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Soil Permeability and Radon Concentration Measurements and a Technique for Predicting the Radon Source Potential of Soil

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ABSTRACT

Soil is the predominant source of radon in most U.S. homes, particularly for those homes with elevated indoor concentrations. Three factors help determine the indoor radon concentration, the radon production rate in the soil, the air permeability of the soil surrounding the building substructure, and the coupling between the soil and the building. Soil permeability and soil-gas radon concentration have been measured in a variety of soils, and both spatial and temporal variations within a building *site* have been observed. A method of combining measurements of soil gas radon and air permeability to provide a characteristic parameter - the radon source potential - has been developed. Permeability and soil-gas radon concentration measurements will be presented, the radon source potential technique will be discussed, and radon source potential results and measured indoor radon concentrations compared.

INTRODUCTION

The importance of soil as a source of indoor radon is widely recognized, and in particular, the rôle of pressure-driven flow of soil gas into homes. Several soil characteristics such as soil air permeability and the radon production rate affect the amount of radon available to houses. These characteristics have a wide range of values across different soils; in the case of permeability, the range can be as much as 9 orders of magnitude, although 4 to 5 orders of magnitude appears to be more typical of soils around homesites. The radium concentration and the radon emanation rates do not vary as much, with a factor of approximately 100 covering most of the range reported for each of these variables; variations of a factor of 10 are more typically observed (1,2). These soil factors are, in turn, influenced by environmental variables, the most important of which is soil moisture. Changes in soil moisture can affect soil gas migration through the soil medium by blocking the pore spaces through which gas moves. Moisture conditions also affect radon emanation rates and the diffusive transport of radon through the soil. Thus it is apparent that as soil and environmental conditions change measured soil gas radon concentrations and permeabilities may vary from site to site, and over time at a specific site.

Measurements of soil gas radon and soil air permeability are useful in investigating the sources and entry mechanisms of radon into homes. In addition to detailed studies of radon entry into specific houses, soil data may provide a basis for predicting whether houses built in certain areas or regions will have the potential for developing elevated indoor concentrations. This paper discusses soil gas and permeability data acquired in the course of two field studies. In addition, the use of soil gas radon and permeability data in a recently-derived method of estimating the radon source potential of soils (3) is illustrated.

EXPERIMENTAL DETAILS

Soil gas radon and soil air permeability data have been collected in the course of several studies recently conducted by the Indoor Radon Group at Lawrence Berkeley Laboratory. This paper focuses primarily on data collected during a study of 7 homes in New Jersey (NJ) from September 1986 to October 1987 (4). These observations are compared with similar, although less-extensive data gathered in a study of 15 homes in the Pacific Northwest (PNW) during the fall and winter of 1985-86 (5). The soil measurement techniques in each of these studies were essentially the same. Soil probes consisting of 1.3 cm outside diameter galvanized pipe were inserted into the soil after first drilling a 1.1-cm-diameter pilot hole to approximately the depth of interest. These probes had an inside diameter of 0.9 cm; additional probe design and insertion details are given in ref. (5). The radon concentration in soil gas increases asymptotically with depth, z, following a $1 - \exp(-z/l)$ functional form, where l, the diffusion length for radon-222 is approximately 1 m, or less, depending upon soil moisture and porosity. The 1- to 1.5-m-probe length used in these studies should therefore be long enough to avoid substantial diffusional losses or losses due to the influence of wind or barometric pressure changes, and thus provide an accurate method of sampling soil gas radon concentrations at depths typical of basement entry locations.

In the study conducted in New Jersey, approximately 20 or more soil probes were arrayed concentrically around each house. The inner-most ring, labeled O (for outside) A, was located 0.5 m from the exterior of the basement wall. Probes in the B-ring were positioned 1.5 m from this wall, while those probes in the C-ring were approximately 3 m from the wall. This probe array permitted determination of the spatial variability of air permeability and radon concentration in the soil around each house. In addition, five or six probes at each house were periodically monitored for soil air permeability and soil gas radon concentration throughout the course of the study, usually every 7 to 10 days. (There was a period during the early part of the winter of 1987 when repairs and improvements were made to the soil permeameter, so no permeability data from that period are available). In the study in the Pacific Northwest, two probes at each of the two study control houses were monitored periodically for soil gas radon concentrations. No periodic soil permeability measurements were made.

Usually measurements of soil air permeability and gas samples were done as separate operations. Permeability measurements were made following the technique suggested by DSMA (6), and the data obtained analyzed by means of the following equation:

$$k = 2.4 \times 10^{-12} \frac{Q}{r\Delta P}, \qquad (1)$$

where k is the soil air permeability in m^2, Q is the air flow in $cm^3\ min^{-1}$, r is the radius of the probe in cm, and ΔP is the absolute value of the pressure difference in Pa. Air flows were made at several pressures, usually 10, 50, and 250 Pa when conditions permitted, although in some cases, low permeability soils required pressures of up to 500 Pa to provide measurable gas flows. Although not discussed in this paper, some differences in the permeabilities inferred from the data acquired at the different pressure conditions have been observed (5). These additional measurement uncertainties are not accounted for here in comparisons of permeabilities measured at different applied pressures. Measurements could be made using either positive or negative applied pressures; most of the data reported here were obtained using a compressed-air cylinder to provide positive pressurization. In this case, care was taken to withdraw any desired radon soil gas samples before dilution air was injected into the soil probe.

