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EXPERIMENTS ON POLLUTANT TRANSPORT FROM SOIL INTO RESIDENTIAL BASEMENTS BY PRESSURE-DRIVEN AIR FLOW

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ABSTRACT

At two residences in Portland, Oregon, we have investigated the coupling between residential basements and the air in nearby soil, and the influence of basement depressurization on the migration of air in soil. With the basements depressurized 25-50 Pa relative to outdoor air, underpressures as great as 20-40% of the basement values were observed at sampling points in the soil. Sulfur hexafluoride was injected into the soil near the houses and its concentration monitored in soil air and in the house over time, both with and without basement depressurization. Depressurization was seen to have a substantial effect on the migration of the tracer within the soil. For basement depressurizations of 25-50 Pa, effective transport velocities through the soil and into the houses were observed to exceed one m h^{-1}. Airborne radon concentration was monitored in the basement of one house during the six-day investigation and was seen to increase substantially each of the seven occasions that the house was depressurized. The techniques employed are applicable to the study of problems of excessive radon entry into buildings and the migration of toxic chemicals from waste dumps and landfills.

Keywords: air pollution, basement, indoor air quality, infiltration, pollution sources, radon, residential buildings, tracer gas, soil gas

INTRODUCTION

Serious indoor air quality problems can arise from the entry of pollutants found in soil air into building substructures. The best characterized, and perhaps most important, such problem is that of indoor radon, a pollutant that accounts for approximately half of the effective dose equivalent to the public from natural radiation (1), and that is estimated to cause several thousand lung cancers annually in the United States (2). Researchers in several countries, including the United States (3), Canada (4), and Sweden (5), are investigating soil as the major source of radon indoors. A second potentially important problem is suggested by the recent discovery of high concentrations of vinyl chloride in several Southern California houses built near a waste-disposal site (6).

For both these problems, the pressure-driven flow of air through the soil and through penetrations in the building substructure is a significant part of the transport process by which the pollutants move from their point of origin (in the ground or in waste material) into indoor air. As an example, in one study of radon in a house with a basement, the entry rate due to pressure-driven flow exceeded by an order of magnitude that due to molecular diffusion (7). In addition, control measures that are based either on blocking soil gas entry pathways or on diverting soil gas from the building structure to the ambient atmosphere have often been successful in reducing indoor radon concentrations (8,9). Furthermore, simple calculations and mathematical models have shown that pressure-driven flows through soil, induced by wind and temperature differences, are sufficient to produce large radon entry rates (3,4).

Despite these research efforts, a detailed understanding of the transport processes and pathways by which soil air enters buildings is lacking. Such information would contribute greatly both to the identification of buildings with unsafe levels of pollutants transported through the soil and to the control of such pollutants. This study was designed to contribute to our understanding of the migration of soil air near residential buildings using techniques which incorporate fan depressurization and tracer gases.

The results are described of experiments measuring the degree of pressure coupling between house basements and soil air. Also, sulphur hexafluoride is used as a tracer gas to study the effects of maintaining a reduced pressure inside a house basement on migration of air in nearby soil.

STUDY SITES

Two houses, both located in Portland, Oregon, were selected for this study. The principal criteria were 1) prior knowledge of a higher-than-average indoor radon concentration, in itself strong evidence of significant soil-gas entry; and 2) a basement substructure.

Relevant characteristics of the houses are given in Table I. The infiltration rate of outside air into each house was predicted using a model and the leakage area of the house, which was measured by fan depressurization (10). This result was combined with the measured radon concentration using a single-cell, mass-balance model to predict the average rate of radon entry into the house (11). The potential contribution to the radon entry rate of all soil within 1 m of the building shell was based on laboratory measurements of radon emanation from soil samples (Table II) and reflects the entry rate that could result from diffusion of radon from soil to the basement walls with subsequent transport of this entire amount into the residence. Even to approach this entry rate, radon must be carried through the basement walls by pressure-driven flow of soil gas rather than by molecular diffusion of radon through the basement floor and walls . Exceeding it -- as in the cases in this study -- strongly suggests that radon is being transported into the houses via pressure-driven flow through distances in the soil of 3-5 m, much greater than the radon diffusion length in soil (0.6 - 1.5 m) or even in air (2.2 - 2.4 m) (12).

Both houses are located in a soil classified as "Urban land - Multnomah complex" (13). The undisturbed Multnomah soils are characterized by a substratum of gravelly, silty loam and gravelly sand that has high permeability and permits relatively rapid movement of water and air. This substratum has a vertical extent of at least 1 m, beginning 0.6 m below the surface. Although site preparation and house construction have undoubtedly disturbed the soil profile, the data in the local soil report were substantiated by evidence of cobbly and gravelly subsoil at both houses (13). We also observed significant inhomogeneities at each site, both in depth to the subsoil and in the composition of the subsoil, and for the latter even within distances as small as 10 cm.

Multnomah soils constitute about 15% of Multnomah County. As least half of these soils have a substratum of very gravelly sand. Thus, the two houses studied here may represent in soil type a significant portion of Portland area residences.

DETERMINING THE COUPLING BETWEEN BASEMENT AND SOIL AIR

At each site a series of measurements was conducted to determine the degree to which soil air was coupled to the basement and to identify the zones around the house where pressure-driven flow was greatest. A large blower of the type used in leakage area measurements was installed in the shell of the house and used to maintain an indoor pressure with respect to outdoor air of minus 30-50 Pa, as measured by a variable reluctance pressure transducer (Validyne model DP103). The pressure differences between points in the soil around the house and the outdoor air were then measured. On a calm day, differences as low as 0.5 Pa could easily be detected.

