Title
RADON ENTRY INTO HOUSES HAVING A CRAWL SPACE

Authors
Nazaroff, W.W.
Doyle, S.M.

Publication Date
1983-12-01

LBL-16637 c.1
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

Submitted to Health Physics

RADON ENTRY INTO HOUSES HAVING A CRAWL SPACE

W.W. Nazaroff and S.M. Doyle

December 1983

APPLIED SCIENCE DIVISION

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

Submitted to
Health Physics

LBL-16637
EEB-Vent 83-18

RADON ENTRY INTO HOUSES HAVING A CRAWL SPACE

W.W. Nazaroff and S.M. Doyle

Building Ventilation and Indoor Air Quality Program
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

December 1983

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division, and by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.It was also supported by the Bonneville Power Administration under Contract No. DE-AI79-83BP11436.

ABSTRACT

The transport of ^{222}Rn from soil, through a vented crawl space, and into the living space of single family residences was studied. Two houses were monitored in detail for periods of five and seven weeks. With crawl space vents open the average indoor ^{222}Rn concentrations were 1.2 and 0.6 pCi l^{-1} (44 and 22 Bq m^{-3}); with the vents sealed the averages rose to 2.2 and 1.0 pCi l^{-1} (81 and 37 Bq m^{-3}). The data suggest that of the radon released into the crawl space from the soil beneath the house, a significant fraction, perhaps 50% or more, enters the living space.

The effect of three meterological parameters -- wind speed, indoor-outdoor temperature difference, and rate of barometric pressure change -- on radon concentration and entry rate were examined. In one of the houses a higher temperature difference corresponded to a higher indoor concentration, suggesting that the increased infiltration rate is more than compensated by an increase in the radon entry rate. On the other hand, a high wind speed tended to reduce the indoor concentration, presumably by increasing both cross-ventilation of the crawl space and the infiltration rate of the living space.

Results suggests that radon transport into the crawl space of at least one of the houses occurred by pressure-driven flow, rather than solely by molecular diffusion. The diffusion coefficient of ^{222}Rn through polyethylene sheeting such as was present in this house, was measured in the laboratory and found to range from 0.65 x 10^{-7} cm^2s^{-1} at 11°C to 1.6 x 10^{-7} cm^2s^{-1} at 25°C, implying that the maximum diffusive flux through the sheet was many times smaller than that necessary to account for the rate of radon entry into the house.

A third house was studied using a tracer gas injected into the crawl space at a controlled rate. The fraction of air leaving the crawl space that entered the living space ranged from 0.3 to 0.65, in good agreement with results for radon transmission in the other two houses, assuming the ^{222}Rn flux into the crawl space was comparable to that which would have resulted from molecular diffusion from soil having a ^{222}Rn diffusion length 1.0 m. By sealing leaks in the floor of this house, the average infiltration rate was reduced by 25%, while the indoor concentration of the tracer gas remained roughly unchanged.

keywords: crawl space, indoor air quality, infiltration, pollutant sources, polyethylene, radon, radon flux, residential buildings, soil, vapor barrier.

INTRODUCTION

Soil is generally recognized to be an important and often the dominant source of indoor radon, an air pollutant that is associated with roughly half of the effective dose equivalent to the general public from natural radiation (UNSCEAR82,Ne83). The dose to individual members of the public varies widely, largely because of differences in the rate of entry into structures. In the case of soil as a source, these differences result both from its intrinsic characteristics, such as its radium content and mechanical composition, and from the degree of coupling of indoor air to the soil. For the latter factor, the design and construction of the building substructure are important elements.

Single-family dwellings in the United States are most often built with one of three substructure types -- basement, crawl space, or slab-on-grade -- or with a combination of these types. Although a significant portion of dwellings have a crawl space (in the Northwestern United States, for example, this is true of 48% of the houses having a single substructure type (Pa80)), research on radon entry into dwellings has thus far focused primarily on houses with basements (AECB79, Ge80, He82, Na83a, Sa82, Sc83). The results of this research suggest that diffusion of radon from soil and building materials, and entry via water, cannot account for many cases where higher indoor concentrations have been observed. The predominant mechanism for radon entry in these cases may be pressure-driven flow of soil gas through penetrations in the basement floor and walls. Temperature differences, wind speed, and barometric pressure changes may all play a role in inducing this flow.

Several distinctions that can affect radon entry exist between houses having a crawl space and those with a basement. For example, whereas the air in a basement is often well-coupled to that in the main floor of a house, a vented crawl space is better coupled to the outside air than to the living space. In other words, in a crawl-space house pressure differences are likely to be larger and more readily sustained across the house floor than across the crawl space walls. Furthermore, given common construction practices, the floor of a crawl-space house, commonly built of wood, is likely to have greater leakage area than the floor and walls of a basement, commonly built of poured concrete or concrete blocks. Finally, the basement walls and floor are in close contact with a large area of soil while the floor of a house with a crawl space is a few feet above the soil.

That houses having a crawl space can have high indoor radon concentrations has been clearly demonstrated: Rundo et al. (1979) measured ^{222}Rn concentrations in 22 such houses near Chicago and found 9 higher than 5 pCi l^{-1} (180 Bq m^{-3}), and 6 of these higher than 10 pCi l^{-1} (370 Bq m^{-3}). The crawl space in each of these houses was, however, unvented, and so, not only is the diffusive flux of radon from the soil under the house likely to enter the living space, but this flux may also be enhanced by pressure-driven flow. This potential enhancement is consistent with a measured flux from the soil under one house of 7.3 pCi $m^{-2}s^{-1}$ (0.27 Bq $m^{-2}s^{-1}$), considerably greater than the range of 0.1-1.4 pCi m^{-2} s^{-1} (0.004-0.052 Bq m^{-2} s^{-1}) cited by Wilkening et al. (Wi72) for measurements from uncovered soil. Whether houses having a vented crawl space can have high indoor concentrations is not known.

The important flow processes for radon transport from soil into a crawl-space house are shown schematically in Figure 1. Radon entering the crawl space from the soil will primarily then enter either the living space or the outdoor air. Its distribution between these two fates not only depends on the characteristics of the house, but also varies with meteorological conditions. During the heating season, for example, the temperature difference between indoor and outdoor air induces a convective loop with a net inward pressure exerted on the floor and lower part of the walls. This pressure, which for a single-story house is roughly 0.5 Pa for every 10°C of temperature difference (Sh80), leads to an air flow carrying radon into the house through cracks and holes, which are commonly found around plumbing, electrical, and heating system penetrations. Air-exchange between the crawl space and outdoor air is induced by temperature differences as well as by wind. However, temperature differences between the crawl space and outdoor air are typically small and crawl-space vents are close to the ground and often well shielded, thereby reducing the effect of wind. So even with a relatively large vent area, a crawl space may not have much cross ventilation.