Soil gas samples were drawn from the probes using an evacuated Lucas cell (usually ~100 or 160 cm^3 volume), after first purging the probe line with soil gas using a hand pump. Filled cells were usually counted several hours after sampling to allow radioactive equilibrium to be established and to allow for the decay of any ^{220}Rn present in the soil gas.

In the case of measurements of radon source potential, the same equipment and techniques were generally used, but radon gas concentrations were sampled dynamically by pulling soil air from the probes through a flow-through Lucas cell inserted in a portable photomultiplier-tube counter. Samples were drawn for approximately 10 minutes, or longer in the case of low permeability soils. During this time, pressure and flow measurements were made to determine the soil air permeability. Flow was then stopped, and three successive one-minute counts were made of the collected activity in the Lucas cell to determine the ^{220}Rn activity. After waiting for another 7 minutes (total of ten minutes since the sample flow was stopped), the activity in the Lucas cell was again counted for a total of one or more minutes, depending upon the count rate. This latter measurement represents the activity due to ^{222}Rn and its decay products.

RESULTS AND DISCUSSION

The spatial and temporal variation of soil air permeability and radon gas concentrations were both measured in the homes in NJ. Measurements at three of the seven NJ homes are discussed here, and compared with data acquired in the PNW. In addition, radon source potential measurements were made at four NJ homes and the results are summarized.

SOIL AIR PERMEABILITY

Permeability data from houses LBL08 and LBL14 (the control home) are shown in Figure 1. At LBL08, the measured permeabilities for three of the soil probes are fairly constant during the course of the measurement period, while two probes show a systematic change in permeability over this same period, as can be seen in Figure 1a. The data acquired at 50 Pa pressure difference are similar to these observations made at 10 Pa. The reasons for the variations observed in probes OCS1 and OAW1 are not known, although since soil moisture conditions have a major effect on soil air permeability, changes in soil moisture is a likely source of the variations observed. This homesite was on the side of a hill where drainage patterns might change subsurface soil moisture conditions at some probe locations. Unfortunately, no reliable soil moisture data were acquired.

Similar measurements made at LBL14 are shown in Figure 1b. These data were taken at 50 Pa; the corresponding 10 Pa data show wide and apparently random variations in the permeabilities measured at three of the probes, and thus may not be reliable. As can be seen, with the exception of three points, the permeabilities show little change over time.

The geometric mean permeability for each probe was computed from the time-series data, and these results are displayed in Table 1. For each of these two homesites, the mean permeabilities indicate a spatial variation of of just over a factor of 25. By comparison, permeability measurements made at ten homes in Spokane, WA, and Coeur D'Alene, ID, usually showed spatial variations at each site of about an order of magnitude, or less, with most measurements in the range of 10^{-10} to 5×10^{-11} m^2 (5). In one house in the Spokane area, an array of 30 probes around one home was used to map soil air permeability; in this case, the soil permeabilities were quite constant, with an average of 5.7×10^{-11} m^2 and a range of $(1.5$ to $8.4) \times 10^{-11}$ m^2 (2).

Spatial variations in both soil permeability and radon soil gas concentrations are shown in Figure 2 for a third NJ house, LBL10. These measurements show large variations in permeability, ranging over almost four orders of magnitude within the homesite. These large spatial variations make site characterization, based on a limited number of measurements, difficult. On the other hand convective transport of soil gas through soils with permeabilities below 10^{-12} m^2 is negligible (1), thus the soils with permeabilities below this value may not be significant sources of indoor radon.

Finally, the data presented here from these three NJ houses do not show any systematic change in permeability as a function of distance from the house, although it is worth noting though perhaps simply coincidental, that the highest permeabilities observed were measured in A-ring probes. One might expect somewhat higher soil permeabilities in the region immediately adjacent to the foundation wall where backfilling of the soil takes place after house construction. However, as can be seen in Table 1 and in Figure 2, permeabilities measured in the A-ring probes are not systematically higher than probes in the surrounding soil, particularly compared with C-ring probes which should be outside the backfill region. A comparison of the permeability data obtained at the intensively-monitored homesite in Spokane, WA also did not show an effect of increasing permeability closer to the house. It is possible that with relatively high permeabilities ($> 10^{-11}$ m^2) in the undisturbed soil to begin with, the soils disturbed during house construction will not have systematically higher permeability values.