The pressure-sampling points in the soil were established by first drilling a 1.4 cm diameter pilot hole, then driving a 2.1 cm (OD) steel pipe, the end of which had been pounded and sharpened to a blade, into the soil, typically to a depth of 0.9 m. Three holes drilled into the pipe near the blade end defined the sampling depth. Polyethylene tubing was inserted into the pipe to the depth of the holes and sealed to the top of the pipe with silicone sealant and tape to enable easy coupling to the pressure transducer.

Figures 1 and 2 present the results of this pressure-field mapping at the two houses studied. In house A the results are dominated by flow through a major penetration at the intersection of the floor and wall of the basement. The area of the penetration was roughly 20 cm^2 and may have originated with the installation of nearby sewer drain pipes. It was sufficient in size -- and the soil in the region was sufficiently permeable -- to permit a flow through it that could be felt by one's hand when the depressurization fan was operating. As shown in Figure 1, the influence of the basement on pressures in the soil was detected at distances up to 5 m from the house in the vicinity of this hole.

In contrast, the results at house B do not appear to be dominated by a single penetration in the substructure. Significant coupling between soil air and basement air was observed on three sides of the house, at distances of up to 3 m, yet there is large variability from one point to another.

On several occasions during the pressure measurements at each site, we verified that the depressurization measured in the soil was a consequence of the fan exhausting air from the house. In each instance, within several seconds of suddenly ending the depressurization of the house, we observed the pressure difference between the soil and the outside air approach zero.

At a number of sampling points at each house no stable reading was obtained. In such cases, it appeared that fluctuations in tubing temperature due to changing wind, solar insolation, and ambient temperature were sufficient to generate pressure change rates of several Pa per minute.

The apparent dominance of a single penetration in the substructure of house A suggested that a relatively simple model might account for the experimental results. Assuming the soil is isothermal and its permeability is isotropic and homogeneous, the pressure in the soil air satisfies Laplace's equation (14). If we model the basement as having a single spherical cavity with a cross-sectional area of 20 cm^2, centered 2.4 m below the surface of a semi-infinite layer, determining the pressure within the soil is analogous to finding the electrical potential in the vicinity of a charged spherical conductor and non-intersecting grounded plate (15).

Model calculations were carried out for several points at house A with the results indicated in parentheses in Figure 1. The modeled results are substantially lower than the measured values. This discrepancy cannot be accounted for by our having underestimated the size of the penetration: its radius would need to be 3 times larger to increase the fractional pressures by a factor of 3, still an order of magnitude smaller than measured. A hypothetical explanation that the soil permeability is substantially higher in the horizontal than the vertical direction was also tested with negative results: the maximum fractional pressure at a probe point 0.9 m below grade is 0.01, regardless of the ratio of horizontal to vertical permeabilities.

Other potential explanations, such as the presence of seams or layers of high permeability, could not be tested within the context of this model. Hence, we can only conclude that at the points in the enlarged zone of Figure 1 the soil air pressure is far more closely coupled to the basement than is predicted by a model which assumes uniform soil permeability.

MIGRATION OF TRACER GAS

To provide more direct evidence on the movement of air in the soil near a basement, a set of experiments was conducted in which sulfur hexafluoride (SF_6) was injected into the soil and its concentration monitored over time at points in the soil and in the house. The tracer gas was injected at a rate of 1-2 cm^3 min^{-1} over a period of a few to several h. For experiments focusing on the movement of air in the soil itself, air containing SF_6 at a concentration of 1-50 ppm was injected; for other experiments focusing on the entry of soil air into the basement, pure SF_6 was injected. Samples of soil air were collected using 10-cm^3 syringes after first extracting 25-40 cm^3 to flush the sampling tube. These samples were analyzed in a gas chromatograph with an electron-capture detector, (Analytical Instr. Development (AID) Model 210). The instrument sensitivity was of order 0.1 ppb and, by means of multiple dilutions, concentrations up to the percent range could be measured, thus giving a practical dynamic range of 8 to 10 orders of magnitude.

The results of one pair of experiments at house B, examining the effect of basement depressurization on migration of air in the soil, are presented in Figure 3. The tracer gas was injected at a point roughly 1.5 m from the basement wall in a zone that showed only moderate coupling with the basement. The experiments were conducted on consecutive days, in each case with injection beginning between 0800 and 0930. The first experiment was conducted with the exhaust fan off and windows and doors open so that the pressure difference between inside and outside was effectively zero. On the second day the house was closed and the fan operated so that the house was depressurized to about 8 Pa below the outside pressure, within the range of pressure differences due to wind and thermal effects during the heating season (3,4). The injected SF_6 concentrations were 1.8 ppm and 47 ppm on the first and second day, respectively.

During these experiments, each of the thirty points in the grid surrounding the injection point (as shown in the enlarged portion of Fig. 2) was sampled, but only the thirteen indicated in Fig. 3 showed normalized SF_6 concentrations (as defined in the caption to Figure 3) in excess of 0.1 at any time during the two tests.

Sampling points are numbered in order of deployment with an appended letter to indicate that the point is shallow (S, 0.3 m) or deep (D, 0.9 m). The results are most usefully discussed by dividing the sampling points into three categories: 1) the shallow points; 2) the deep points situated between the injection point and the basement; and 3) the deep points of equal or greater distance from the basement wall than the injection point.

