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MEASURING RADON SOURCE MAGNITUDE IN RESIDENTIAL BUILDINGS

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Abstract

We describe the procedures we use in residences for rapid "grab-sample" and time-dependent measurements of the air-exchange rate and radon concentration; the radon source magnitude is calculated from the results of simultaneous measurements of these parameters. Grab-sample measurements in three survey groups comprising 101 U.S. houses showed the radon source magnitude to vary approximately log-normally with a geometric mean of 0.37 and a range of 0.01 to 6.0 pCi l^{-1} h^{-1}. Successive measurements in six houses in the northeastern United States showed considerable variability in source magnitude within a given house; in two of these houses the source magnitude showed a strong correlation with the air-exchange rate, suggesting that soil gas influx can be an important transport process for indoor radon.

keywords: radon, houses, air-exchange rate, pollutant sources

INTRODUCTION

Characterizing radon sources and the processes by which radon is transported into buildings is an important component in developing a comprehensive understanding of radon as a contaminant of indoor air. For sources such as building materials, domestic water, and natural gas, characterization is relatively straightforward; however, these sources do not appear to contribute to indoor radon concentrations in amounts sufficient to account for the levels observed in a large number of houses surveyed in the United States and Canada. Rather, evidence is mounting that local rock and soil (referred to simply as "soil" throughout this paper) are the dominant sources of radon in these houses. The characterization of soil as a source of indoor radon is difficult, because, for example, the permeability and radon emanating power of soil vary with changes in moisture content, radon can migrate over long distances in soil, and radon can enter a house by either bulk flow or diffusion.

A potentially important approach in investigating the origin of radon indoors is to calculate the effective radon source magnitude by simultaneously measuring the radon concentration and the air-exchange rate in a house. It is the initial results obtained from such measurements that strongly suggest soil to be the dominant source of radon in a significant proportion of U.S. houses. Presuming this to be the case, we can use measurements of radon source magnitude to ascertain the potential for high radon levels in a geographic area. Furthermore, by measuring radon source magnitude continuously in conjunction with meteorological parameters such as wind speed, indoor-outdoor temperature

difference, and barometric pressure, we can gain a better understanding of processes which transport radon from its source material to indoor air.

To date, we have measured radon source magnitudes in about 100 U.S. houses. In most of these homes we used a single simultaneous measurement of radon concentration and air-exchange rate to determine the radon source magnitude at one point in time; however, in several we made successive measurements of the radon source magnitude over periods of time ranging from 3 to 30 days. Our most significant findings are: (1) that the radon source magnitude varies over a wide range from one house to another; (2) that the radon source magnitude in a house can change dramatically even over a period as short as several hours; and (3) that frequently the radon source magnitude in a single house shows a positive correlation with the infiltration rate -- consistent with the hypothesis that soil is important as a source of indoor radon and that bulk flow is important as a transport mechanism, as we shall discuss.

In this paper we describe the instrumentation and techniques used in our studies to calculate the radon source magnitudes in residences. We present the results of successive measurements of source magnitudes taken in six houses in the eastern part of the United States, and use these along with the results of a grab-sample survey of 101 houses variously located in the United States as a basis for discussing some aspects of the origin and transport of radon in U.S. houses.

METHODOLOGY

Theory

The mass-balance equation for indoor radon can be written as

$$\frac{dR_i(t)}{dt} = S_R(t) + \lambda_v(t)R_o(t) - \lambda_{Rn}R_i(t) - \lambda_v(t)R_i(t) \quad , \tag{1}$$

where $R_i(t)$ is the indoor radon concentration, $R_o(t)$ is the outdoor radon concentration, $S_R(t)$ is the indoor radon source magnitude per unit volume, $\lambda_v(t)$ is the air-exchange rate, and λ_{Rn} is the time constant for radioactive decay of radon (0.00756 h^{-1}). Since λ_v (almost always greater than 0.1 h^{-1}) is much larger than λ_{Rn}, we ignore the third term on the right hand side of Eq.(1). We define the "effective" indoor radon source magnitude, Q_R, as the sum of the first two terms on the right hand side of Eq.(1) so that for steady-state conditions we have

$$Q_R^s = S_R^s + \lambda_v^s R_o^s = \lambda_v^s R_i^s \quad , \tag{2}$$

where the superscript s denotes the steady-state value. In this way a simultaneous measurement of the air-exchange rate and the indoor radon concentration can be used to compute the effective source magnitude, assuming that steady-state conditions prevail. The difference between the effective source magnitude, Q_R, and the value for indoor sources, S_R, is small if the indoor radon concentration is much greater than the outdoor concentration, as is often the case.

By continuously measuring the radon concentration and the air-exchange rate, we can calculate the source magnitude even under changing conditions. Equation (1) is solved to obtain

$$\langle Q_R \rangle_{0,t'} = \frac{R_i(t') - R_i(0)}{t'} + \langle R_i \lambda_v \rangle_{0,t'} \quad , \tag{3}$$

where $\langle\rangle_{0,t'}$ indicates a time-weighted average over the interval 0 to t' of the contents of the brackets. Because we measure radon averaged over finite time intervals, we do not know $R_i(t')$ or $R_i(0)$. We approximate these two quantities as

$$R_i(t') \simeq \tfrac{1}{2} \left(\langle R_i \rangle_{0,t'} + \langle R_i \rangle_{t',2t'} \right) ,$$

and

$$R_i(0) \simeq \tfrac{1}{2} \left(\langle R_i \rangle_{-t',0} + \langle R_i \rangle_{0,t'} \right) . \tag{4}$$

We further approximate $\langle R_i(t)\, \lambda_v(t) \rangle_{0,t'}$ by $\langle R_i(t) \rangle_{0,t'} \langle \lambda_v(t) \rangle_{0,t'}$. This approximation is accurate as long as there is no correlation between R_i and λ_v, or as long as both of these parameters do not vary significantly during a measurement interval. Assuming a continuous measurement of radon concentration, our estimate of the effective radon source magnitude is

$$\langle Q_R \rangle_{0,t'} = \frac{\left(\langle R_i \rangle_{t',2t'} - \langle R_i \rangle_{-t',0} \right)}{2t'} + \langle R_i \rangle_{0,t'} \langle \lambda_v \rangle_{0,t'} \quad . \tag{5}$$

Grab-Sampling: Technique and Instrumentation

Radon

Grab-sample measurements of radon are made using scintillation cells, either cells fabricated in our laboratory after the design of Lucas (Lu57) or commercially-available cells (EDA, Model RDX 388). The procedure used for taking the sample varies: (1) The sample is taken directly with the scintillation cell which is then either counted in the field or sent back to our laboratory for analysis. (2) The sample is taken in a radon-impermeable sampling bag (Environmental Measurements, Inc., air-sampling bag, made of Tedlar) which is sent back to our laboratory and analyzed by transferring a portion of the sample to a scintillation cell. (3) A metal vessel of known volume (typically 1 liter) is used to collect the sample, and then returned to our laboratory where the radon is extracted by passing the sample through a glass-wool trap cooled to -196^{o} C in a liquid N_2 bath; the extracted radon is then transferred to a scintillation cell. This procedure is described by Lucas (Lu77), and our implementation of it is reported by Ingersoll (In80). The procedure for concentrating radon is important for measurement precision and improvement of our sample throughput rate when measuring radon concentrations below about 1 pCi/l.

