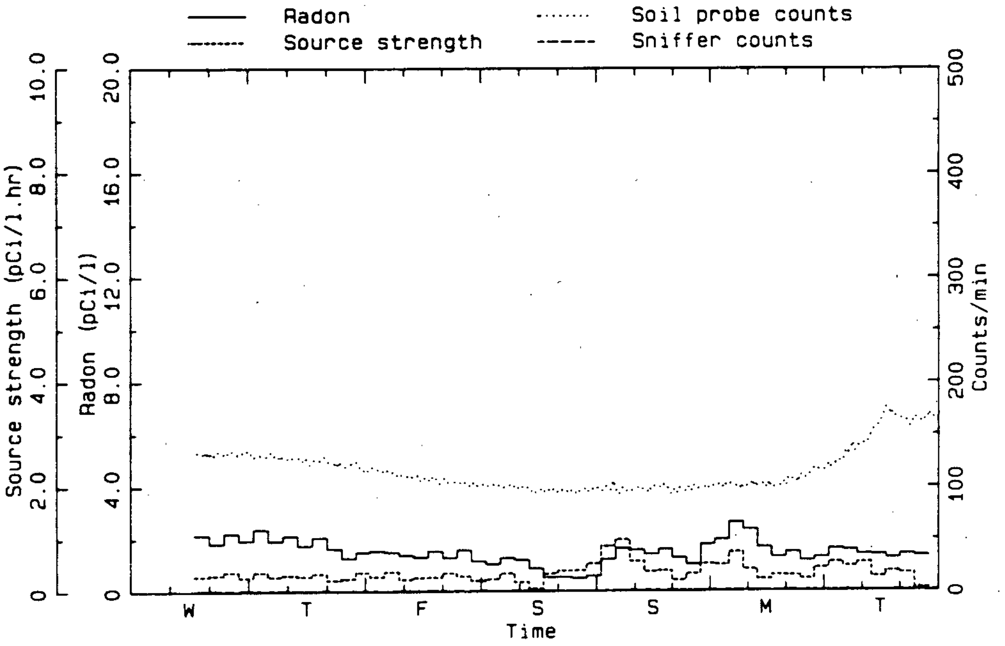
Figure 7 Radon concentration, source strength, soil activity, and activity at the sump during the period from 3 March through 9 March.



AARDVARK I - 02/17/82 TO 02/23/82

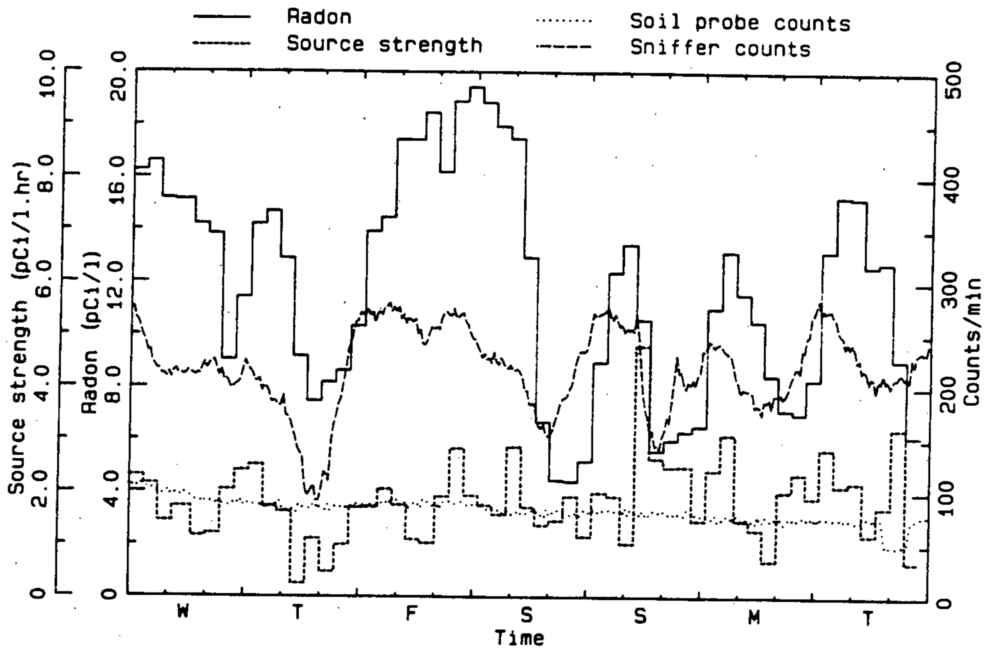
XBL 833-8763



AARDVARK I - 03/24/82 TO 03/30/82

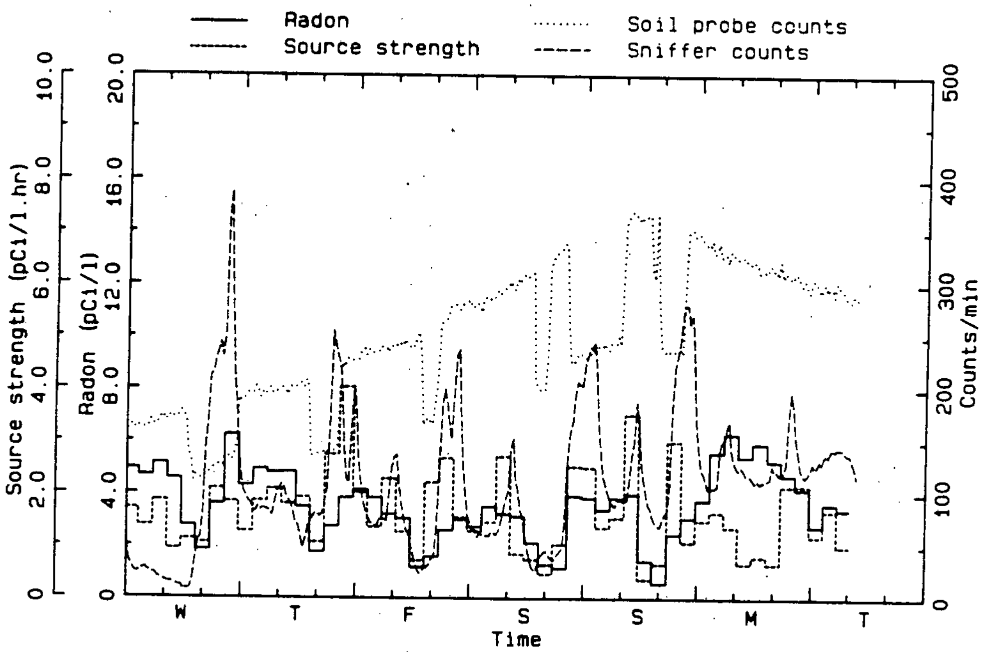
XBL 833-8764

Figures 8-9 Radon concentration, source strength, soil activity (labeled soil probe counts), and radon activity at the sump (labeled sniffer counts) during the periods 17 - 23 February and 24 through 30 March.



AARDVARK I - 06/16/82 TO 06/22/82

XBL 833-8765



AARDVARK I - 07/14/82 TO 07/20/82

XBL 833-8766

Figures 10-11 Radon concentration, source strength, soil activity (labeled soil probe counts), and radon activity at the sump (labeled sniffer counts) during the periods 16 - 22 June and 14 - 20 July.

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