For the shallow points, the concentration of tracer gas is very much reduced with the house depressurized relative to the results taken with the house at neutral pressure. Point 23S is typical, showing only a slight concentration during the depressurization run. This observation implies a net downward migration of soil air in this area when the basement is depressurized, suggesting that much of the flow of air into the basement occurs at a level close to the floor. This behavior is consistent with the evidently permeable subsoil and the postulated existence of basement penetrations predominantly at or near the level of the floor.

The deep points between the injection point and the basement show more rapid appearance and peaking of SF_6 concentrations during depressurization, notably at point 26D, which lies between the injection point and the zone of greatest coupling between the basement and soil air. These points also show an enhanced migration velocity under the influence of the exhaust fan: relatively high concentrations appear rapidly at point 47D with depressurization, yet SF_6 is not at all detectable at points at an equivalent distance from the injection site with the house at neutral pressure.

Finally, the deep points at greater distances from the house show concentrations that are both reduced and persist for a shorter time when the house is depressurized than when it is not. Of the four points in this category, two -- 29D and 30D -- do not have detectable concentrations during the depressurization test.

A model calculation was carried out to determine whether the results of the neutral pressure run could be accounted for by molecular diffusion of SF_6 in soil air. The measured concentration profiles in Figure 3 for the neutral pressure experiment show the same temporal behavior as the model calculation (shown for point 26D only); however, some of the measured values show much higher peak concentrations (e.g., points 22D and 24D). In the model calculation we assumed SF_6 was injected over a period of 2 hours at a point in an infinite, homogeneous, isotropic soil. It was assumed to disperse solely due to molecular diffusion. The resulting normalized concentration profile is (16)

$$C = \frac{R^2}{4\pi D\tau\varepsilon} \quad \{\mathrm{erfc}\,(R/\sqrt{4Dt}) - \mathrm{erfc}\,(R/\sqrt{4D(t-\tau)} \quad u(t-\tau)\} \qquad (1)$$

where R = distance between injection and sampling point,

t = time,

τ = injection duration (7200 s),

ε = soil porosity (assumed to be 0.33),

D = effective interstitial diffusion coefficient for SF_6 in soil, and

$u(z)$ = unit step function = 1 if $z > 0$; =0 if $z < 0$.

The effective diffusion coefficient, D, was estimated to be 0.012 cm^2/s. This value corresponds to a diffusion coefficient for SF_6 in air of 0.092 cm^2/s, derived from Chapman-Enskog theory (17-18) and in reasonable agreement with a measured value of 0.088 cm^2/s (19). The reduction in the diffusion coefficient for the case of SF_6 in soil air was assumed to be proportional to the observed reduction in radon diffusion coefficient from 0.10 cm^2/s in open air to a typical value of 0.013 cm^2/s in soil (12). This assumption is justified assuming the pore size is much larger than the mean free path of both gases and that there is no chemical interaction between the soil and the gases (20).

Since the model assumes infinite soil extent, the results are most applicable to points distant from the soil surface and the basement wall, such as point 26D. (See Figure 3.) The model results suggest that with the house at neutral pressure, under the relatively calm weather conditions prevailing during the experiments, the tracer gas migration in soil might be accounted for solely by molecular diffusion.

A few experiments were conducted to directly investigate the migration of air from the soil into the basement. Following the experiments at house B we discovered that the Tedlar bag used as a reservoir to contain the tracer gas had leaked. The leakage rate was determined to be 4 - 5 $cm^3 \ min^{-1}$, 2 - 2.5 times the delivery rate of gas to the soil. Because of the relatively rapid dispersion that occurs in outdoor air, we do not believe that this leak seriously affected the results. There is further evidence in support of the hypothesis that the leak had a negligible effect: during the experiments, elevated SF_6 concentrations were measured at soil sampling points between the injection point and the house; and the times to first appearance, and to achieve a steady-state concentration, are longer than would be expected if SF_6 leaking from the bag entered the house directly. Nevertheless, we cannot rule out the possibility that the rapid appearance of SF_6 in the basements of these houses was due, in part, to the leak.

The results of one experiment, conducted at house B using the same injection point as for the soil migration experiments, are shown in Figure 4. Here, with the house depressurized by 30 Pa, SF_6 appears in the basement within 45 minutes of the start of injection, implying a net migration velocity through the soil greater than 1 m h^{-1}. A mass-balance approach was used to estimate the entry rate of SF_6 into the basement; the steady-state value so determined after the end of injection was 0.35 cm^3 min^{-1}. Such an entry rate was observed for roughly 4 h during this experiment, thus accounting for approximately 1/3 of the total SF_6 injected. The entry rate was not seen to be diminishing at the time the experiment was terminated.

Two similar experiments were conducted at house A. In the first, the injection point was located 1 m from the basement, and the basement was depressurized by 42 Pa. The tracer gas was detected in the basement within 15 min, and within 1 h after the beginning of injection a steady-state indoor concentration had been reached. The second injection point was 5 m from the basement wall. With a comparable depressurization to that in the first test at house A, a constant SF_6 concentration was observed after 2.5 h.