The scintillation cells are calibrated in batches. A calibration factor is determined for the batch by filling several of the cells with a known amount of radon, derived from a standard-reference-method solution of ^{226}Ra (National Bureau of Standards). The response of individual cells within the batch is checked by filling several cells with a constant, unknown concentration of radon, and comparing their count rates. The responses of individual cells fabricated at Lawrence Berke-

ley Laboratory (LBL) have been found to be within a range of 5%. We occasionally check our calibration factor against those independently determined by other laboratories. (In a recent check we were among six of the nine laboratories participating whose calibration factors agreed within a range of 10% (Ge81).)

Air-Exchange Rate

We measure air-exchange rate by tracer gas decay, most commonly using sulfur hexafluoride (SF_6), but occasionally ethane, as the tracer. The tracer gas is injected into the house and mixed to a uniform concentration by means of portable fans or the furnace fan. The concentration is monitored over time and the resulting data are fit to an exponential decay curve of the form

$$C(t) = C(0) \exp(-\lambda_v t) , \qquad (6)$$

where the time constant, λ_v, is the air-exchange rate.

SF_6 concentrations are measured with a commercially-available, non-dispersive infrared (NDIR) analyzer (Foxboro-Wilks, Model Miran 101). The analyzer is calibrated by measuring its response to gases derived from compressed-air tanks containing known concentrations of SF_6.

Continuous Measurement: Techniques and Instruments

Radon

The radon concentration is measured over time with a Continuous Radon Monitor (CRM) developed by Thomas (Th79), and designed and fabri-

cated at LBL. Figure 1 presents a schematic diagram of our most recent version of the CRM, whose unique feature is that the output is provided as an analog rather than a digital signal, simplifying the interface of the CRM to recording devices (strip-chart recorder or a data logger). The output voltage has a range of 0 to 1023 mV, corresponding to 0 to 1023 counts in the counter. After reaching 1023 the counter automatically resets. Converting the count total to an analog voltage introduces an uncertainty on the order of one count, which is insignificant compared to the statistical uncertainty in measuring radioactive decay. We use three-hour integration intervals for analyzing the CRM data.

The CRM is calibrated following the procedure of Busigin et al. (Bu79); the radon concentration is calculated as follows:

$$\langle R_i \rangle_{t',t'+3h} = 2.19 \langle n \rangle_{t',t'+3h} - 0.13 \langle R_i \rangle_{t'-3h,t'} \quad , \tag{7}$$

where n is the net count rate in min^{-1}. Aside from calibration uncertainties, the relative standard deviation in the measurement of a steady-state radon concentration is typically 6% at 5 pCi/l, 21% at 1 pCi/l, and 48% at 0.4 pCi/l (Na81).

Air-Exchange Rate

We have developed an automated system, the Aardvark, for continuously measuring the air-exchange rate and the radon concentration in an occupied residence. It is described in detail in another report (Na81). Briefly, the Aardvark uses the tracer gas decay technique with SF_6 to measure the air-exchange rate. The operation of the system is

controlled by a microcomputer system, which also performs preliminary data analysis. The data are recorded on magnetic tape and printed on a terminal.

The mechanical system of the Aardvark is presented in Figure 2. As illustrated, a blower is used to draw and return air at a total rate of 80 l/m through as many as four sampling lines and up to four delivery lines. A bypass loop provides 20 l/m to the SF_6 analyzer and 2 l/m to a CRM which is interfaced to the system. The analyzer is automatically calibrated at user-specified intervals by measuring its response to three concentrations of SF_6 drawn from compressed-air tanks.

To ensure good distribution and thorough mixing of the tracer gas in a house with a forced-air furnace, we use only one delivery line, installing its end in the return-air duct of the furnace system. A relay is used to bypass the thermostat and turn on the furnace fan during injection of the tracer gas. In a house that does not have air-distribution ductwork, mixing is accomplished by using three or four delivery lines, attaching the end of each to a portable fan which is turned on during injection. In either case, three or four sampling lines are used to reduce the dependence of the air-exchange rate measurement on the location of the sampling point(s).

Air-exchange rates are measured by the Aardvark over 90-minute intervals. The average of two consecutive measurements is used in equation (5) to calculate the radon source magnitude.

RESULTS

Survey of Radon Source Magnitude in U.S. Housing

Radon source magnitudes were determined in a survey comprising three housing groups: "energy-efficient" houses in the U.S. (one in Canada) (16 houses, Ho80); conventional houses in the San Francisco Bay Area (29 houses, Be79); and conventional houses in rural Maryland (56 houses, Mo81). Although this survey was not intended to be a random sampling, we believe the results provide an indication of what we might expect generally in the U.S. housing stock.

On the night prior to measurements occupants were asked to close windows and doors to establish a correspondence between the radon concentration measured and the ratio of source magnitude to air-exchange rate. Upon first entering the house, we collected one to three grab-samples of air for radon analysis; the samples were taken from the main living space, well away from doors and windows. A tracer-gas decay measurement of the air-exchange rate was then made over a one to two-hour interval. A summary of these measurements is presented in Table 1.

In all three housing groups the air-exchange rates were found to be fairly low -- an arithmetic mean of 0.41 h^{-1}. In as much as all doors and windows were closed during the measurements, these values represent infiltration only (i.e., uncontrolled leakage through the building envelope). Furthermore, because most of the measurements were made in the spring and summer when the weather is mild, we can assume that the average annual infiltration rate for these houses is higher than the values we report.

A histogram (see Figure 3) of radon source magnitudes measured in all 101 houses shows a broad distribution of values, ranging from 0.01 to 6 pCi l^{-1} h^{-1}. Individual measurements are distributed in an approximately log-normal fashion, with a geometric mean of 0.37 pCi l^{-1} h^{-1}, and a geometric standard deviation of 4.0. The geometric means of the radon concentration and radon source magnitude measured in the San Francisco Bay Area houses were considerably lower than the corresponding values for the other two housing groups.

Time-Dependent Measurements of Radon Source Magnitude in Selected U.S. Houses

In the six houses located in the northeastern United States, we measured radon source magnitudes over periods of 3 to 30 days. Five of these houses, located in New York and Maryland, were built within the last ten years; all were tract houses, built with some attention to energy efficiency. The sixth house, located in New Jersey, is over 100 years old but has been retrofitted to reduce energy use. In three of the houses radon measurements were made continuously and air-exchange rate measurements were made intermittently, typically once per day. In the other three houses, both air-exchange rate and radon concentration were monitored continuously over three- to five-day periods.

Four of the houses, those in New York and New Jersey, were occupied during the measurements. Because of the cold weather, the windows and doors in all of the houses were closed almost all of the time. A summary of the results is presented in Table 2, which gives both the arithmetic mean and the range of the radon concentration, the air-exchange rate, and the radon source magnitude for each of the six houses. With

the exception of Roch 49, which exhibits a much lower radon concentration and source magnitude, the mean values of each parameter obtained for these houses are narrowly distributed. The radon source magnitudes, especially in CB, AM-1 and SG-1, were found to vary significantly over the monitoring period, and the air-exchange rates were found to vary over a comparable or narrower range.