SOIL GAS RADON

Soil gas radon concentrations measured periodically throughout the year are illustrated in Figures 3 and 4 for LBL08 and LBL14, respectively. Some of the soil gas samples at LBL08 were obtained during the operation of the sub-slab depressurization (SSD) mitigation system installed in this home; as a result, the radon concentrations in these gas samples were up to a factor of 10 lower than when the SSD system was not operating. For all but probe OCS1 these data points have been eliminated from the time-series data shown in Figure 3 and from data used in the computation of the descriptive statistics shown in Table 2. In the case of probe OCS1, which was about 3 m from the basement wall, no systematic reduction in radon concentrations could be associated with operation of the SSD system and no data points were eliminated from the time series.

In LBL14, the control home, the mitigation system was not installed until mid-July, and thus only a few data points have been eliminated in the time-series data for the A- and B-ring probes. The time-series soil data from LBL14 show a systematic reduction in radon concentration during the winter time period for all but one probe, OAS2. This effect, most noticeable for the A- and B-ring probes, is probably due to the pressure and flow field established by the house in the winter months, when the basement-outdoor pressure differential is larger (4). This produces a pressure-gradient in the soils near the house, resulting in dilution of the soil-gas radon concentration by atmospheric air entering the soil. Mean soil gas radon concentrations are compared in Table 2 for the winter (mid-December to mid-March) and non-winter time periods. This dilution effect appears to be largest at probe locations close to the house and where the air permeability is highest. While two of the C-ring probes at LBL08 and -14 show only a slight effect, probe OCN3 at LBL14 does have about a factor of two reduction during the winter, suggesting that the soil gas flow field extends out as far as 3 m under the right circumstances.

For probe OAS2 at LBL14, no winter-time reduction in the mean soil gas concentration was observed. This may be due to the fact that the soil at this location had the highest observed permeability. Thus even during the non-winter time period when the indoor-to-outdoor pressure difference is reduced but was often still negative (4), the soil gas concentrations may still be diluted by the flow of air into the soil from the atmosphere, resulting in an overall depression in soil gas radon concentrations.

The top layer of soil at these houses was frozen and often covered with snow for much of the time between about mid-December to approximately mid-March. Increases in soil radon concentrations under such conditions have been reported (7), however the radon data from the C-ring probes at both homes do not appear to be affected by the change in conditions at the soil surface. This is probably because the 1.5 m probe depths are deep enough to avoid significant reduction in soil radon concentrations due to diffusion.

The radon soil gas concentrations at LBL08 and LBL14 also vary spatially, although not as much as the permeabilities at these two homes. The mean soil gas values for LBL14 do not vary significantly, as can be seen in Table 2, while for LBL08, the range in mean concentrations is about a factor of 5. More significant spatial variations in soil gas radon values are shown in Figure 2 for house LBL10. Here, soil gas ranges from 350 to 670 pCi/L at the low end, to upwards of 90,000 pCi/L, a range of almost a factor of 200.

In two control homes in the Pacific Northwest, the mean soil radon concentrations (5) were in the 200 to 500 pCi/L range, as indicated in Table 2. Individual data points from these four probes, obtained periodically from October to April, ranged from less than 100 to more than 600 pCi/L. As seen in Table 2, the geometric standard deviations (GSD) for the PNW data are about the same as observed in NJ.

RADON SOURCE POTENTIAL

The radon source potential is a parametric indication of the risk of having elevated indoor radon concentrations in homes built on a soil whose air permeability and soil gas radon concentrations are measured. This potential is in units of activity per time (pCi h^{-1} or Bq s^{-1}) - essentially the maximum sustainable entry rate of radon-222 into the building from soil. The theoretical description of radon migration in soils and the details of the derivation of the radon source potential are presented in ref. (3). The main assumptions embedded in the analysis are: 1) the major soil characteristics, such as permeability, radium content, and moisture conditions, are isotropic and homogeneous, 2) bulk air flow is the dominant ^{222}Rn transport process - *i.e.* molecular diffusion is neglected, 3) the major entry route into the model structure is a penetration at the perimeter of the basement wall, which can be thought of as either a shrinkage or drainage gap at the floor-wall joint or as a perimeter drain-tile system with openings into an interior sump, and 4) the nominal indoor-outdoor pressure difference at the level of the entry opening is 4 Pa.

Because calculations suggested that at soil permeabilities greater than ~ 3.5×10^{-11} m^2 the soil radon concentrations may become depleted by the atmospheric air at sites near the house, measurement of soil gas radon was done with a with a system that initially establishes a flow of soil gas, rather than using a grab sample procedure. In this way, soil radon concentrations would be measured under dynamic conditions approaching those established by pressure gradients due to wintertime house conditions. This analysis appears to be confirmed by the temporal changes observed in radon soil gas concentrations at LBL08 and -14, as discussed above.

The results of the radon source potential measurements are shown in the second and third columns of Table 3. As can be seen, permeabilities measured at house 2 vary by more than two orders of magnitude, while those observed at house 3 vary by about a factor of 60. The equilibrium soil gas radon concentrations do not vary as much at houses 3 and 4, but do vary by an order of magnitude at house 3, and by as much as three orders of magnitude from site to site.