EFFECT OF DEPRESSURIZATION ON INDOOR RADON LEVELS

If pressure-driven flow of soil gas is a predominant source of indoor radon, increased depressurization of a structure can lead to an enhanced radon entry rate that offsets the increase in air-exchange rate. Such a consequence was observed in two regards in a study of a house with a basement in Chicago (7): operation of a fireplace was much more effective in increasing the air-exchange rate than in reducing the indoor radon concentration; and the variation of radon concentration with changes in weather-driven infiltration was much less than predicted by a model based on a constant radon entry-rate. Consequently, the use of exhaust ventilation systems to maintain adequate indoor air quality may not be as effective in providing low indoor radon concentrations as would be predicted assuming a constant radon entry rate.

To examine the effects of depressurization on indoor radon levels, we continuously monitored the indoor radon concentration in the basement of house B during the six-day series of experiments. The radon monitor was based on a flow-through scintillation flask through which air was continuously drawn (18); its response was analyzed using one-hour sampling intervals (19). At a concentration of 200 Bq m^{-3}, the statistical uncertainty in a one-hour measurement was approximately 10%.

The measurement results, presented in Fig. 5, show that depressurization has a strong effect on the indoor radon concentration: the onset of each of the seven periods of fan operation corresponds to a marked increase in the indoor radon concentration. This result strongly suggests that an enhanced entry rate of radon into the basement occurs with depressurization, at least on a transient basis, thus reinforcing our conclusion that for this house depressurization causes substantial flow of air through the soil.

The average radon concentration measured during this period was 183 Bq m^{-3}, in excellent agreement with the heating season average. The average depressurization of the house during this study, 4.8 Pa, may be comparable to the average winter value. More thorough quantitative analysis of these data is probably not warranted because during many of the intervals during which the exhaust fan was not operated, windows and doors in the upper portion of the house were open.

CONCLUSIONS

This work has demonstrated that when a house basement is depressurized to a degree comparable to that induced by wind and temperature differences the pressure field and air movement in nearby soil are influenced. These effects probably account for the higher-than-average indoor radon concentrations observed in these two houses and could be a major factor in accounting for the relatively high indoor radon concentrations in many houses with basements. The two houses differed in substructure characteristics: in one the flow path appeared to be dominated by a large hole in the substructure shell; in the other no dominant entry path was identified. Both houses are located in a zone in which the subsoil has significant sand, gravel, and cobble components, and thus is highly permeable.

Both the pressure-field mapping and tracer-gas migration techniques are potentially useful for additional studies of the movement of soil air near structures. The pressure-mapping approach is simple and quick to execute, requires relatively inexpensive equipment, and could prove useful in identifying important pathways through a building substructure. The tracer-gas technique has several attractive features including a large dynamic range, small sample-volume requirements, and easy sample storage.

Further experiments at these or other houses could usefully attempt to quantify more precisely the transit times of air from points in the soil into the basement and determine the cumulative fraction of the tracer gas released that enters the basement as a function of time. An alternative experimental approach may prove useful: injecting the tracer gas into the basement while maintaining it at an overpressure and monitoring the concentration in the soil at points around the house as a function of time. This approach could be more efficient than the one reported here in examining the potential for soil-gas entry around the entire house.

Although the specific application of this study was entry into the basement of radon generated in the soil within several meters of the buildings, these experimental techniques could readily be modified to investigate the transport of other airborne pollutants through soil and into houses. A specific possibility of current interest is the entry of toxic chemicals that have migrated from landfills and waste dumps. Such a study would be distinguished from the current one principally in the range and time-scale over which local pressure-driven transport must be considered.

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Table I. House Characteristics

Parameter	House A	House B
Type	Two-story, wood framed; full basement with poured concrete floor and walls.	Two-story, wood framed; full basement with poured concrete floor and walls.
Volume (m^3)	962	578
Floor Area (m^2)[a]	383 269 w/o basement	260
Basement floor depth (m)	2.4	1.4
Heating system	Hot water, radiator	Forced air
Leakage area (m^2)	0.168	0.079
Infiltration rate (h^{-1})[b]	0.58	0.45
Radon concentration (Bq m^{-3})[c]		
Basement	278	192
1st floor	104	178
2nd floor	126	192
Radon entry rate (Bq h^{-1})[d]	9.4×10^4	5.0×10^4
Potential radon contribution of soil within 1 m (Bq h^{-1})	2.2×10^4	1.4×10^4

[a] Floor area of total occupied space.

[b] Determined from leakage area measurement and infiltration model for 90-day period beginning January 16, 1983 (10).

[c] Measured over three-month interval beginning in the first half of January, 1983 (23).

[d] Computed from mass-balance considerations based on radon concentration and infiltration rate as given above (11).

Table II. Soil Characteristics

Sample #	Depth (m)	Moisture Content (% mass)		Rn-222 Emanation Rate (10^{-5} Bq $kg^{-1}s^{-1}$)		Radium Concentration (Bq kg^{-1})	
		Field[a]	Air-Dry[a]	Field[a]	Air-Dry[a]	Ra-226	Ra-224[b]
A-3	0.3	13.4	4.7		1.5		
A-4	0.5-0.6			1.7	1.6	25	17
A-6	0.1-0.3	20.7	3.7		1.9		
B-1	0.3			1.7	1.8	37	27
B-2	0.3	14.8	4.7		1.5		
B-5	0.1-0.3	16.6	4.1		1.8		

[a] "Field" is the condition of the soil sample as it was collected; "Air-Dry" is the condition after the sample has been exposed for several days to a laboratory atmosphere.

[b] Ra-224 content is the "fixed" concentration, i.e., that which produces Rn-220 that decays within the sample. (The Ra-226 concentration gives the total of fixed plus emanating radium).