The presence of the house and nearby landscaping may also significantly influence the flux of radon from the soil into the crawl space relative to the flux from a comparable soil in an uncovered field. If the crawl space is unvented, temperature difference and wind-induced pressures may lead to a flow of air through the soil and into the crawl space as into a basement. Even for a vented crawl space this effect may exist, although it will undoubtedly be much smaller. Perhaps the most important effect will result from a change in the spatial distribution of soil moisture, which is known to affect radon diffusion length (Ta64), emanation ratio (St82, St83) and soil permeability (Bu04).

Interest in energy conservation in dwellings makes attractive several measures that may affect the indoor radon concentration in crawl-space houses. An important example is partially sealing crawl-space vents during the heating season. The Uniform Building Code (1982) requires 0.67 m^2 of vent area for each 100 m^2 of house floor area, but, "in cases where moisture due to climate and groundwater conditions is not considered excessive", allows a reduction to 10% of this requirement if the ground is covered with a vapor barrier. This measure saves energy by reducing heat loss through an uninsulated floor, but also reduces cross ventilation of the crawl space, and thus may lead to higher indoor radon concentrations. Weatherization measures directed at reducing infiltration can also increase indoor radon levels. However, because radon enters the house from the soil with infiltrating air, it may be possible to reduce radon entry rates as well as infiltration rates by applying tightening measures to the house floor, thereby reducing energy consumption without adversely affecting indoor air quality.

The purpose of the current study was to investigate the entry of radon into houses having a crawl space, considering, in particular, the effect of some energy conservation measures and possible control techniques. Our approach was to survey a small sample of houses from which two were selected for detailed monitoring of radon concentrations and source parameters. This work was supplemented by measurements in the laboratory and in a controlled residence designed to elucidate the processes by which radon is transported from soil into a crawl space and from there into a house. In this paper, after discussing some general considerations regarding radon transport into crawl-space houses, we present the results of measurements in eight houses that were quickly characterized and in two houses that were monitored in detail, of radon diffusion through polyethylene, and of the transport of a tracer gas from the crawl space into the living space of an unoccupied residence.

TRANSPORT MECHANISMS AND ENTRY RATES

In this section we describe in general the transport of radon from soil through a crawl space and into the living space of a house, delineating the range of entry rates and concentrations that one may expect based on literature data, and describing some of the factors that influence transport. Other potential sources and transport processes -- building materials and entry via domestic water, in particular -- are ignored, in the former case because of the small amounts of crustal materials commonly used in crawl-space houses, and in the latter because the characteristics of radon entry via water are independent of the substructure type.

The case we consider is a single-story house with ceiling height, h, typically 2.4 m, and a vented crawl space. The nominal rate of radon entry from the soil into the crawl space is given by the flux from uncovered soil. (As mentioned in the previous section, the actual flux may differ from the nominal value due to the presence of the house.) Wilkening et al. (1972), reviewing 1000 such measurements for ^{222}Rn worldwide, give a mean value of 0.43 pCi $m^{-2}s^{-1}$ (0.016 Bq $m^{-2}s^{-1}$) and a range of average values for about 40 areas, excluding a few over lava which exhibited much lower values, of 0.1 - 1.4 pCi $m^{-2}s^{-1}$ (0.004 - 0.052 Bq $m^{-2}s^{-1}$). Flux due entirely to molecular diffusion can be expressed as the product of four terms:

$$F = \lambda_{Rn} \ell \rho p \ , \qquad (1)$$

where λ_{Rn} is the decay constant of ^{222}Rn (2.1 x 10^{-6} s^{-1}); ρ is the bulk soil density, which, for dry soil without organic matter, is typically in the range (1.0 - 1.7) x 10^6 g m^{-3} (Ra83); ℓ is the diffusion length of ^{222}Rn in soil, commonly in the range 0.6 - 1.5 m, but as low as 0.01 m for saturated soil (Ta64); and p is the emanating ^{226}Ra concentration of the soil, i.e., the ^{226}Ra concentration times the fraction of ^{222}Rn produced that is free to move through the soil pore space rather than being bound within a mineral grain. Only limited data exist for p; these indicate a range of less than 0.1 to 1.2 pCi g^{-1} (less than 4 to 44 Bq kg^{-1}) (Ba72, In83, Na83a, Pe66). Taking typical values of ρ = 1.4 x 10^6 g m^{-3}, ℓ = 1.0 m, and p = 0.25 pCi g^{-1} (9.3 Bq kg^{-1}) gives a flux of 0.74 pCi $m^{-2}s^{-1}$ (0.027 Bq $m^{-2}s^{-1}$), within the range cited above but somewhat greater than the mean.

Despite the comparable activity concentrations of ^{238}U and ^{232}Th in surface soils (My83), one would expect substantially different activity concentrations of ^{222}Rn and ^{220}Rn in crawl-space houses. Because of its relatively large decay constant (0.013 s^{-1}), much of the ^{220}Rn entering the crawl space from the soil will decay there. Since the radon decay products are chemically active, an important issue in assessing the radiological impact of ^{220}Rn indoors is the degree to which its decay products penetrate the building shell without becoming deposited on the surface of cracks and holes. If the degree of penetration is large the radiation dose from ^{220}Rn decay products may approximate that due to ^{222}Rn decay products. In the current study, measurements of ^{220}Rn and its decay products were not made, and henceforth the term radon refers to ^{222}Rn.

Of radon that enters the crawl space from the soil, the fraction, f, that is transmitted to the living space rather than outside depends, on average, upon the physical characteristics of the structure, such as the size and location of the vents, the degree of shielding, and the leakage area of the floor. It may be influenced by the operation of a forced-air furnace whose ducts are located in the crawl space both because air may leak into a return duct carrying radon directly into the house, and because the temperature of the crawl space air will increase, possibly increasing cross ventilation. The transmitted fraction will also vary with environmental conditions, particularly the respective temperatures of the indoor, crawl space, and outside air, and the wind speed. Given f, the radon entry rate into the residence, per unit volume, is then

$$\sigma = fF/h' = f\lambda_{Rn}\rho\ell p/h'. \tag{2}$$

Here h' is the ratio of the interior volume of the house to the floor area of the crawl space; it is somewhat less than the ceiling height, h. For steady-state conditions the indoor radon concentration will then be given by

$$I = \sigma/_{\lambda_v} + I_o , \tag{3}$$

where λ_v is the ventilation rate and I_o is the outdoor radon concentration. We ignore the removal of radon from indoor air by radioactive decay as it is generally much smaller than the removal by ventilation.