We observed a positive correlation between the measured air-exchange rate and radon source magnitude for five of the houses, as indicated in Figures 4 through 8. (In the case of Roch 49, the concentrations of radon were too low to determine whether or not such a correlation existed.) Figures 4 and 5 are scatter plots of the measurements made in CB and Roch 6, respectively, and the line plotted in each figure represents the least-squares fit to the data. For CB this line has a slope of 2.57 pCi l^{-1}, and a y-intercept of 0.23 pCi l^{-1} h^{-1}; the respective values for Roch 6 are 1.09 pCi l^{-1} and 0.21 pCi l^{-1} h^{-1}. Figures 6, 7, and 8 are plots of the air-exchange rate and radon source magnitude vs. time measured in Roch 60, AM-1 and SG-1, respectively. The average wind speed, derived from measurements made on-site at five-minute intervals, is also plotted for AM-1 (Ke81). In each of the three houses, the highest peaks in the radon source magnitude correspond in time with the highest peaks in the air-exchange rate. This correspondence is most evident in Figure 7, the plot for AM-1, showing that on 4/18 when the radon source magnitude increased from 0.7 to 2.6 and then decreased to 0.35 pCi l^{-1} h^{-1}, the air-exchange rate increased from 0.26 to 1.22 and then decreased to 0.72 h^{-1}.

DISCUSSION

Source Magnitude Distribution

Knowledge of the distribution of radon source magnitudes in U.S. housing would contribute greatly to efforts towards characterizing public exposure to indoor radon, as well as towards designing programs to reduce that exposure. Because our survey did not represent a random sampling of U.S. houses, the distribution of values we have reported may well differ from the actual distribution of radon source magnitudes. For example, half of the 16 energy-efficient houses surveyed were solar homes, generally relying on rock-bed heat storage, a potentially significant source of radon. The other two housing groups, although they reflect more typical design and construction practices, were selected from only two geographic areas of the country. Our data may also show a seasonal bias since most measurements were made in the spring and summer months; if, as we have observed, large variations in radon source magnitude occur over time, then it is very possible that systematic differences also occur from one season to another. Another item affecting the interpretation of these measurements is the contribution of radon in the outside air to the effective radon source magnitude. When trying to ascertain the effect of changes in the air-exchange rate on indoor radon concentrations, particularly for houses at the lower end of the distribution, this factor assumes importance.

We mention two other factors which, although potentially important, are unlikely to have much influence on the measured distribution: (1) the uncertainties associated with the imprecision in measuring radon concentrations and the air-exchange rates as well as in approximating

steady-state conditions, and (2) the apparent variability in radon source magnitude over short time periods within a given house. These two factors could cause a dispersion of the values reported here even if all of the houses had the same mean value; however, even this dispersion would not account for the wide range of source magnitudes observed in our survey. In other words, in spite of these considerations we conclude that the radon source magnitudes in U.S. houses are indeed widely distributed, and a substantial fraction are on the order of several pCi l^{-1} h^{-1}.

In most of the houses with source magnitudes on the order of 1 pCi l^{-1} h^{-1} or more, it is unlikely that building materials or domestic water are the dominant sources. Ingersoll measured radon emanation rates from 100 samples of concrete from across the United States and found values ranging from 0.2 to 2.0 pCi kg^{-1} h^{-1} (In81). If we take the case of a one-story house with 2.4 m ceilings, then a 0.2 m-thick concrete slab with a typical density of 2000 kg m^{-3} would contribute only 0.02 to 0.2 pCi l^{-1} h^{-1} to the source magnitude. We took a few measurements of radon in tap water in Maryland and found concentrations on the order of 1000 pCi/l; using Hess' observation that 10,000 pCi/l of radon in water typically results in 0.65 pCi/l of radon in air in a house with an air-exchange rate of 1 h^{-1}, the resulting source magnitude would be 0.07 pCi $l^{-1}h^{-1}$. On the other hand, Wilkening reports that data from roughly 1000 measurements of radon flux from soil range up to 1.4 pCi m^{-2} s^{-2} (mean value of 0.4 pCi m^{-2} s^{-2}), a value which would contribute 2.1 pCi l^{-1} h^{-1} (mean value of 0.7 pCi $l^{-1}h^{-1}$) to the source magnitude in the house postulated above, assuming the flux from the soil into the house is the same as the flux from uncovered soil (Wi72). The

fact that even the maximum flux from uncovered soil is not large enough to account for the highest indoor source magnitudes observed suggests the possibility that in some cases radon may be more efficiently transported from soil into a house than into the atmosphere.

In addition to the variations observed from one house to another our survey revealed a significant difference in radon source magnitude between the San Francisco Bay Area and the communities studied in rural Maryland. This difference suggests that radon source magnitude may depend on geological or structural factors. If so, it may be useful to conduct limited surveys of radon source magnitudes in a region to determine whether radon levels are high enough to justify further measurements in that area.

That radon source magnitudes show a broad log-normal distribution has important implications for any effort to control public exposure to radon in houses. For such a distribution, the best cost-benefit ratio can be obtained by addressing control efforts toward those houses with the highest source magnitudes. Since the source magnitude in closed houses appears to be more broadly distributed than the air-exchange rate, specifying a minimum air-exchange rate for all houses does not appear to be a cost-effective control strategy.

Correlation Between Air-Exchange Rates and Radon Source Magnitude

The correlation between air-exchange rate and radon source magnitude is evident in Figures 4-8. The correlation is particularly clear for the two houses with the highest (mean) source magnitudes, CB and AM-1. It is our hypothesis that in these two houses, and perhaps in Roch 6,

Roch 60 and SG-1, as well, surrounding soil is the dominant source of radon; the radon enters the house in high concentration with soil gas that is driven by the same forces that cause infiltration -- wind speed and indoor-outdoor temperature difference. A simple model consistant with this correlation is that on average a constant fraction of the air that infiltrates the house comes from the soil and carries with it a high concentration of radon; as the wind speed and temperature difference increase, the flow rate of soil gas into the house also increases, therefore, the radon source magnitude increases. For example, if the radon concentration in the soil gas is 500 pCi/l, a commonly reported value, then the soil gas portion of infiltration air need be only 0.5% of the total (corresponding to 16 l/m at an air-exchange rate of 0.4 h^{-1}) to account for the slope of the line in Figure 4. The y-intercept of 0.2 pCi l^{-1} h^{-1} could represent the contribution to the source magnitude of radon diffusing from and through the building materials. Much of the scatter in these data could reflect changes in the concentration of radon in the soil gas at the soil/house interface, or changes in the fraction of infiltrating air coming from the soil.

The data for AM-1 also show a strong correspondence between radon source magnitude and the air-exchange rate, particularly on 4/18 when the air-exchange rate steadily rose over a period of 20 hours, increasing greatly during the middle of this period concomitantly with an increase in wind speed. During the first 15 hours of this period, the radon source magnitude also increased strongly; however, at noon, when the last significant increase in air-exchange rate (to 1.2 h^{-1}) occurred, the radon source magnitude declined by nearly 25%. In fact, throughout this period it appears that the increases in radon source

magnitude become smaller relative to the increases in the air-exchange rate. It is possible that the concentration of radon in the soil gas drops as the soil gas is drawn into the house at a higher rate. That the source magnitude dropped to a low value of 0.35 pCi l^{-1} h^{-1} that afternoon, even though the air-exchange rate was still fairly high at 0.7 h^{-1}, is consistent with this hypothesis.

The correlations we observed between air-exchange rate and radon source magnitude would not be expected to apply if the changes in air-exchange rate were a result of opening windows and doors or changing the rate of mechanical ventilation. As pointed out earlier, measurements in these houses were made during winter and spring when the outside temperatures are relatively low, and therefore, we assume that the doors and windows were closed as much as possible. Given these conditions the changes in air-exchange rates can be assumed to reflect changes in weather conditions which appear also to affect the radon source magnitude in some of these houses.