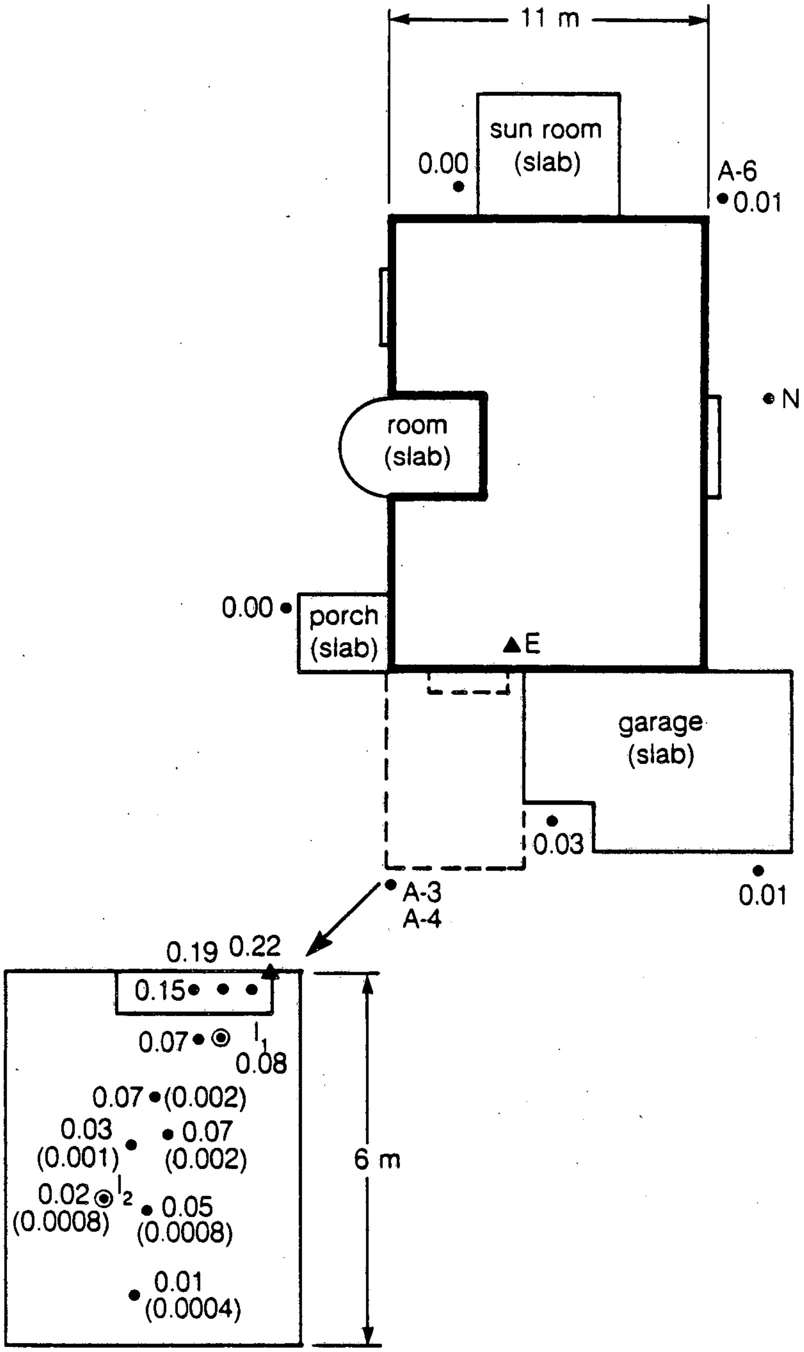

Figure 1. Plan view of house A. The numbers indicate the fractional pressure drop measured between points in the soil and the outdoor air relative to the basement depressurization of 42 Pa. The numbers in parentheses are based on a model in which the permeability of the soil is assumed to be homogeneous and isotropic. The letter N indicates that no stable reading was obtained. The five sampling points in the upper right of the enlargement were approximately 2.5 m below grade; all others were 0.9 m below grade. Tracer gas was injected in two experiments at the points labeled I_1 and I_2. Soil sample points are labeled A-3, A-4, and A-6 (see Table II). A large hole in the concrete substructure, thought to be a major entry point for soil gas, was found at point E. The heavy line indicates the basement perimeter.