Assuming a flux equal to the worldwide average cited above, a ventilation rate of 0.5 h^{-1}, and an outdoor radon concentration of 0.1 pCi l^{-1} (4 Bq m^{-3}), typical of outdoor air along the west coast of the United States, the indoor radon concentration for our sample house will range from 0.1 to 1.4 pCi l^{-1} (4 to 52 Bq m^{-3}), for values of f between 0 and 1.

One of the goals of the current study was to determine values of f under a range of conditions. By measuring indoor and outdoor radon concentrations, and radon flux from the soil (or, alternatively, emanating ^{226}Ra content, soil bulk density, and radon diffusion length), f can be determined from equations (2) and (3). However, radon may be transported into the crawl space from the soil by processes other than molecular diffusion. Wind and convection-induced flow may play a role as briefly discussed above. In addition, barometric pressure changes are known to induce a flow of air into or out of the soil, influencing the radon flux (C174). Evidence of such processes was observed in this study, as will be discussed below. These processes, unfortunately, make determination of radon flux into the crawl space, necessary to calculate f, problematic.

SITE SURVEY: EIGHT HOUSES

Prior to selecting two houses for detailed monitoring, several measurements were made in eight houses. Three of these houses, belonging to employees of Lawrence Berkeley Laboratory, are located in the San Francisco Bay area, one each in the communities of Albany, Lafayette, and Concord. The other five houses are occupied by employees of the Bonneville Power Administration; three are within the city limits of Portland, Oregon, while the other two are in the nearby communities of Beaverton, Oregon and

Brush Prairie, Washington. The houses had neither furnaces nor return-air ducts in the crawl space, although in most cases supply ducts were located there. Whereas the three houses near San Francisco had fully vented crawl spaces with neither vapor barriers nor sub-floor insulation, each of the houses in the Portland area had a polyethylene ground sheet, four had fiberglass insulation beneath the floor, and four had partially-sealed crawl space vents.

Results of the survey measurements, presented in Table 1, are generally consistent and show radon concentrations and soil characteristics within the range considered to be typical. The irregular flux measurements observed in the Portland houses are thought to be due to the presence of the ground sheet: flux was measured under the sheet edge and transient changes in flux following disturbance of the sheet may have influenced the results.

It is somewhat surprising that even for the integrated measurements the crawl space radon concentration is sometimes seen to be lower than the indoor concentration, contrary to expectations if soil is the predominant source. This result may reflect poor mixing of air in the crawl space: with open vents the radon concentration in the crawl space will vary from the outdoor concentration near at least some of the vents to a maximum value well away from the vents. The ground sheet may influence the spatial distribution of radon considerably, as well, by changing the flux profile from the soil.

DETAILED MONITORING: TWO HOUSES

Because the site survey revealed generally consistent results, we selected houses for detailed monitoring primarily for minimum occupancy and for convenience in installing our monitoring instrumentation, rather than for their radon characteristics. The houses we selected, SF-B and P-C, each had two adult occupants who both worked outside the home, and no children. Each house had a simple rectangular geometry with an attached garage (having a slab-on-grade foundation) and crawl-space vents on three sides. Other characteristics of the houses, including several that were pertinent to the determination of ventilation rate, are given in the first two columns of Table 2.

Each house was monitored for a period of 5-7 weeks. Eight parameters were measured continuously, on-site, and these were supplemented by data from the National Weather Service on barometric pressure and rainfall. The eight parameters were radon concentration in indoor, outdoor, and crawl-space air, radon flux from the soil, indoor and outdoor temperature, and wind speed and direction.

Radon concentrations and flux were measured by continuous radon monitors (Th79) using scintillation flasks similar to the design by Lucas (1957), modified to have two ports, and coupled to 5-cm photomultiplier tubes. In each case air is drawn through a sampling line at 0.9 l min^{-1}, passes through a 5-l decay volume to eliminate ^{220}Rn, and, after passing through a filter, enters the flask. Airborne concentrations were sampled from the living room, from a point adjacent to the house about 1.5 m above grade, and from the center of the crawl space. The flux monitor sampled air from the outlet port of an accumulator box, 0.1-m high, covering about 0.95 m^2 of soil, and with its edges set about 1 cm below the soil surface. The inlet port of the accumulator, located opposite the outlet port, was open to atmosphere. In house SF-B the accumulator was deployed in the center of the crawl space; in house P-C, because of the vapor barrier, the box was deployed adjacent to the house, about 2 m from the foundation, covering a thin patch of weeds.

The radon monitors were calibrated for steady-state response by comparing their response to those of four similar monitors calibrated following the procedure of Busigin et al. (1979), and referred to a standard-reference-method solution of ^{226}Ra from the National Bureau of Standards. Background count rates were determined by sampling air containing a low concentration of radon (approx. 0.1 pCi l^{-1}, or 4 Bq m^{-3}) for 12-hour periods before and after field monitoring. Typical steady-state efficiencies and background count rates were thus determined to be 2.8 pCi $l^{-1}min^{-1}$ (100 Bq $m^{-3}min^{-1}$) and 0.3 min^{-1}, respectively. Ignoring calibration uncertainty, the 90% confidence limits for week-long measurement periods are ± 0.1 pCi l^{-1} (4 Bq m^{-3}) for concentrations less than 2 pCi l^{-1} (74 Bq m^{-3}) and are dominated by background uncertainty. Absolute calibration uncertainty is estimated to be on the order of 10%; however the relative uncertainty among the four devices is only a few percent. For three-hour measurement intervals, the basis for computing radon entry rate, the 90% confidence limits range from ± 0.2 pCi l^{-1} to ± 0.4 pCi l^{-1} (7 to 15 Bq m^{-3}) for concentrations in the range 0.5 - 2.0 pCi l^{-1} (18-74 Bq m^{-3}).

Indoor and outdoor temperatures were measured with thermistors, in the outdoor case with an aspirator and a radiant shield. Wind speed and direction were measured with a cup and vane assembly, mounted at 7.6 and 8.8 m heights at SF-B and P-C, respectively.

Ventilation rates were calculated from an infiltration model (Gr82):

$$\lambda_v = \frac{3600}{V} A_o \left(f_w^2 v^2 + f_s^2 \Delta T \right)^{1/2} , \tag{4}$$

where λ_v is the ventilation rate (h^{-1}), V is the house volume (m^3), v is the wind speed ($m\ s^{-1}$), T is the absolute value of the indoor-outdoor temperature difference (°C), A_o is the effective leakage area of the house (m^2), and f_w (dimensionless) and f_s ($m\ s^{-1}\ {}^oC^{-1/2}$) are the wind and stack parameter, respectively, which account for local and terrain shielding, house height, and the distribution of leakage area in the floor, walls and ceiling. The effective leakage area was measured for each house by fan pressurization, the average of determinations for pressurization and depressurization being used, and was assumed not to vary with sealing the crawl-space vents. The distribution of leakage area was assumed to be uniform per unit area of the house shell. Infiltration was assumed to account for the entire ventilation rate: it is the predominant ventilation mechanism of most U.S. houses during the heating system. A daily log maintained by the occupants indicated that the use of exhaust fans was restricted to a few percent of the time. Exterior doors and windows were generally closed, except that in the Portland house the occupants slept with their bedroom window open, and the door to the remainder of the house closed.