We have considered various explanations for the observed correlation between radon source magnitude and air-exchange rate, but in the case of two houses, CB and AM-1, the data seem to point quite clearly to the aforementioned soil-gas theory. For example, since we include in our calculation of source magnitude the contribution from outdoor radon, we expect a positive correlation between the source magnitude and the air-exchange rate; however the observed slopes are much steeper than the slope of the regression line resulting from this effect alone, which would equal the outdoor radon concentration, typically 0.1 pCi/l. Errors in measuring the air-exchange rate could also lead to a false correla-

tion. For example, if the radon concentration and air-exchange rate were constant, then a scatter plot of a series of measurements of radon source magnitude and air-exchange rate would show a positive correlation with a slope equal to the radon concentration. The range of air-exchange rates in such a plot would reflect the precision of the measurement. How precise our air-exchange rate measurements are is difficult to estimate and probably varies from one house to another, depending on the mixing rates within the house and on the number and location of sampling lines. The first eight measurements in Roch 60 indicate that it is possible to achieve a standard deviation of less than 0.05 h^{-1} in the measurement of air-exchange rate. Such a level of precision is sufficient to preclude the possibility that the correlation between air-exchange rate and radon source magnitude for CB and AM-1 is due to measurement uncertainty. In the case of Roch 6, Roch 60 and SG-1 however, the apparent correlations could reflect measurement uncertainty in as much as the measurements of air-exchange rate in each of these houses are distributed over fairly narrow ranges.

CONCLUSIONS

We have measured radon source magnitudes in over 100 houses by simultaneously measuring the radon concentration and the air-exchange rate; in six of these houses source magnitude measurements were made over time, in some cases continuously. The data from these measurements corroborate the hypothesis that soil is an important source of indoor radon in U.S. houses, and, furthermore, support the theory that soil gas influx, rather than molecular diffusion, is the dominant transport process by which radon from soil enters ho ses, at least in those with

large source magnitudes.

Such studies could be fruitfully extended in at least two directions: A well-designed survey project could be undertaken to determine the actual distribution of radon source magnitudes in the U.S. housing stock to provide a basis for regulatory action aimed at controlling public exposures to radon. Continuous measurement of the source magnitude over a period of three months to a year in individual houses where source magnitudes are high would also be useful, especially if measurements of the radon concentration in soil gas, the radon flux through an opening between the house and the soil, and weather parameters were made simultaneously.

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Table 1. Data from 101-House Survey of Radon Concentration and Air-Exchange Rate

Sample	Monitoring Period	No. of Houses	Radon (pCi/l) GM[a]	Radon (pCi/l) GSD[b]	Air-Exchange Rate (h^{-1}) GM[a]	Air-Exchange Rate (h^{-1}) GSD[b]	Source Magnitude (pCi l^{-1} h^{-1}) GM[a]	Source Magnitude (pCi l^{-1} h^{-1}) GSD[b]
U.S. Energy-Efficient Residences[c]	May-August 1979	16	2.6	2.2	0.23	2.2	0.61	2.5
San Francisco Bay Area[d]	July-September 1979	29	0.4	2.2	0.28	2.5	0.10	2.5
Maryland[e,f]	May-October 1980	56	1.8	4.0	0.35	2.2	0.62	3.4
Total		101	1.2	4.0	0.31	2.3	0.37	4.0

[a] $GM = \exp\left[\frac{1}{N}\sum_{i=1}^{N} \ln X_i\right]$

[b] $GSD = \exp\left[\frac{\sum_{i=1}^{N} [\ln X_i - \ln(GM)]^2}{(N-1)}\right]^{\frac{1}{2}}$

[c] Source: Hollowell, C.D., Berk, J.V., Boegel, M.L., Ingersoll, J.G., Krinkel, D.L., and Nazaroff, W.W., 1980, Radon in Energy-Efficient Residences, Lawrence Berkeley Laboratory Report LBL-9560, Berkeley, CA.

[d] Source: Berk, J.V., Boegel, M.L., Ingersoll, J.G., Nazaroff, W.W., Stitt, B.D., and Zapalac, G.H., 1979, "Radon Measurements and Emanation Studies," in Energy Efficient Buildings Program: chapter from the Energy and Environment Division Annual Report 1979, Lawrence Berkeley Laboratory Report LBL-10704, Berkeley, CA.

[e] Source: Moschandreas, D.J., Rector, H.E., and Tierney, P.O., 1981, A Survey Study of Residential Radon Levels, Geomet Technologies Report ES-877, Rockville, MD.

[f] In six of these 56 houses, the radon concentration was found to be less than the detection limit of the measurement procedure (0.4 pCi/l with 50% relative standard deviation). For these houses the radon concentration was assumed to be 0.1 pCi/l for purposes of calculating the geometric mean radon concentration and source magnitude.

Table 2. Summary of Radon Source Magnitude Measurements for Six Houses Monitored Over Time

House ID	Location	Monitoring Period	No. of Meas.	Radon[a] (pCi/l)	Air-Exchange[a] Rate (h^{-1})	Radon Source Magnitude[a,e] (pCi l^{-1} h^{-1})
CB[b]	N.J.	11/16-12/17/80	36	3.2 (0.7-5.1)	0.41 (0.1-0.87)	1.3 (0.0-3.3)
ROCH 6[b]	N.Y.	1/8-1/22/81	25	1.6 (0.8-2.2)	0.38 (0.21-0.55)	0.65 (0.3-0.9)
ROCH 49[b]	N.Y.	2/6-2/20/81	11	0.1 (0.0-0.4)	0.40 (0.21-0.57)	0.05 (0.0-0.2)
ROCH 60[c]	N.Y.	4/16 4/20/81	32	2.2 (1.2-3.0)	0.31 (0.18-0.45)	0.7 (0.4-1.3)
AM-1[d]	MD.	4/16-4/20/81	28	2.9 (0.6-5.5)	0.44 (0.15-1.22)	1.1 (0.3-2.6)
SG-1[d]	MD.	4/21-4/23/81	18	2.3 (1.4-3.3)	0.28 (0.14-0.60)	0.65 (0.1-1.4)

[a] Arithmetic mean values for three-hour intervals; range of values given in parentheses.

[b] Occupied house, radon measured by CRM, air-exchange rates measured by tracer gas decay one or two times per day.

[c] Occupied house, radon measured by CRM, air-exchange rates measured continuously by tracer gas decay.

[d] Unoccupied house, radon measured by CRM, air-exchange rate measured continuously by tracer decay.

[e] The mean radon source magnitude is rounded to the nearest 0.05 pCi l^{-1} h^{-1}.

Figure Captions

1. Schematic diagram of the Continuous Radon Monitor (CRM).

2. Schematic diagram of the mechanical system of the Aardvark, an automated system for continuously measuring air-exchange rate and radon concentration in occupied houses.

3. Frequency distribution of radon source magnitude. For each house, the radon entry rate per unit house volume is calculated as the product of the radon concentration and the air-exchange rate, measured after the house had been closed for several hours.

4. Scatter plot of radon source magnitude versus air-exchange rate for house, CB. The data were collected between November 16 and December 17, 1980. The line represents a least-squares fit to the data.

5. Scatter plot of radon source magnitude versus air-exchange rate for house, Roch 6. The data were collected between January 8 and January 22, 1981. The line represents a least-squares fit to the data.