These measurements have been converted into a radon source potential, F, based upon the assumptions discussed above; these F values are listed in column four of Table 3. The range of values shown is based on the assumed size of the entry opening, ranging from 0.1 to 15 cm. Even though this is a factor of 150, the resulting radon entry potentials have a range of approximately a factor of 2, indicating that the calculations are not very sensitive to the size of the penetration. Other models of soil gas entry into buildings have similarly shown that the entry rate does not depend significantly upon the size of gap, above limiting widths of approximately 0.1 cm (8). Overall, the radon source potential estimates based on the individual probe measurements vary by about a factor of 10 for two of the houses, and by almost a factor of 60 at house 3. Again, these variations are due to variations in both the measured soil air permeability and radon gas concentrations.

In order to compare the radon source potential estimates with the measured basement radon concentrations, the geometric mean of the radon source potential was computed for each house based on an overage opening size, and then converted into a steady-state radon concentration by dividing by the nominal ventilation rate and the model house volume, 0.5 h^{-1} and 5×10^5 L, respectively. This quotient is shown in column 5 of the Table. As can be seen, the agreement with the measured indoor concentrations is reasonable, considering the assumptions involved.

SUMMARY AND CONCLUSIONS

The spatial and temporal variability in two of the parameters influencing radon entry rates into building, soil air permeability and soil gas radon concentration, have been examined. The permeability data periodically obtained at two homesites did not show large variations during the one-year experimental period. The permeability values for seven of the nine probes for which there were reasonable numbers of samples taken were fairly constant. For the other two probes, some larger temporal changes were evident, possibly reflecting the influence of changing soil moisture conditions at the two probe sites.

Spatial variations in permeability were much larger, in one case, up to four orders of magnitude differences were observed. Such variability makes site characterization measurements difficult without an extensive sampling network. Even then, the permeability measurement techniques utilized here sample a fairly small soil volume; 90% of the pressure drop driving the Darcian flow from which the permeability is inferred is in a region within 10 to 20 cm of the probe tip (3).

Soil gas radon concentrations also vary with time. In probes not thought to be influenced by the effects of the soil pressure gradient established by the house (basically the C-ring probes discussed above) the temporal variations are about one order of magnitude, or less. At probes closer to the house, the effects of atmospheric dilution on soil gas radon concentrations is evident in the comparison of the winter and non-winter time periods. As with permeability, radon in soil gas varies from probe to probe around the house, in some cases, this variation was observed to be less than a factor of ten, while at one homesite, a factor of ~200 was seen.

A method of interpreting soil gas radon and air permeability measurements has been developed to yield a characteristic parameter, the radon source potential. The radon source potentials derived from measured soils data at four test homes yield model house radon concentrations that are consistent with the measured indoor concentrations in these homes. Temporal and spatial variations in permeability and soil gas radon have been observed; the large spatial differences observed in both these may have a more important influence on the radon source potential at a specific site than temporal differences.

There are a number of issues requiring further investigation before such a method can be applied as a predictive tool in a wide variety of situations. Among these is the role of diffusion as a means of supplying radon for transport into structures. Although it is clear that diffusion alone, either through concrete or through openings in the building shell makes only a limited contribution to indoor radon concentrations, radon may diffuse from low permeability soil regions to zones of higher permeability and subsequently migrate by bulk flow into a structure. A second question is the coupling of the building shell with the surrounding soil. The method as outlined here assumes a fixed entry geometry, however there are other important entry pathways, such as flow through porous concrete or cinder block wall, that may require consideration.