The radon entry rate into the living space was computed from a mass balance based on the measurement of the indoor radon concentration and the modeled infiltration rate (Na83b). The contribution due to outside air was subtracted, assuming the outdoor concentration to be 0.1 pCi l^{-1} (4 Bq m^{-3}). Although the outdoor concentration was monitored, in house SF-B the instrument failed and in house P-C the concentration was usually below the detection limit of about 0.2 pCi l^{-1}. The crawl-space ventilation rate was also computed from a mass balance assuming that the measured flux reflected the average flux for the crawl-space soil, and that the crawl-space air was well-mixed. Finally, the fraction of radon flux from the soil and transmitted through the crawl space that was necessary to account for the computed radon entry was calculated.

In each house measurements were made with crawl-space vents both open and sealed. In SF-B three week-long periods with the vents sealed were interposed between periods with the vents open. In P-C a two-week period with the vents sealed was followed by a three-week period during which they were open.

The results of these measurements are displayed in Figures 2 and 3, and summarized in Tables 3 and 4. The average indoor radon concentration in each house is in the typical range. The higher concentration in the Portland house appears to be primarily a result of its lower infiltration rate, 0.32 h^{-1} compared to 0.55 h^{-1}. The computed radon entry rate is also somewhat higher, 0.5 to 0.4 pCi $l^{-1}h^{-1}$, perhaps a reflection of the higher emanating ^{226}Ra content of its soil, 0.22 to 0.19 pCi g^{-1}, and despite the presence of the ground sheet.

A key result of this study is the observation that the fraction of radon transmitted through the crawl-space into the house is high. In fact, based on our flux measurements, which may, as discussed in a subsequest section, reflect inaccuracies, this fraction exceeds 1.0 for both houses when the crawl-space vents were sealed. Despite the possible inaccuracies, however, it is reasonable to conclude that under the conditions prevailing during the monitoring periods at these houses, a substantial fraction of the radon that enters the crawl-space from the soil is transmitted into the house, even with the vents open.

A second important result from these measurements is the effect of sealing the crawl-space vents on the indoor radon concentration: in each house, each week-long measurement period with the vents sealed has a higher indoor radon concentration than any of the corresponding periods with the vents open. Overall, the average concentrations with the vents sealed are 67% and 83% higher than the concentrations with the vents open for SF-B and P-C, respectively. Not surprisingly, the concentration in the crawl space increases to even a greater degree: the value with vents sealed is twice the value with vents open for SF-B and three times for P-C.

A striking result, important to understanding radon transport processes, is seen in the plots of radon concentration at the soil surface (proportional to radon flux) in Figures 2 and 3. Whereas in house SF-B the flux varies to a small degree and only over relatively long periods, the flux at house P-C shows rapid fluctuations. The differences between these two houses is probably a reflection of different soil types: the soil at SF-B is predominantly clay and should thus have a lower permeability than the larger-grained soil at P-C. The highly variable flux at P-C indicates that radon does not leave the soil there solely through molecular diffusion, but rather that pressures induced at least by barometric pressure changes also play a significant role. Transport of radon by bulk flow of soil gas reduces the effectiveness of a ground sheet in inhibiting radon flux; as will be discussed in the next section, the radon entry rate into P-C significantly exceeds that which can be attributed to diffusion through the ground sheet.

Further evidence that pressure-induced flow may contribute greatly to radon flux into the crawl space is seen in Figure 3 on March 29-30. On these days coincident with a modest drop in barometric pressure and a period of heavy rain, the radon concentrations indoors and in the crawl space rise to their highest values for the entire monitoring period. The measured flux, on the other hand, rises more modestly, consistent with the scale of the change in barometric pressure. During these days the radon entry rate into the house is several times greater than can be accounted for by the measured flux. The explanation for the high radon concentrations may be the funneling of radon from the soil into the crawl space: with a heavy rainfall, the permeability of the soil surrounding the house is greatly reduced while the permeability of the soil beneath the house remains unchanged; as the barometric pressure falls, soil gas may then flow into the crawl space at a higher rate than it does out of the soil surrounding the house. This effect is not observed during other periods of falling pressure, perhaps because there are no other instances during the monitoring period with sufficient rainfall. An alternative explanation is that the percolation of water through the soil may cause a piston-like displacement of soil gas which then flows into crawl-space. At SF-B, a similar period of heavy rainfall and falling barometric pressure occurred on December 21 and 22, and yet, while the radon concentration in the crawl space rises somewhat, the indoor concentration is very low. In this case the absence of a pronounced effect may reflect the low permeability of the soil, even when it is dry.

To examine the effects of various weather parameters on radon concentrations and entry rate, three-hour average data were sorted into eight bins according to whether the temperature difference between indoor and outdoor air, the wind speed, and the rate of change in barometric pressure were less than or greater than median values. The mean and standard error for each bin for indoor and crawl space radon concentration and entry rate are presented in Table 5; data from the two houses for periods with vents sealed and open are considered separately. Semi-quantitative information on the effect of the three weather parameters is obtained by examining pairs of numbers in which only one parameter has changed; considering all of the data, sixteen such pairs exist for each radon measurement and for each weather parameter. The significance of differences between paired means was estimated using the two-sample t-test (Fr78). The following comments are based primarily on differences in mean values for which the null hypothesis that the true means are equal can be rejected with 99% confidence.

Wind speed shows the clearest effect, but only in house SF-B with periods of low wind speed tending to have higher indoor and crawl-space radon concentrations and higher entry rates, particularly for small temperature differences. This result is consistent with our expectation: wind provides cross-ventilation of the crawl space reducing concentrations there; it also increases the ventilation of the crawl-space and the effect will be greater for small temperature differences. At P-C there is no highly significant effect of wind. This may indicate either that unmeasured variables are important, or that wind may enhance the transport of radon from the soil into the crawl-space.

The indoor-outdoor temperature difference appears to be another important factor in house SF-B, where a higher temperature difference results in a higher radon entry rate. With high wind speeds and the vents sealed, the indoor radon concentration is also significantly higher in this house when the temperature difference is greater. A higher temperature difference increases both the infiltration rate of the house and the flow of air (and radon) from the crawl-space into the living space. At low wind speeds, convection may dominate both the exchange of crawl-space air with outside air, and the flow of air from the crawl space into the house; the partitioning between these two flows may depend only to a small degree on the magnitude of the temperature difference. However, with a high wind speed a change in temperature difference will affect this partitioning. In house P-C there is a strong tendency, although not highly significant, for a low wind speed and a small temperature difference to result in a higher crawl-space radon concentration; however the effect of these two parameters on indoor concentration and entry rate is ambiguous.