6. Plot of air-exchange rate and radon source magnitude versus time for house, Roch 60.

7. Plot of wind speed, air-exchange rate, and radon source magnitude versus time for house, AM-1.

8. Plot of air-exchange rate and radon source magnitude versus time for house, SG-1.

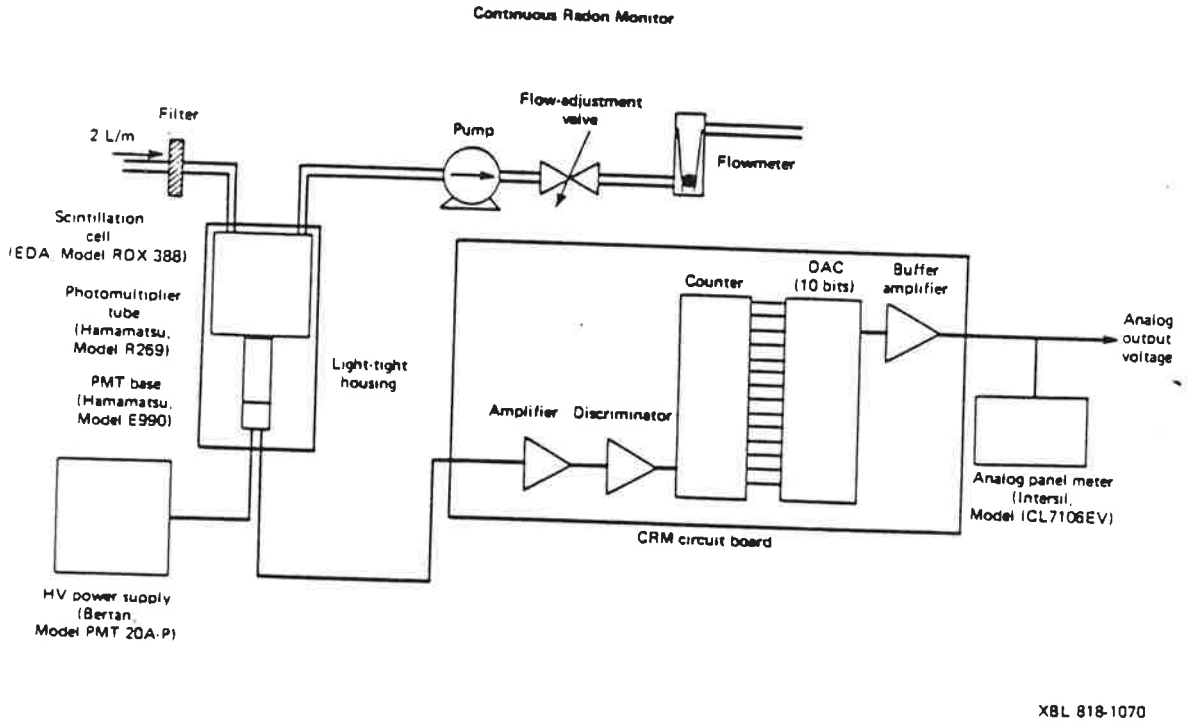
Continuous Radon Monitor
Filter
2 L/m
Pump
Flow-adjustment valve
Flowmeter
Scintillation cell
(EDA Model RDX 388)
Photomultiplier tube
(Hamamatsu, Model R269)
PMT base
(Hamamatsu, Model E990)
Light-tight housing
Counter
DAC (10 bits)
Buffer amplifier
Analog output voltage
Amplifier
Discriminator
Analog panel meter
(Intersil, Model ICL7106EV)
CRM circuit board
HV power supply
(Bertan, Model PMT 20A-P)
XBL 818-1070