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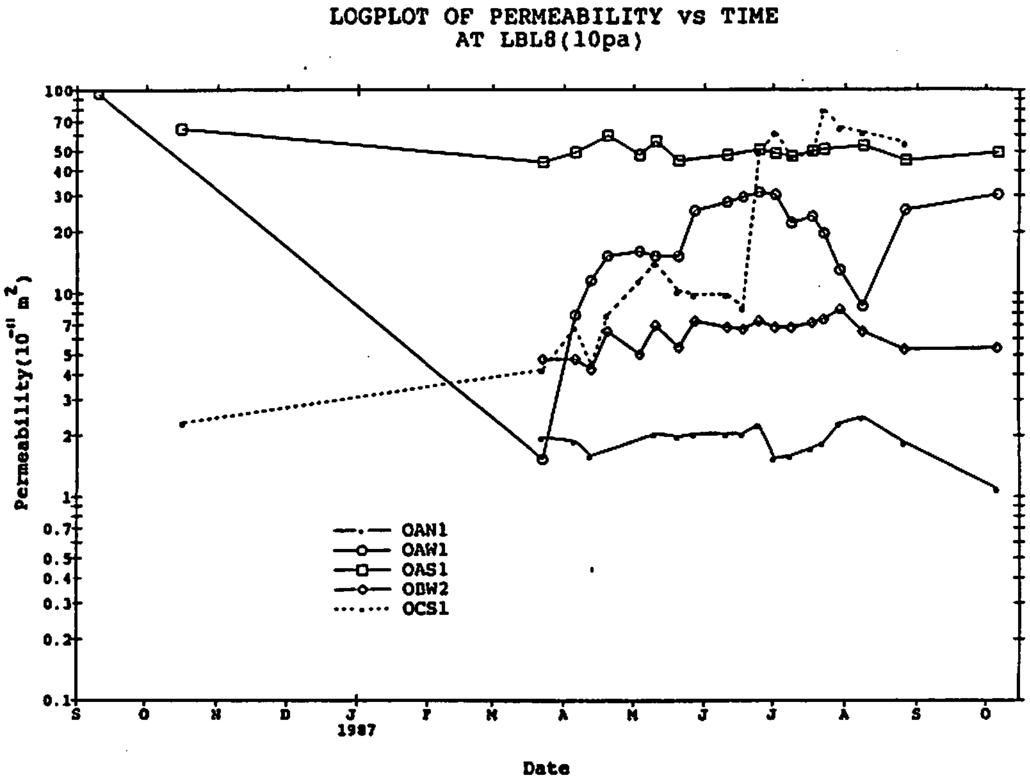

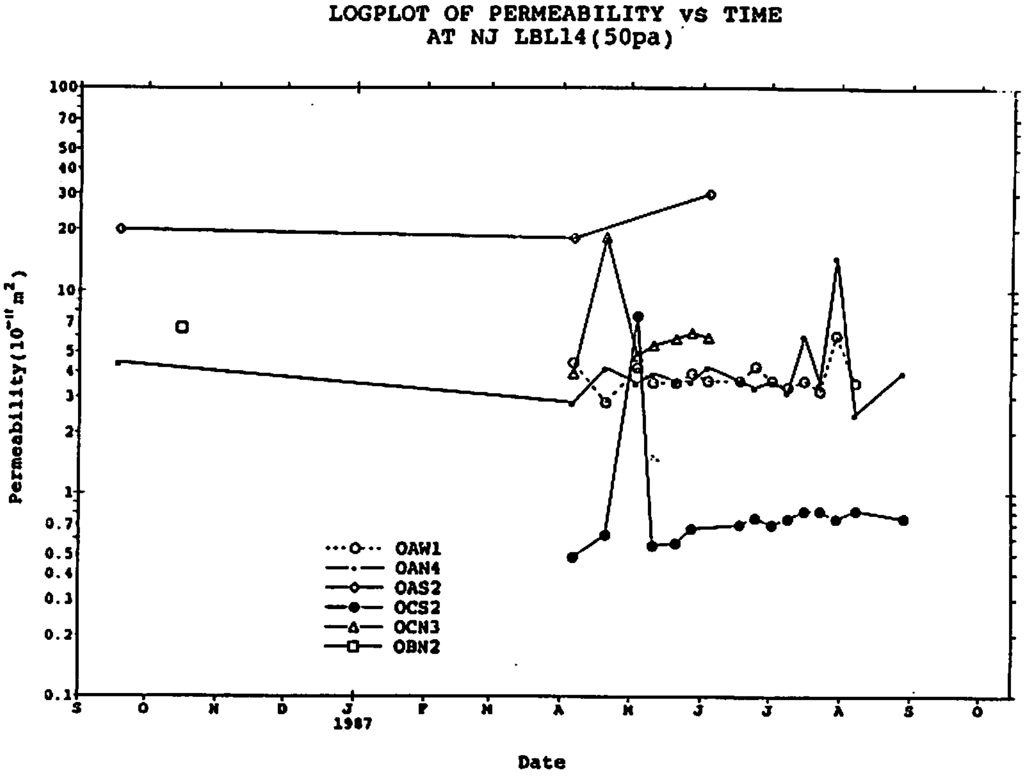

Figure 1. Soil air permeability measured at house LBL08 (part a) and at LBL14 (part b) as a function of time. Permeability is expressed in units of 10^{-11} m^2.