Despite our expectation that falling barometric pressure should increase radon flux from the soil, thereby increasing radon concentrations indoors and in the crawl-space, and the radon entry rate, no clear pattern of effects is observed in the data.

Finally, it is noteworthy that the crawl-space ventilation rate was much lower in the Portland house than in the Lafayette house, despite the fact that the vent areas, shielding and weather were comparable. One major difference between the two houses that may account for this result is the presence only in the Portland house of subfloor fiberglass insulation. By reducing the rate of heat loss through the floor, the difference between the temperatures of the air in the crawl-space and outside is diminished, thereby reducing the convective cross-ventilation of the crawl-space and, consequently, potentially increasing the transmission of radon into the living space. This reduction in cross-ventilation, which could also increase the potential for structural problems from excessive moisture, might be inexpensively offset by mechanically ventilating the crawl space.

DIFFUSION OF RADON THROUGH A POLYETHYLENE GROUND SHEET

The presence of a ground-sheet vapor barrier may have a significant impact on radon flux from soil into a crawl space, both by retarding diffusive flux and by increasing soil moisture. At house P-C the vapor barrier consisted of two sheets of 0.15 mm black polyethylene, each about 5-m wide, which were overlapped by about 0.3 m where they met, and which covered a very large fraction of the soil. The only openings were small gaps between the foundation walls and the ground sheet, and around posts about which the vapor barrier was loosely gathered.

To assess the diffusion of radon through polyethylene we conducted laboratory measurements of the diffusion coefficient. The apparatus consisted of an aluminum chamber whose internal volume was bisected by a sheet of test material, and source and sample air streams, each of which flowed continuously through its respective side of the chamber. The source stream was contained in a closed loop and had radon concentrations in the range (1-5) x 10^5 pCi l^{-1} (4 x 10^6 - 20 x 10^6 Bq m^{-3}). The sample air stream, derived from compressed N_2, flowed at 0.2-0.3 l min^{-1}, first through the sample side of the chamber, then through a continuous radon monitor as described in the previous section, and finally through a 1-liter grab-sampling flask. Two or three grab samples were collected from the sample air stream and analyzed for ^{222}Rn concentration, using scintillation flasks (Lu57) and a volume-sharing transfer process, after the radon monitor indicated a steady-state count rate. Radon concentrations were found to be in the range 20-200 pCi l^{-1} (740-7400 Bq m^{-3}). Grab samples taken from the source loop at the beginning and end of the diffusion exposure period were similarly analyzed. These samples generally showed a loss rate of radon about four times as rapid as that due to decay, resulting in a 10-20% decrease in concentration over the 4-6 h experiment. In calculating the diffusion coefficient, the dependence of the radon concentration in the source loop on time was assumed to be exponential. The diffusion coefficient was calculated as

$$D = \frac{Q\,C_{sample}}{C_{source}} \frac{L}{A} , \qquad (5)$$

where Q is the sample stream flow rate, L is the thickness of the test material and A is its exposed area (154 cm^2).

Eleven measurements were conducted using both clear and black polyethylene sheets of 0.1-mm, 0.15-mm and 0.25-mm thickness, and at three temperatures: 4, 11 and 25 deg C. The sheet color and thickness had no discernible effect on the diffusion coefficient; however temperature did have a substantial effect, as seen in Table 6.

The results we obtained agree fairly well with the limited data in the literature. Pohl-Rüling et al. (Po80) report on the loss rate of radon from containers made of various materials; assuming the vessels to be cubical, their results indicate a diffusion coefficient of 1.0 x 10^{-7} cm^2 s^{-1} for 0.05-mm-thick polyethylene, and a similar value for polyvinyl chloride. Jha et al. (Jh82) measured the diffusion coefficient of radon through several materials other than polyethylene; they found D = 5 x 10^{-8} cm^2s^{-1} for 0.5-mm-thick polyvinyl chloride, and values more than an order of magnitude smaller for polyester and polycarbonate.

The effect of a 0.15-mm-thick ground sheet on the diffusive flux of radon from the soil can be evaluated accurately only if the diffusion length and porosity of the soil are known. However, an upper limit on the diffusive flux through the ground sheet can be derived by assuming that radon moves freely through the soil so that the radon concentration beneath the ground sheet is the same as that in the soil pores far below the surface. That concentration is given by $\rho p/\varepsilon$, where ε is the soil porosity. The bulk density of soil collected in the crawl space of house P-C was measured in the laboratory to be 1.36 g cm^{-3}, implying a porosity of 0.5, assuming the soil grain density to be 2.7 g cm^{-3} (Hu71,Ra83). Thus, assuming the emanating ^{226}Ra content of the soil to be 0.22 pCi g^{-1} (8 Bq kg^{-1}) as measured in the laboratory, the concentration of radon in the soil gas at depth below this house is about 600 pCi l^{-1} (2.2 x 10^4 Bq m^{-3}). The maximum diffusive flux through the ground sheet is determined as

$$J = -D \frac{\Delta C}{\Delta Z} . \qquad (6)$$

Taking D in the range (0.65-1.6) x 10^{-7} cm^2s^{-1}, the maximum flux is in the range 0.026 - 0.064 pCi $m^{-2}s^{-1}$ (0.0010 - 0.0024 Bq $m^{-2}s^{-1}$), only 10-25% of the measured flux over open soil which is, in turn, insufficient to account for the calculated entry rate.

The emanation of radon from soil grains and its transport through interstitial spaces are significantly affected by the soil moisture content, limiting the accuracy of this estimate of diffusive flux through the groundsheet. For example, a laboratory study showed a fourfold range in exhalation from one soil sample with minimum values occuring for completely dry soil, due to a reduced emanation coeficient, and for saturated soil, due to a low diffusion coefficient (St83). Our measurements of emanating ^{226}Ra concentration were determined after soil samples had been exposed to laboratory air for several days, thereby, in general, having a different moisture content than that <u>in situ</u>. Nevertheless, it is unlikely that such an inaccuracy could account for the order-of-magnitude discrepancy between the estimated diffusive flux and that necessary to account for the calculated entry rate.

Consistent with other evidence at this house, this result then clearly suggests that radon migration from the soil into the crawl space is not dominated by molecular diffusion. Although some radon may diffuse beneath the sheets to uncovered areas, this contribution is likely to be very small as the dimensions of covered areas are large compared to even the diffusion length of radon in open air (2.2-2.4 m).