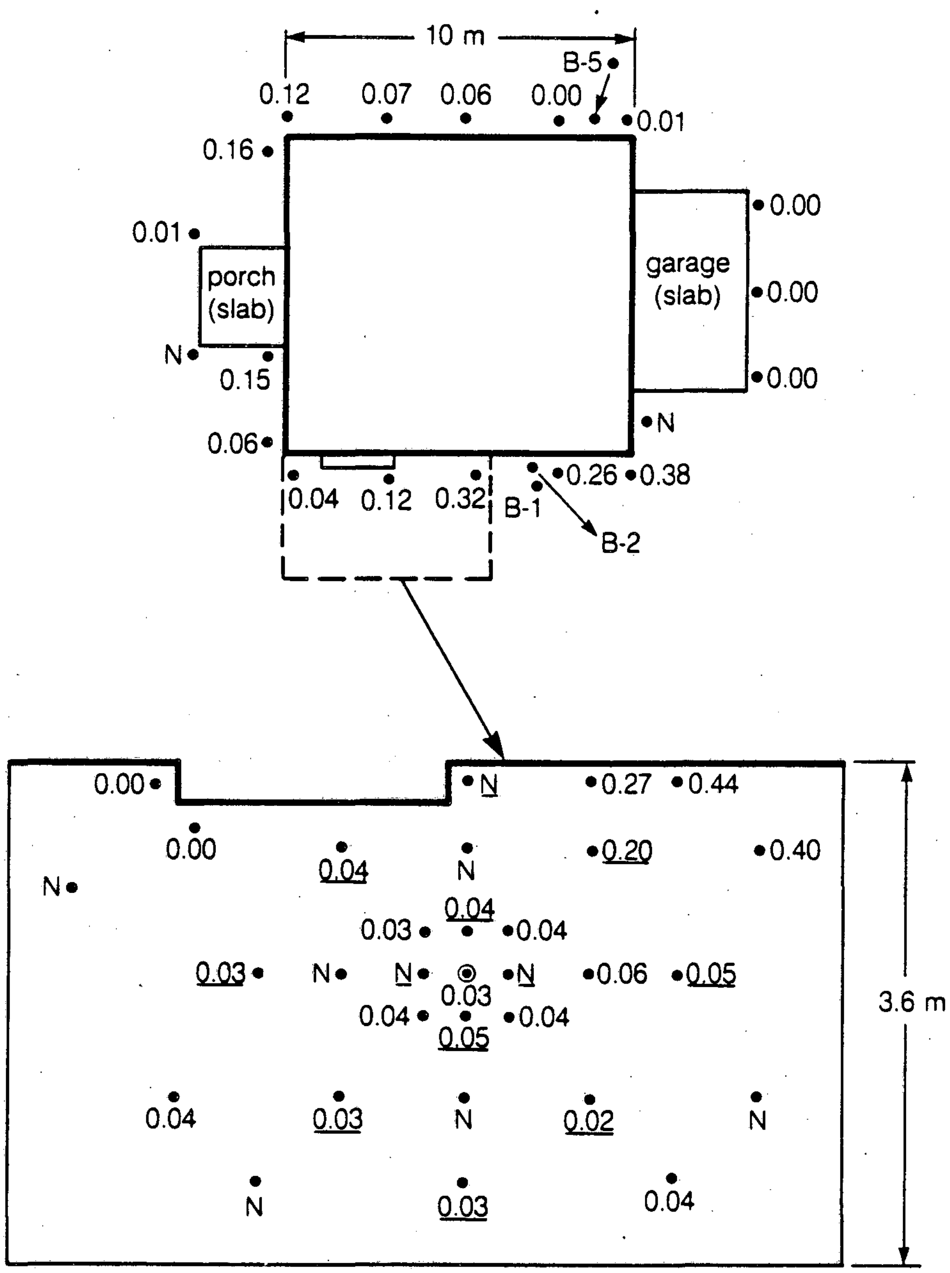

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Figure 2. Plan view of house B. The numbers indicate the fractional pressure drop between sampling points in the soil and the outdoor air relative to the basement depressurization of 30 Pa. The letter N indicates that no stable reading was obtained. The twelve underlined numbers correspond to sampling points 0.3 m below grade; the injection point (circled) was 0.6 m below grade; all other points were 0.9 m below grade. The enlarged area was used to study the migration of tracer gas in the soil with and without basement depressurization (see Fig. 3). Soil sample points are labeled B-1, B-2, and B-5 (see Table II). The heavy line indicates the basement perimeter.