Figure 1

AARDVARK MECHANICAL SYSTEM

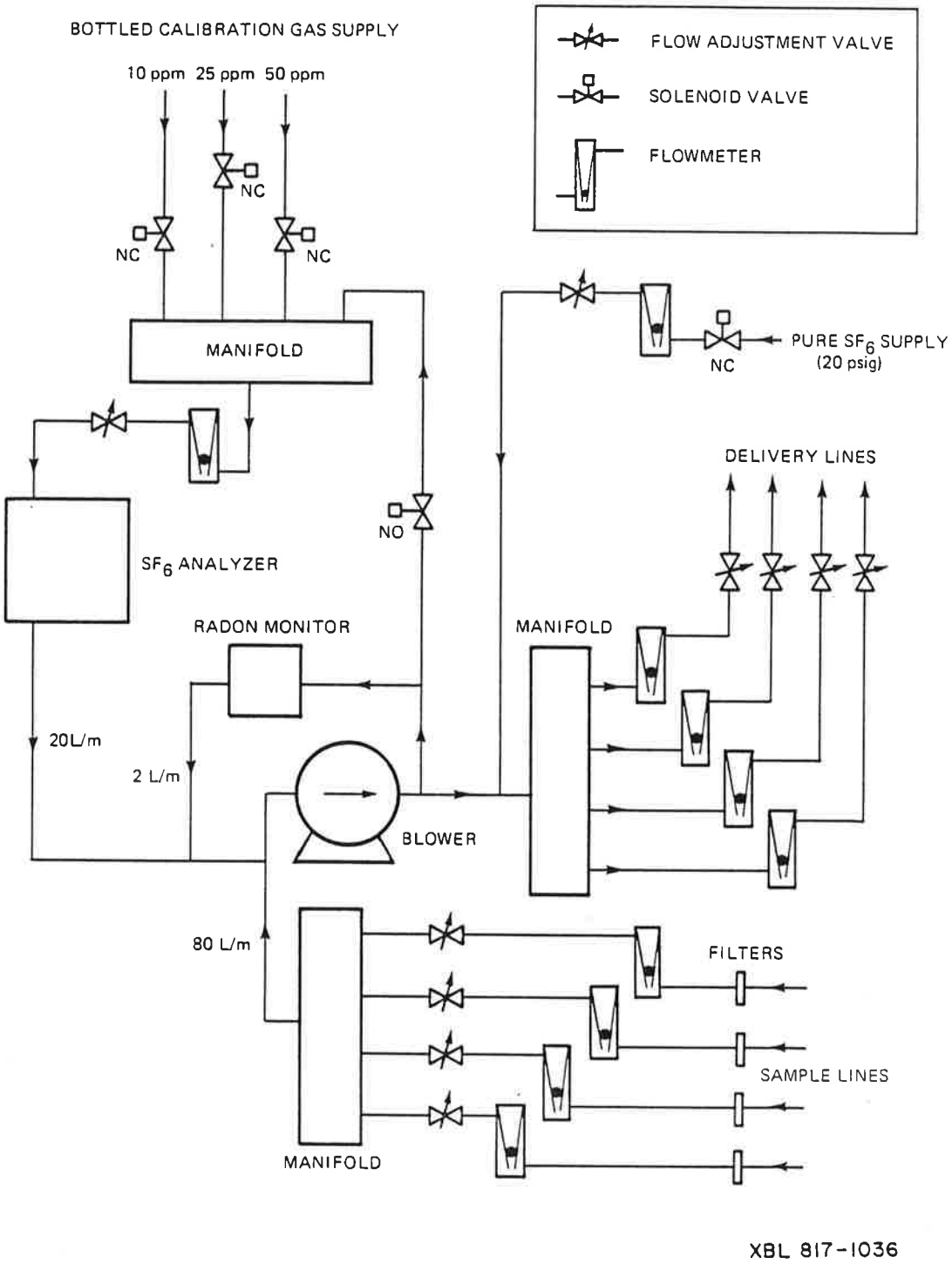

Figure 2

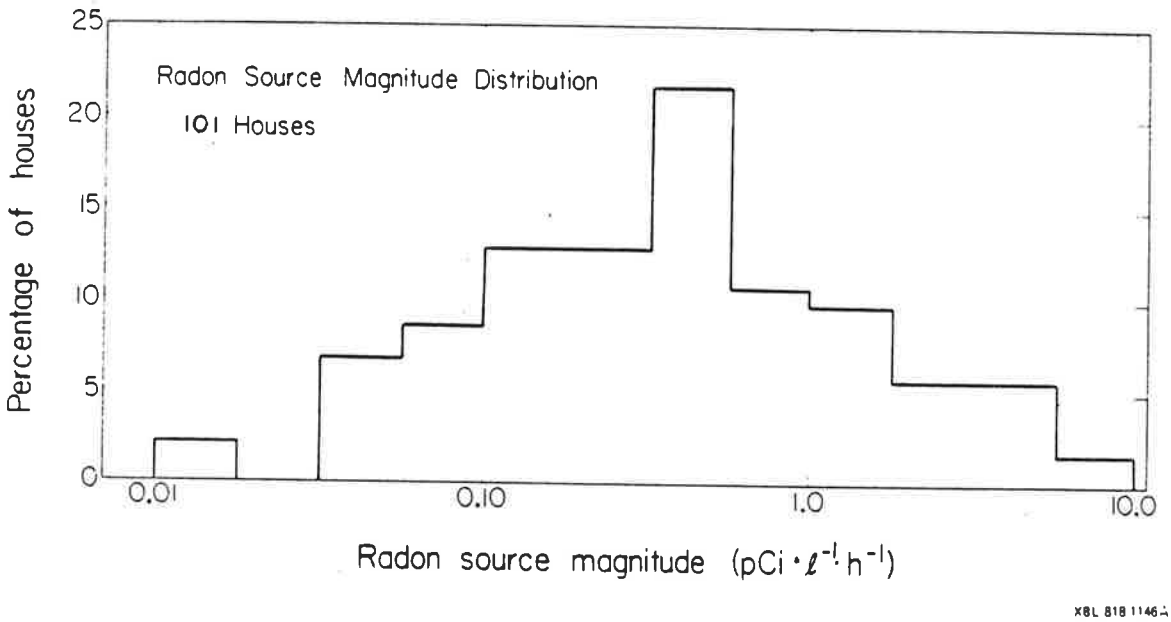
Radon Source Magnitude Distribution
101 Houses
Percentage of houses
25
20
15
10
5
0
0.01
0.10
1.0
10.0
Radon source magnitude (pCi · ℓ⁻¹ h⁻¹)
XBL 818 1146A

Figure 3

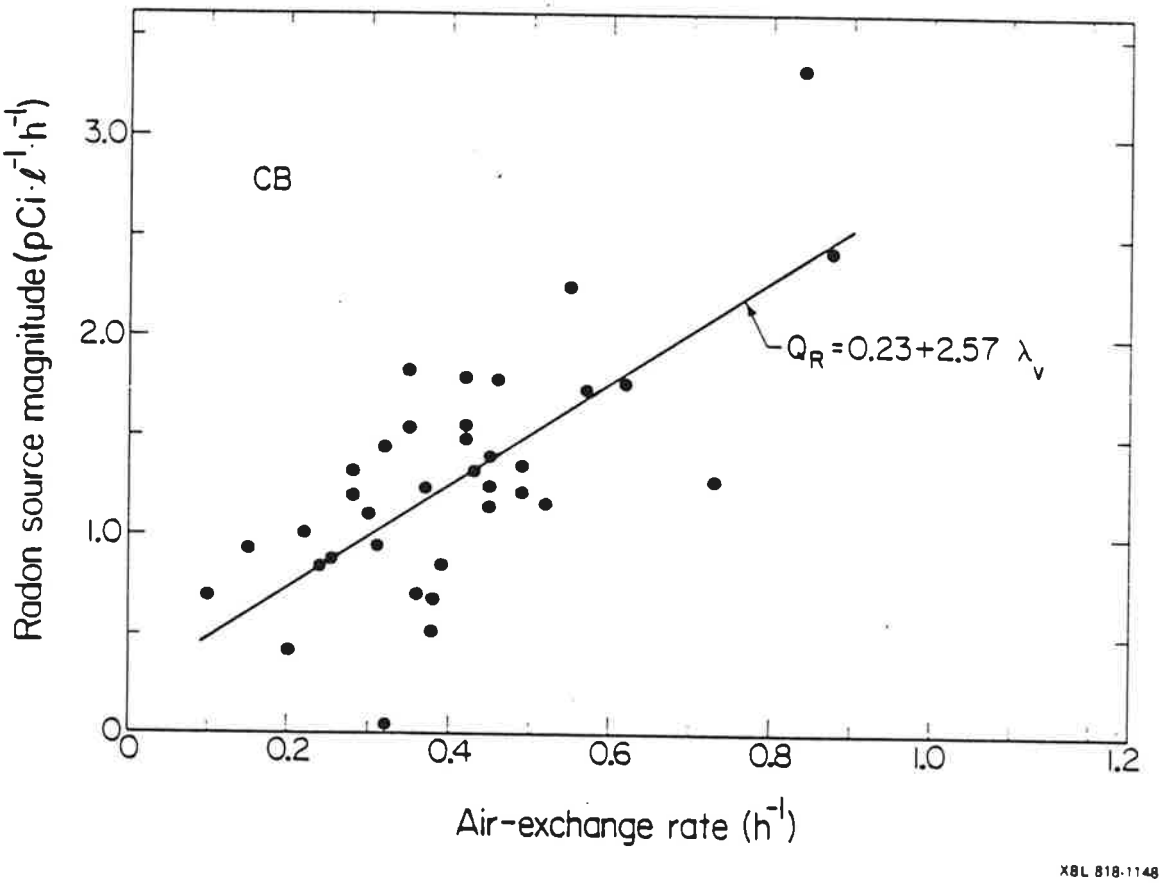
Radon source magnitude (pCi·ℓ⁻¹·h⁻¹)
3.0
2.0
1.0
0
CB
$Q_R = 0.23 + 2.57\ \lambda_v$
0
0.2
0.4
0.6
0.8
1.0
1.2
Air-exchange rate (h⁻¹)
XBL 818-1148