THE EFFECT OF SEALING LEAKS IN THE FLOOR

Given the general picture outlined above for radon transport through a crawl space, a promising technique for simultaneously reducing infiltration and radon entry is to seal leaks in the floor. To test the effectiveness of this technique, we made detailed measurements over a two-week period at a third house, this one unoccupied and located in San Leandro, CA. The house characteristics regarding crawl space and living space ventilation are given in Table 2. Our experience in the other two houses led to concerns about our ability to accurately measure radon flux into the crawl space, so we decided to use a tracer gas, sulfur hexafluoride (SF_6), for this portion of the study.

Our approach was to inject SF_6 at a constant rate of 890 cm^3h^{-1} into the crawl space and monitor its concentration, using infrared analyzers, in the crawl space and living space. The tracer gas was injected near the center of the crawl space and distributed by an oscillating fan. The injection rate was held constant by a mass-flow controller and measured daily with a bubble flowmeter. The SF_6 analyzers were calibrated daily by sampling bottled gases containing 0, 8 and 25 ppm SF_6.

As in the two houses previously discussed, measurements were made with crawl space vents both sealed and open. Because these measurements were made during the summer, a 1500-W electric heater was operated continuously to maintain a higher temperature indoors than outside. The data indicate that the infiltration-driving conditions were comparable to those in the other two houses.

Midway through the monitoring period a "house-doctoring" approach was used to reduce the leakage area of the floor (D182). A blower door was used to depressurize the house and leaks between the crawl space and the living space were identified with smoke sticks. The predominant leaks we found were in the furnace ducts, at the joint between the floor of the original structure and the floor of a room addition, and around plumbing and electrical penetrations. These leaks were sealed with a combination of polyethylene sheeting, duct tape and caulk. For the purposes of the test, leaks in the furnace system were eliminated by sealing the supply and return registers in the house, including the gaps between their perimeters and the floor; sealing the ducts would require somewhat more time than sealing the other leaks. The total effort required to measure the leakage area several times and to seal the leaks was two person-days.

During the entire experiment the fireplace and exhaust-fan openings were sealed. The preliminary leakage area measurement yielded 1220 cm^2; after sealing the furnace registers the leakage area was reduced 11% to 1080 cm^2; and following the attempt to seal floor leaks the leakage area was 890 cm^2, or 75% of its original value. As in the other two houses, wind speed and indoor and outdoor temperature were measured continuously and a model was used to calculate infiltration rate. The leakage area was assumed to be uniformly distributed prior to the house doctoring work. The reduction in leakage area, 330 cm^2, was subtracted from the value previously attributed to the floor, 435 cm^2.

The measurement results are displayed in Figure 4 and summarized in Table 7. The indoor SF_6 concentration averages 25% and 50% higher with the vents sealed than with the vents open for the periods before and after floor-tightening, respectively, in contrast to the substantially larger increases in indoor radon concentration observed at the other two houses. Again this is suggestive that the flux of radon from the soil is influenced by small pressures: sealing the crawl-space vents increases the positive inward pressure at the bottom of the walls due to the stack effect.

Even though the calculated infiltration rate following the house doctoring was reduced by more than 25%, the SF_6 concentration in the living space changed very little. This result suggests that indoor radon concentrations in crawl-space houses may not be raised by weatherization measures that reduce the leakage area of the floor in cases where soil is the predominant source.

Our results indicate that 30-65% of the SF_6 released into the crawl space entered the house, much less than the corresponding transmission factor determined for radon in the other two houses. Considering, for example, measurements made with open crawl-space vents before the floor was tightened, we see that the tracer gas data are internally consistent. A crawl space air-exchange rate of 3 h^{-1} implies a flow of 290 m^3h^{-1} into the crawl space, half of which exits through the vents, the other half entering the house. The infiltration rate of the house, 0.6 h^{-1}, implies a flow of 230 m^3h^{-1}, of which 145 m^3h^{-1}, or 63%, enters through the floor, the remainder entering through the walls. Thus the expected ratio of SF_6 concentration in the living space to that in the crawl space is 0.63, close to the measured value of 0.56.

DISCUSSION: THE TRANSMISSION FACTOR

Table 8 presents a summary of the transmission factors measured in this study. The table also gives values that are calculated assuming a radon flux from the soil as given in equation (1) with emanating ^{226}Ra concentration as measured for soil samples from the two houses, and diffusion lengths of 0.6, 1.0, and 1.5 m, spanning the typical range. Transmission factors for houses SF-B and P-C agree well with the values determined using SF_6 for the San Leandro house if a flux corresponding to a diffusion length of 1.0 m is assumed. This agreement does not imply, however, that molecular diffusion can account for the transport of radon from soil into the crawl space, at least at P-C. As we previously demonstrated, the ground sheet should have had a pronounced effect on radon flux into the crawl space if this were the case. Rather, it appears that a combination of diffusion and pressure-driven flow may yield a flux that is comparable to that resulting from diffusion alone from uncovered soil having a diffusion length of 1.0 m.

The discrepancy between the measured flux and that corresponding to a diffusion length of 1.0 m implies either that we have failed to identify major sources of radon in these houses or that the flux measurement typically detects only 50% of the true flux. The possibility of overlooking a major radon source seems very unlikely. In both cases water supplies are derived from surface sources, and in neither house does the indoor radon concentration show a time pattern that would characteristically result from the intermittent use of water bearing a high radon concentration. And since both houses have wood-frame construction and wood floors, crustal materials used in the buildings appear insufficient to account for the entry rates observed. Furthermore, the dramatic effect of sealing the crawl-space vents argues strongly that soil is the predominant source of radon in both cases.

Three factors may contribute to a significant error in flux measurement, in each case causing an underestimate. First, at each house we observed that when the accumulator was removed, the soil beneath it was visibly wetter than adjacent soil. Combining this observation with the fact that at each house the measured flux tends to decrease with time suggests that the added moisture may lead to diminished flux by reducing the diffusion length. The second factor is the possible diffusion of radon out of the accumulator under its edge. This could result in a 10% loss, estimated by calculating the flux through a 1 cm x 4 m area of soil that is 2 cm thick and has a diffusion length of 1 m. This loss could have been avoided by placing the edge of the accumulator deep into the soil as suggested by Wilkening (Wi77). The third factor results from pressure-driven transport processes, the evidence for which, at least for house P-C, has already been discussed. If such flows exist, they may be quite different in soil under the house and soil under the accumulator. Furthermore, for large effects, such as those resulting from changes in barometric pressure, the air flow rate into the accumulator may exceed the sampling rate of 0.9 l min^{-1}, and some radon may thus flow through the accumulator without being measured.