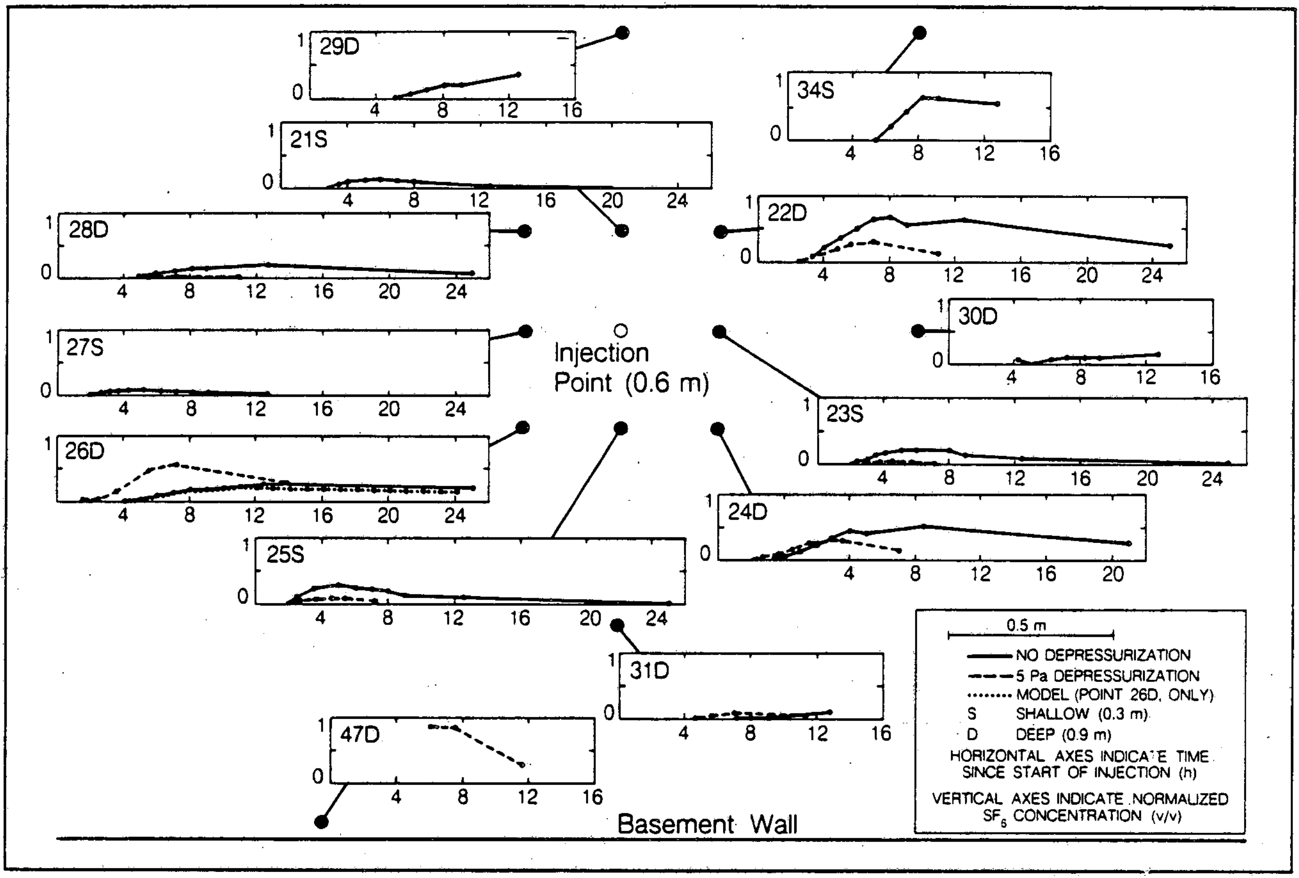

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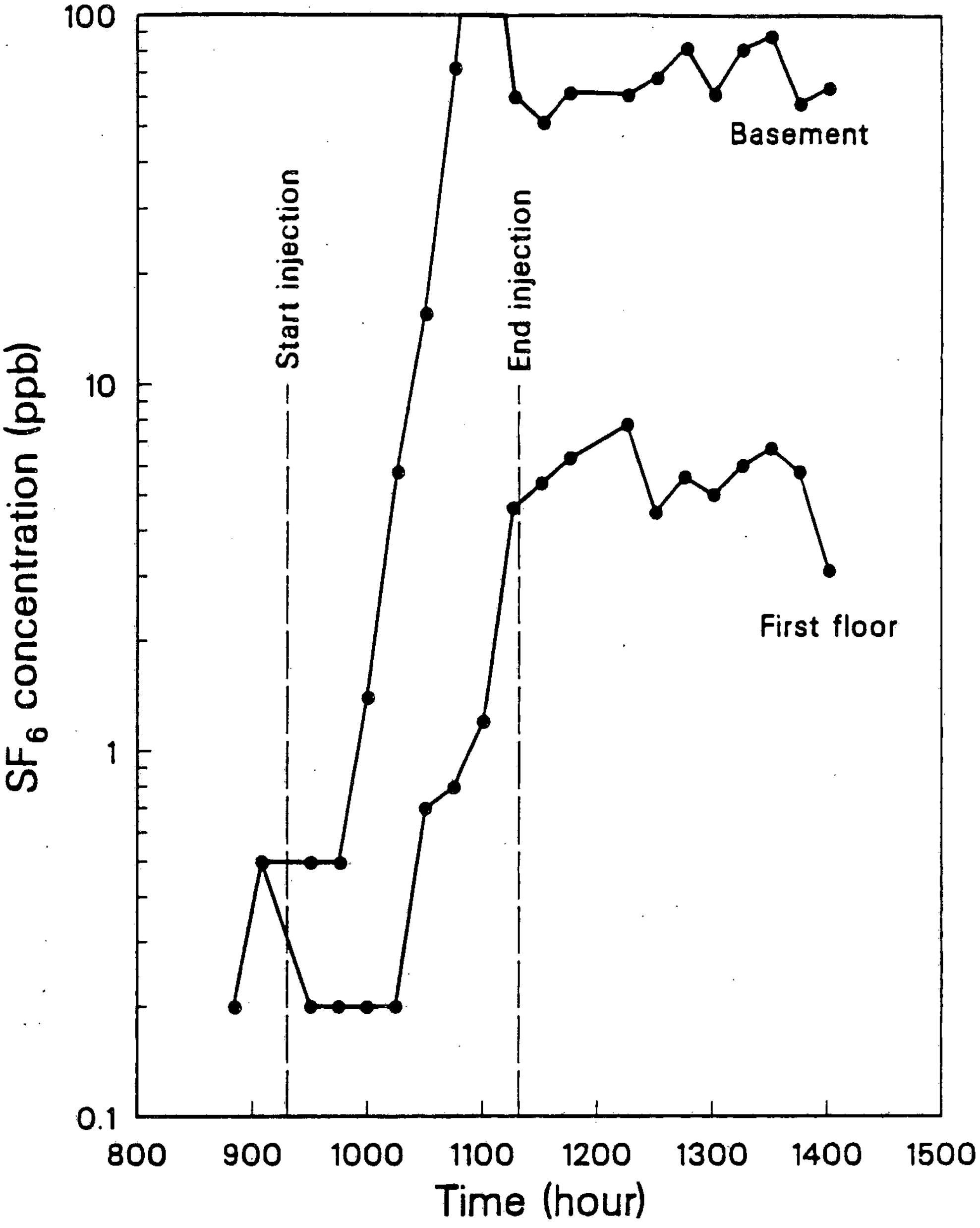
Figure 3. Normalized tracer gas concentrations vs. time at 13 sampling points in the soil adjacent to house B. On each of two successive days SF_6 was injected into the soil for two hours. On the first day the windows and doors of the house were open; on the second day they were closed and a fan used to depressurize the house to 8 Pa below the outdoor air. The normalization required dividing the SF_6 concentration (ppb) by the injected volume of SF_6 (cm^3, pure equivalent) and multiplying the result by the cube of the distance between the injection and sampling point (m). Thus, a value of 1.0 implies that all of the injected tracer gas could be accounted for by a cube the side of which has a length equal to the injection point - sampling point distance, and which contains a uniform concentration equal to that measured. The modeled concentration profile at point 26D assumes that the effective diffusion coefficient for SF_6 in soil is 0.012 cm^2/s, that the soil is infinite in extent, homogeneous and isotropic, and that its porosity is 0.33.