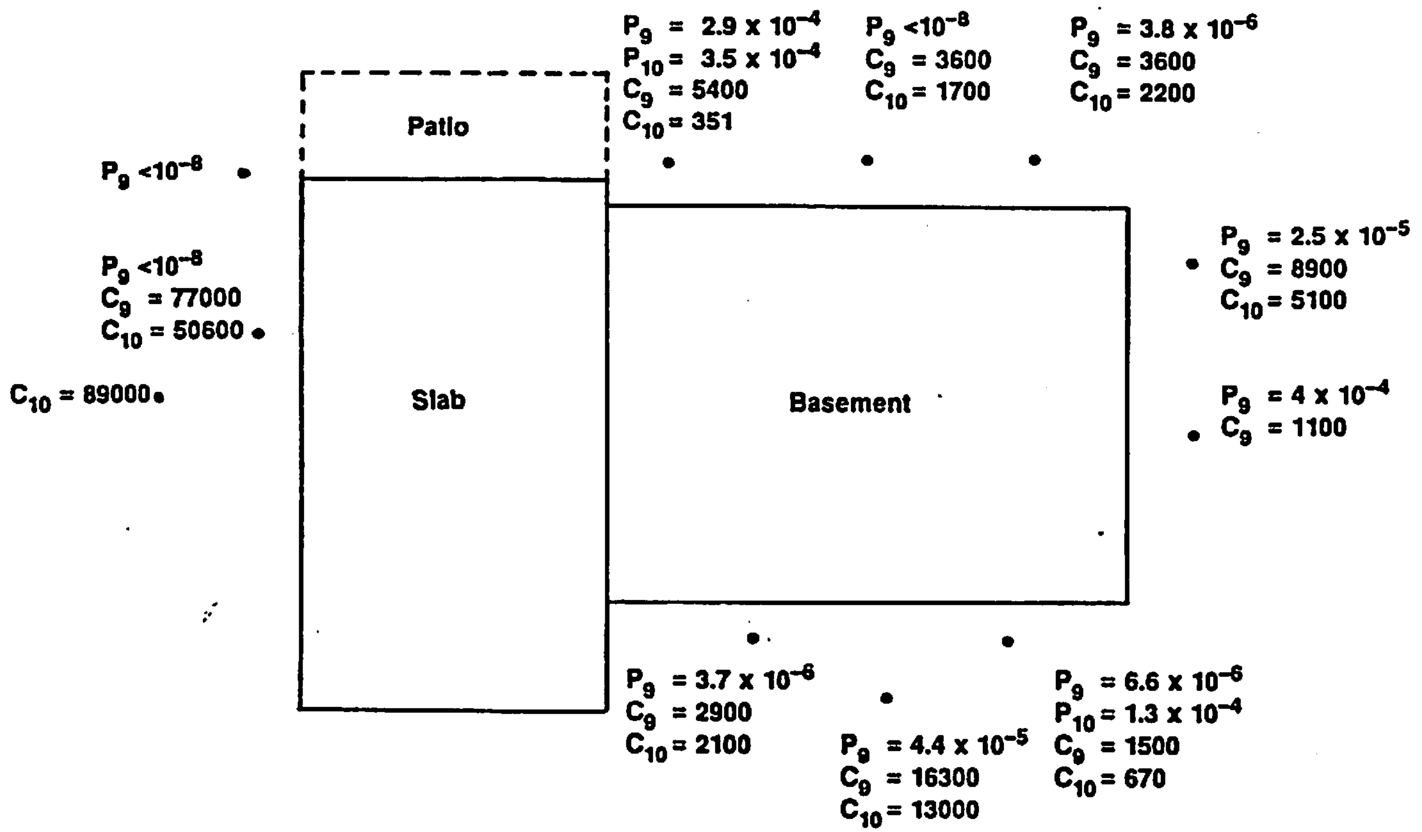

Figure 2. Soil air permeability and soil radon gas concentrations at a depth of 1.5 m around house LBL10. The subscripts 9 and 10 on the concentration, C, and permeability, P, denote measurements made in September and October 1986, respectively. The radon concentrations are in units of pCi/L and permeability is in units of cm^2; the permeability values should be multiplied by 10^{-4} to convert to m^2.