CONCLUSIONS

To reiterate the principal findings presented in this paper, it appears 1) that a significant fraction of the radon flux into a vented crawl space enters the living space; 2) that sealing crawl space vents may significantly increase indoor radon concentrations; 3) that a polyethylene ground sheet, which should substantially reduce the diffusive flux of radon from the ground, does not appear to have effectively reduced radon transport in the one case studied, probably because of pressure-driven flow around the sheet; and 4) that it may be possible to substantially reduce infiltration rates in existing crawl-space houses without increasing indoor radon levels by sealing penetrations in the floor.

Each of the houses in this study in which radon was measured had concentrations in what is usually considered the typical range for U.S. housing. Similarly, emanating ^{226}Ra content and radon flux from the soil are in the normal range, perhaps slightly less than average. The results of this study suggest then that one may find high radon concentrations (for example, exceeding 10 pCi l^{-1}, or 370 Bq m^{-3}) in some houses with crawl spaces in areas where the soil flux is high and particularly if the crawl space is poorly ventilated. Systematic identification of regions with high radon potential in the soil will clearly aid finding such houses.

Too few houses were monitored in the current study to give definitive, quantitative answers to questions about the effects of various measures on radon concentrations in houses with a crawl space. A promising measure to reduce infiltration rates, thereby saving energy, while having little if any negative impact on indoor radon concentrations, is to seal leaks in the floor. This technique may also be beneficial in reducing indoor moisture in cases where the soil is wet, and it should be investigated further. On the other hand, sealing crawl space vents appears to significantly increase indoor radon levels; if this approach to improving comfort and reducing energy use in residences is to continue, its impact should be investigated in a systematic study on a broader scale.

A possible mitigation technique not considered in this study is the use of mechanical ventilation for the crawl space. Assuming a flux of radon into the crawl space of the houses studied comparable to that resulting from molecular diffusion with a diffusion length of 1.0 m, the flow of air from the crawl space to outside is roughly 100 m^3h^{-1}; for an exhaust fan to be effective, its flow rate would have to be comparable to this figure. Inexpensive blowers which are require only 20 W of power, are available to provide this flow rate, and it may therefore be useful to study the effectiveness of this technique.

ACKNOWLEDGMENTS

We gratefully acknowledge several of our colleagues at Lawrence Berkeley Laboratory for their assistance during the course of this project: A.R. Smith and B.A. Moed measured emanating ^{226}Ra in soil samples and analyzed a number of charcoal cannisters for accumulated ^{222}Rn; L. Davis and A.W. Robb assisted in fabricating some of the monitoring equipment used in this study; and J.F. Koonce provided considerable assistance in making measurements at house SF-B. We further acknowledge the assistance of P. Thor, project manager for Bonneville Power Administration (BPA), who both arranged for the five Portland houses we studied and made available to us integrated radon concentration data he had collected. M. McKinstry, also of BPA, measured the leakage area of house P-C. We also express our gratitude to the occupants of the nine houses we studied, particularly those of the three we examined in detail, for permitting us to disrupt their households.

The manuscript has benefited from the review of A.V. Nero, F.J. Offermann, and P. Thor. Of course, the responsibility for all errors of fact or interpretation lies with the authors.

This work was supported by the Bonneville Power Administration, and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division, and by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

AECB79 Atomic Energy Control Board, Canada, 1979, Second Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, AECB-1164, Bancroft, Ontario, 12-14 March.

Ba72 Barretto P.M.C., Clark R.B. and Adams J.A.S., 1972, "Physical Characteristics of Radon-222 Emanation from Rocks, Soils and Minerals: Its Relation to Temperature and Alpha Dose", in: Natural Radiation Environment II (Edited by J.A.S. Adams et al.), U.S. Dept. of Commerce, National Technical Information Service, Rep. CONF-720805-P.2, pp. 731-740.

Bu04 Buckingham E., 1904, "Contributions to our Knowledge of the Aeration of Soils", U.S. Dept. of Agriculture, Bureau of Soils, Bulletin No. 25, Washington, D.C.

Bu79 Busigin A., van der Vooren A.W. and Phillips C.R., 1979, "Interpretation of the Response of Continuous Radon Monitors to Transient Radon Concentrations", Health Phys. 37, 659-667.

Cl74 Clements W.E. and Wilkening M.H., 1974, "Atmospheric Pressure Effects on ^{222}Rn Transport Across the Earth-Air Interface", J. Geophys. Res. 79, 5025-5029.

Di82 Diamond R.C., Dickinson J.B., Lipschutz R.D., O'Regan B. and Shohl B., 1982, "The House Doctor's Manual", Lawrence Berkeley Laboratory, Rep. PUB-3017, Berkeley, CA.

Fr78 Freedman D., Pisani R. and Purves R., 1978, Statistics, (New York: W.W. Norton) pp. 454-469.

Ge80 George A.C. and Breslin A.J., 1980, "The Distribution of Ambient Radon and Radon Daughters in Residential Buildings in the New York - New Jersey Area", in: Natural Radiation Environment III (Edited by T.F. Gesell and W.M. Lowder), U.S. Department of Energy Rep. CONF-780422 (Vol. 2), 1272-1292.

Gr82 Grimsrud D.T., Modera M.P. and Sherman M.H., 1982, "A Predictive Air Infiltration Model -- Long-Term Field Test Validation", ASHRAE Trans. 88 (Part 1) 1351-1369.

He82 Hess C.T., Weiffenbach C.V. and Norton S.A., 1982, "Variations of Airborne and Waterborne Rn-222 in Houses in Maine", Environ. Int. 8, 59-66.

Hu71 Hurlbut C.S., 1971, Dana's Manual of Mineralogy 18th edn (New York: John Wiley and Sons).

In83 Ingersoll J.G., 1983, "A Survey of Radionuclide Contents and Radon Emanation Rates in Building Materials Used in the U.S.", Health Phys. 45, 363-368.

Jh82 Jha G., Raghavayya M. and Padmanabhan N., 1982, "Radon Permeability of Some Membranes", Health Phys. 42, 723-725.

Lu57 Lucas H.F., 1957, "Improved Low-Level Alpha-Scintillation Counter for Radon", Rev. Sci. Instrum. 28, 680-683.

My83 Myrick T.E., Berven B.A. and Haywood F.F., 1983, "Determination of Concentrations of Selected Radionuclides in Surface Soil in the U.S.", Health Phys. 45, 631-642.

Na83a Nazaroff W.W., Feustel H., Nero A.V., Revzan K.L., Grimsrud D.T., Essling M.A. and Toohey R.E., 1983, "Radon Transport into a Single-Family House with a Basement", Lawrence Berkeley Laboratory, Rep. LBL-16572, Berkeley CA. Submitted to Atmospheric Env.

Na83b Nazaroff W.W., Offermann F.J. and Robb A.W., 1983, "Automated System for Measuring Air-Exchange Rate and Radon Concentration in Houses", Health Phys. 45, 525-537.