XCG 865-289

Figure 4. Tracer gas concentration in the basement and main floor of house B during and following injection of 247 cm^3 of pure SF_6 at the injection point indicated in Figs. 2 and 3. The house was maintained at an underpressure of 30 Pa with respect to outdoor air.

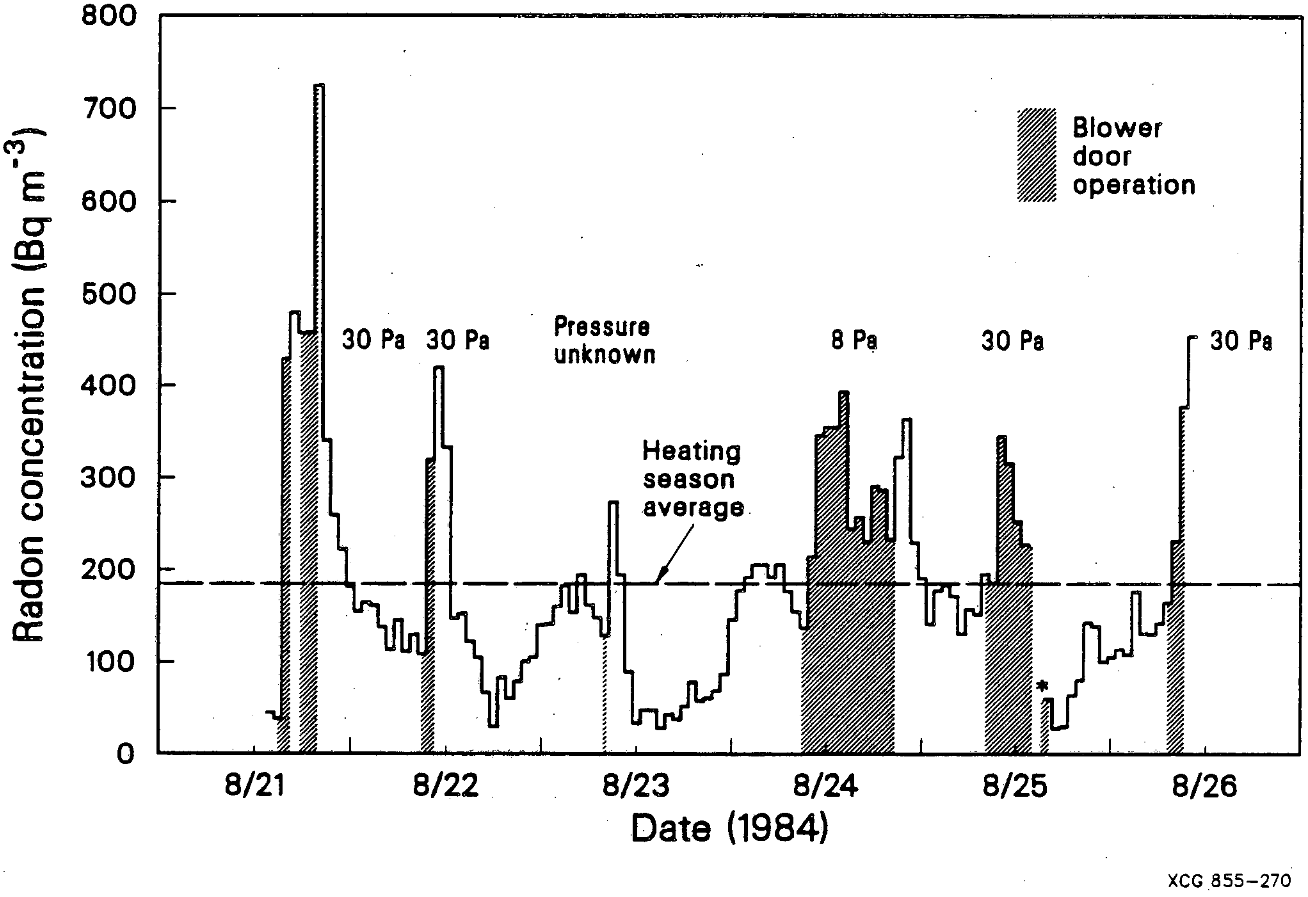


Figure 5. Radon concentration vs. time in house B. Seven periods of operation of the exhaust fan are indicated as shaded regions, with the depressurization, when monitored, noted. The * refers to a period for which there are no radon data.

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