Figure 4

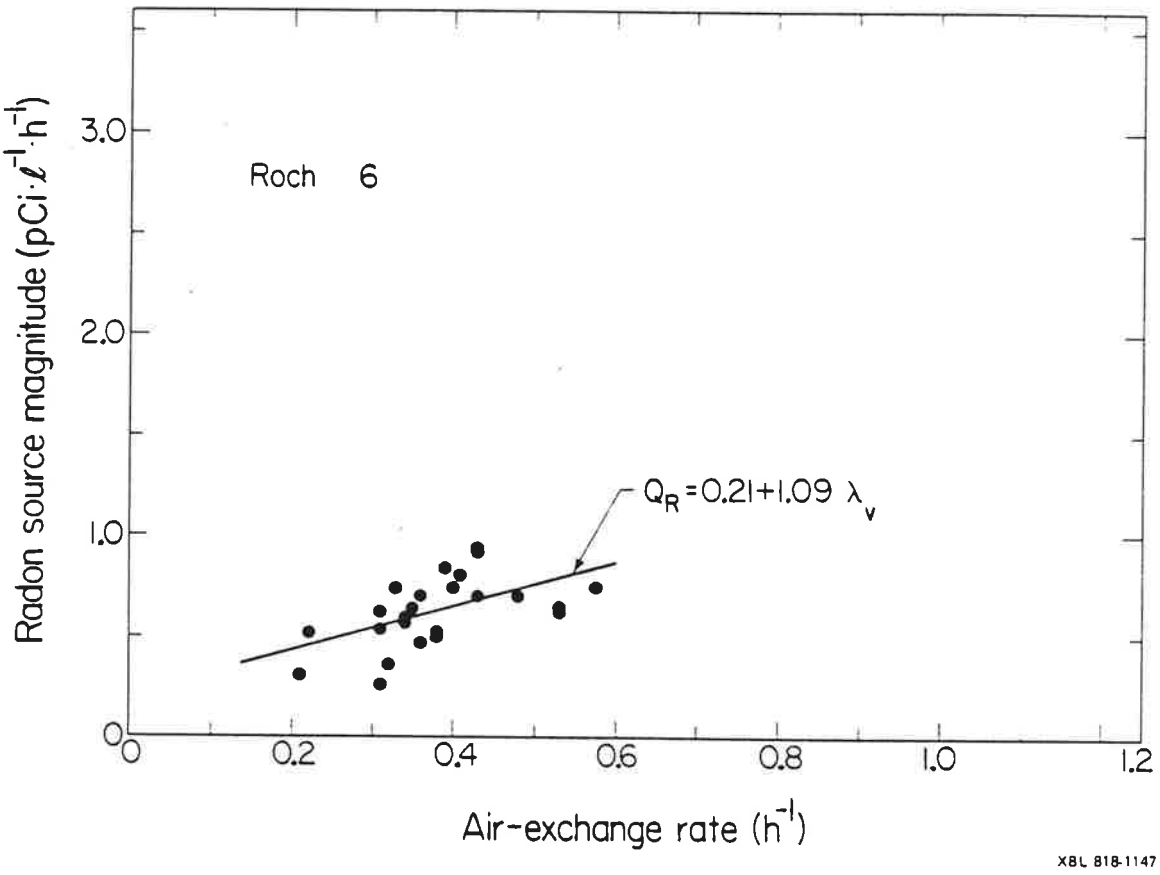
Roch 6
$Q_R = 0.21 + 1.09\ \lambda_v$
Radon source magnitude (pCi·ℓ$^{-1}$·h^{-1})
Air-exchange rate (h^{-1})
0
1.0
2.0
3.0
0.2
0.4
0.6
0.8
1.0
1.2
XBL 818-1147

Figure 5

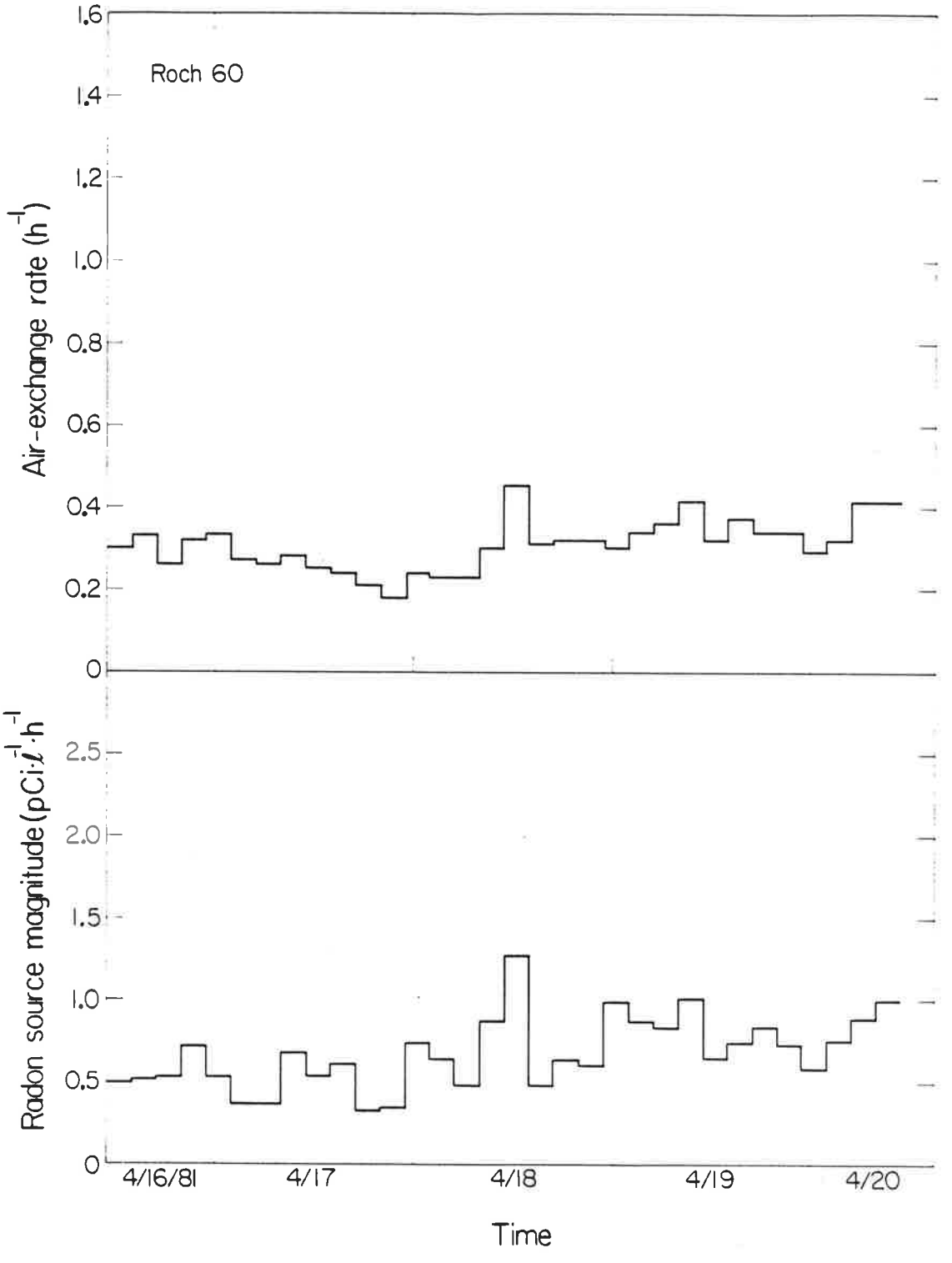
Roch 60
Air-exchange rate (h^{-1})
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Radon source magnitude ($pCi \cdot \ell^{-1} \cdot h^{-1}$)
2.5
2.0
1.5
1.0
0.5
0
4/16/81
4/17
4/18
4/19
4/20
Time
XBL 818 1145