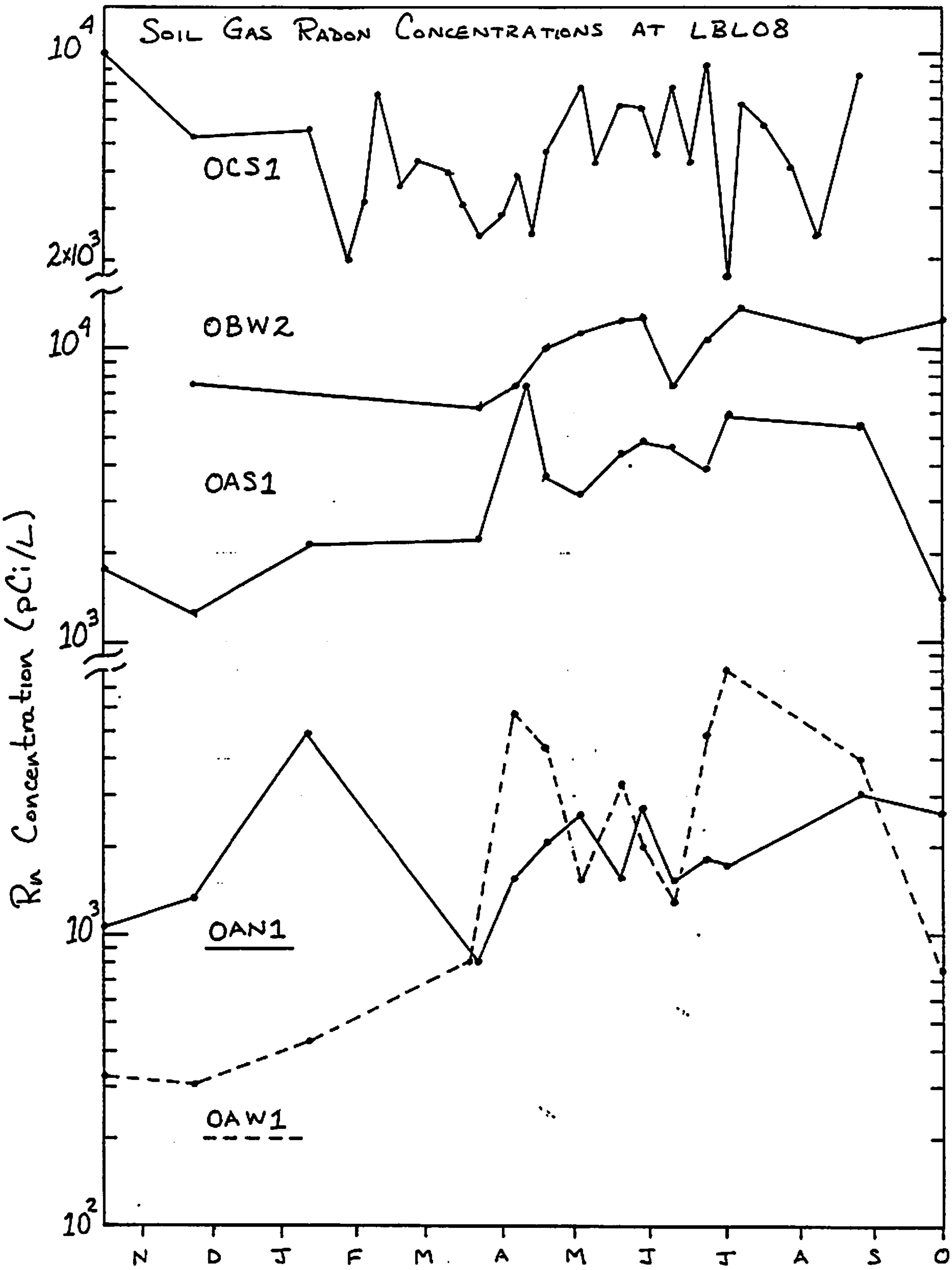

Figure 3. Soil gas radon concentrations at LBL08 as a function of time from October 1986 to October 1987. Note the breaks in the concentration scale.