Figure 6

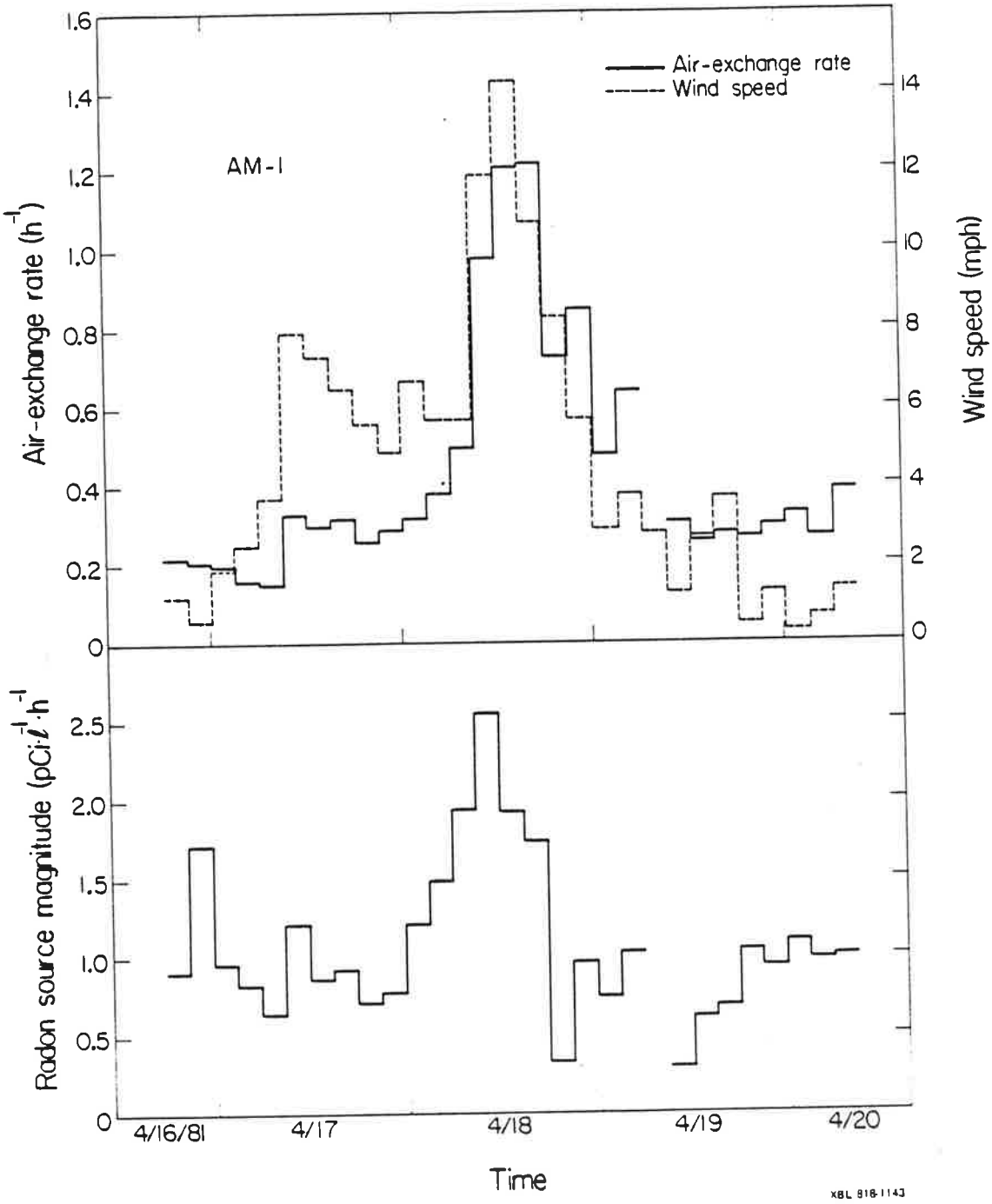
Air-exchange rate
Wind speed
AM-1
Air-exchange rate (h⁻¹)
Wind speed (mph)
Radon source magnitude (pCi·ℓ⁻¹·h⁻¹)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
14
12
10
8
6
4
2
0
2.5
2.0
1.5
1.0
0.5
0
4/16/81
4/17
4/18
4/19
4/20
Time
XBL 818-1143

Figure 7

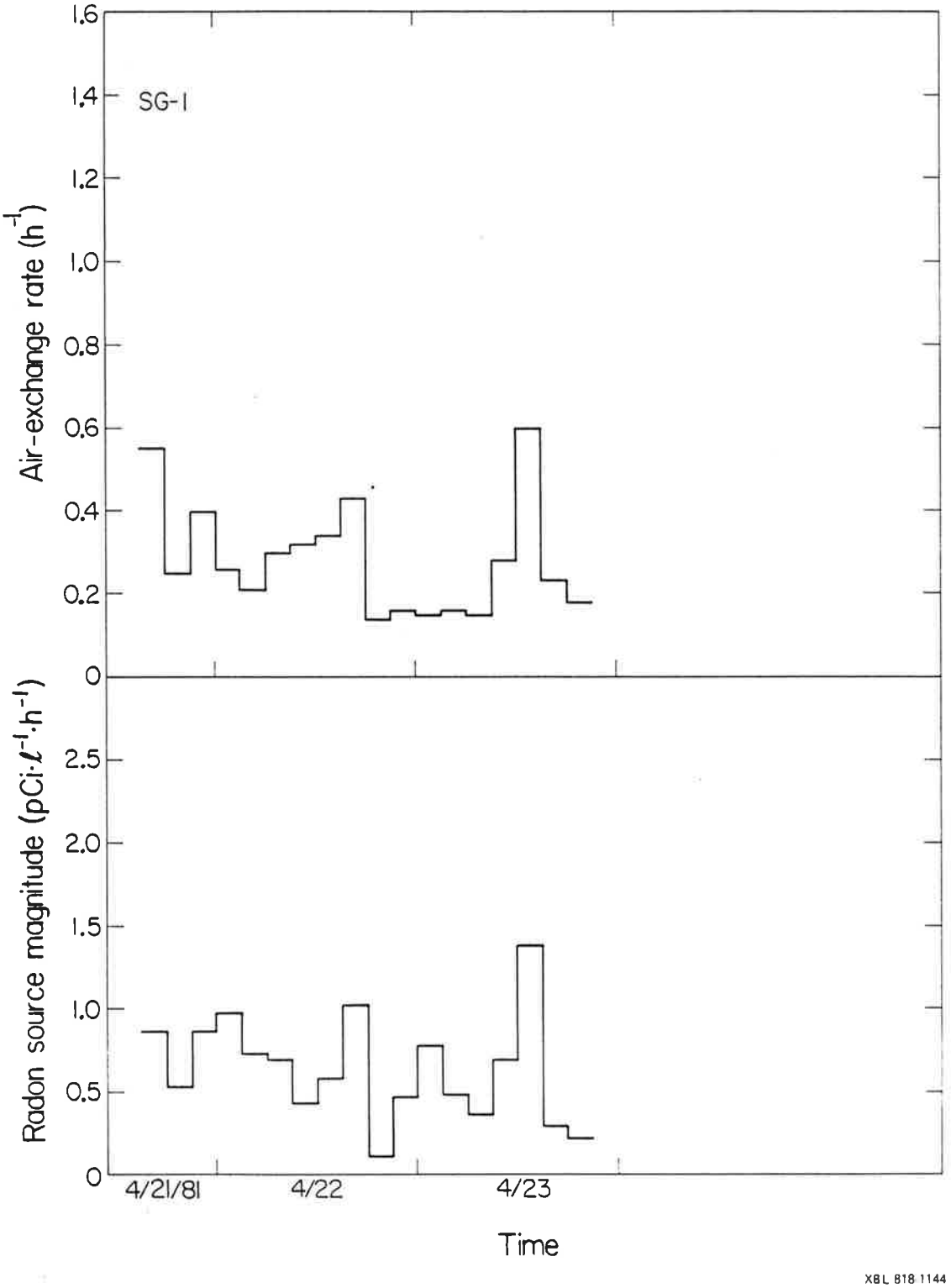
SG-1
Air-exchange rate (h^{-1})
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Radon source magnitude (pCi·ℓ$^{-1}$·h^{-1})
2.5
2.0
1.5
1.0
0.5
0
4/21/81
4/22
4/23
Time
XBL 818 1144

Figure 8