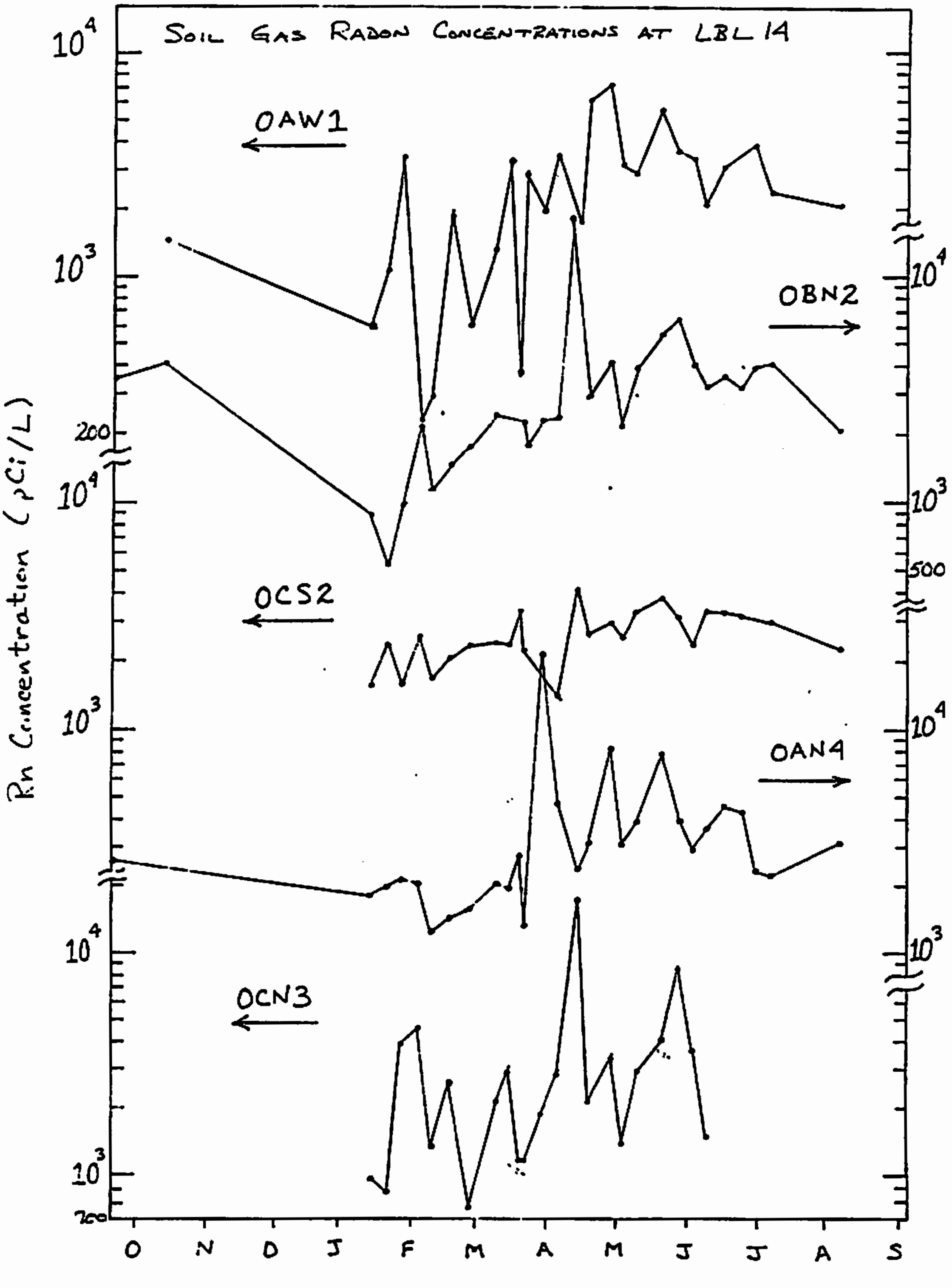

Figure 4. Soil gas radon concentrations at LBL14 from October 1986 to September 1987. Note that the concentration scale for the data alternates between the left and right axes.

Table 1. Time-averaged Soil Air Permeabilities Observed in New Jersey

House	Probe	k (10^{-11} m^2) GM (number)	GSD
(NJ) 08 at 10 Pa	OAN1	1.9 (17)	1.2
	OBW2	6.2 (19)	1.2
	OCS1	17.5 (19)	3.1
	OAS1	50.1 (17)	1.1
	OAW1	1.8 (20)	2.2
(NJ) 14 at 50 Pa	OAW1	3.8 (15)	1.2
	OAN4	4.0 (18)	1.5
	OAS2	22.1 (3)	-
	OCS2	0.81 (15)	1.9
	OCN3	6.3 (6)	-
	OBN2	6.6 (1)	-

Table 2. Time-averaged Soil Gas Radon Concentrations

		Geometric Mean [Rn] (pCi/L) (number of observations in parentheses)			
House	Probe	Winter[a]	Non-winter[b]	Entire period[c]	GSD
(NJ) 08	OAN1	-	-	1900 (14)	1.6
	OBW2	-	-	9940 (12)	1.3
	OCS1	3840 (8)	4760 (21)	4490 (29)	1.6
	OAS1	-	-	3230 (14)	1.8
	OAW1	-	-	1680 (14)	3.0
(NJ) 14	OAW1	880 (10)	3160 (17)	1900 (27)	2.5
	OAN4	1860 (10)	3490 (17)	2740 (27)	1.6
	OAS2	1780 (10)	1400 (16)	1560 (26)	1.5
	OBN2	1350 (9)	3630 (19)	2650 (28)	2.0
	OCS2	2150 (10)	2820 (15)	2530 (25)	1.3
	OCN3	1780 (10)	3230 (11)	2380 (21)	2.1
(PNW) 108C	1	-	-	500 (10)	1.2
	2	-	-	220 (9)	2.0
(PNW) 026C	1	-	-	310 (10)	1.7
	2	-	-	390 (9)	1.6

a. The winter season covered the period between mid-December and mid-March.

b. The non-winter period covered measurements made at other times of the year.

c. For the NJ homes, the measurements spanned almost an entire year.
For the PNW homes, the measurements were made from October to April.

Table 3. Radon Source Potential Measurements and Observed Basement Radon Concentrations

House-Probe	k (10^{-11} m^2)	[Rn][a] (pCi/L)	F[b] (µCi/h)	[Rn-222] calc.[c] (pCi/L)	[Rn-222] obs. (pCi/L)
1-1	2.7	730	0.4-0.8	2.4	25
2-1	33.	27000	90-160	250	205
2-2	70.	10800	70-120		
2-3	0.54	108000	12-27		
3-1	1.1	3200	0.8-1.7	11	23
3-2	70	2100	17-28		
3-3	1.7	1350	0.5-1.1		
4-1	0.17	320	0.02-0.05	0.08	2.7
4-2	0.1	120	0.006-0.014		

a) Equilibrium soil gas radon concentration

b) Radon source potential calculated using a range of entry gap widths from 0.1 to 15 cm.

c) Calculated using a geometric mean value for F, a ventilation rate of 0.5 h^{-1} and a house volume of 500 m^3.