Ne83 Nero A.V. and Nazaroff W.W., 1983, "Characterizing the Source of Radon Indoors", Lawrence Berkeley Laboratory, Rep. LBL-16636, Berkeley CA. Submitted to Rad. Prot. Dosimetry.

Pa80 The Pacific Northwest Residential Energy Survey, 1980, Bonneville Power Administration Rep. #82-0122 (5467), Portland, OR.

Pe66 Pearson J.E. and Jones G.E., 1966, "Soil Concentrations of 'Emanating Radium-226' and the Emanation of Radon-222 from Soils and Plants", Tellus 18, 656-661.

Po80 Pohl-Rühling J., Steinhausler F. and Pohl E., 1980, "Investigation on the Suitability of Various Materials as ^{222}Rn Diffusion Barriers", Health Phys. 39, 299-301.

Ra83 Rawls W.J., 1983, "Estimating Soil Bulk Density from Particle Size Analysis and Organic Matter Content", Soil Sci. 135, 123-125.

Ru79 Rundo J., Markun F. and Plondke N.J., 1979, "Observation of High Concentrations of Radon in Certain Houses", Health Phys. 36, 729-730.

Sa82 Sachs H.M., Hernandez T.L. and Ring J.W., 1982, "Regional Geology and Radon Variability in Buildings", Environ. Int. 8, 97-103.

Sc83 Scott A.G., 1983, "Computer Modelling of Radon Movement", in EML Indoor Radon Workshop, 1982 (Edited by A.C. George et al.), Environmental Measurements Laboratory,Rep. EML-416, New York, pp. 82-83.

Sh80 Sherman M.H., 1980, "Air Infiltration in Buildings", Ph.D. Thesis, Lawrence Berkeley Laboratory, Rep. LBL-10712, Berkeley CA, Appendix C.

St82 Strong, K.P. and Levins D.M., 1982, "Effect of Moisture Content on Radon Emanation from Uranium Ore and Tailings", Health Phys. 42, 27-32.

St83 Stranden E., Kolstad A.K. and Lind B., 1983, "The Influence of Moisture and Temperature on Radon Exhalation", paper presented at International Seminar on Indoor Exposure to Natural Radiation and Related Risk Assessment, Capri, Italy, October 3-5.

Ta64 Tanner A.B., 1964, "Radon Migration in the Ground: A Review", in: Natural Radiation Environment (Edited by J.A.S. Adams and W.M. Lowder) (University of Chicago Press), 161-190.

UBC82 Uniform Building Code, 1982, (Whittier, CA: International Conference of Building Officials).

UNSCEAR82 United Nations Scientific Committee on the Effects of Atomic Radiation, 1982, Ionizing Radiation: Sources and Biological Effects, (New York: UN).

Wi72 Wilkening M.H., Clements W.E. and Stanley D., 1972, "Radon-222 Flux Measurements in Widely Separated Regions", in: Natural Radiation Environment II (Edited by J.A.S. Adams et al.), U.S. Energy Research and Development Administration Rep. CONF-720805, pp. 717-730.

Wi77 Wilkening M.H., 1977, "Measurement of Radon Flux by the Accumulation Method", presented at Workshop on Methods for Measuring Radiation in and Around Uranium Mills, Albuquerque, NM, May 23-26, 1977.

MEASUREMENT	HOUSE SF-A	SF-B	SF-C	P-A	P-B	P-C	P-D	P-E
Indoor:								
^{222}Rn[a] (pCi l^{-1})[b]	-	-	-	1.4	0.5	0.8	2.3	0.3
^{222}Rn (pCi l^{-1})	-	-	-	0.9	0.9	0.8	2.1	0.4
^{218}Po (pCi l^{-1})	0.2	0.4	0.3	0.6	0.4	0.5	1.4	0.3
PAEC (WL)	0.0017	0.0028	0.0027	0.0017	0.0020	0.0025	0.0081	0.0027
Crawl Space:								
^{222}Rn[a] (pCi l^{-1})	-	-	-	0.5	0.5	2.2	4.3	0.6
^{222}Rn (pCi l^{-1})	0.6	0.8	2.5	-	-	-	-	-
^{218}Po (pCi l^{-1})	0.3	0.4	1.6	0.7	0.7	1.1	0.4	0.4
PAEC (WL)	0.0014	0.0030	0.0060	0.0023	0.0050	0.0036	0.0023	0.0020
Outdoor:								
^{218}Po (pCi l^{-1})	0.1	-	0.1	0.2	0.5	0.2	0.3	0.2
PAEC (WL)	0.0016	-	0.0021	0.0008	0.0039	0.0017	0.0017	0.0017
Soil:								
Eman. ^{226}Ra (pCi g^{-1})	0.15	0.19	0.20	0.18	0.21	0.22	0.21	0.21
^{222}Rn Flux (pCi $m^{-2}s^{-1}$)	0.4	0.5	0.5	0.6	0.5	1.1	11.4	0.03

[a] Integrated measurement, January - March, 1983.

[b] 1 pCi = 0.037 Bq.

Table 1. Measurement results for eight-house site assessment. Prefixes SF and P indicate that the house is located in the San Francisco, CA or Portland, OR area, respectively. San Francisco area measurements were made in mid-October 1982. Grab-sample measurements were made in Portland in early February 1983; integrated radon measurements were made over a three-month period beginning in January 1983.

PARAMETER	LAFAYETTE, CA	PORTLAND, OR	SAN LEANDRO, CA
House ID	SF-B	P-C	-
Floor Area (m^2)	114	107	150
Volume (m^3)	295	262	360
Leakage Area (cm^2)	870	455	1220/894[a]
Terrain Class	3.5	3.5	3.5
Shielding Factor	3.0	2.75	3.0
Crawl Space Height (m)	0.6	0.7	0.6
Number of Vents	10	6	14
No. House Sides Vented	3	3	4
Vent Area (m^2)	0.70	0.55	0.57
Crawl Space Groundsheet	none	0.015 cm polyethylene	none

[a] Sealing furnace registers and leaks in floor reduced leakage area by 326 cm^2.

Table 2. Physical characteristics of three houses in which detailed measurements were performed. Terrain class and shielding factor, estimated from visual inspection, are used in the infiltration model (Gr82).

		RADON			WEATHER		VENTILATION			
Dates	Hrs. Meas.	Indoor (pCi l^{-1})	Crawl Space (pCi l^{-1})	Soil Flux (pCi $m^{-2}s^{-1}$)	Wind Speed (m s^{-1})	ΔT (°C)	Crawl Space (h^{-1})	Indoor (h^{-1})	Radon Entry Rate (pCi $l^{-1}h^{-1}$)	f
Vents Sealed[b]										
12/3-12/10/82	153	1.0	2.8	0.25	1.2	7.3	0.5	0.47	0.4	1.1
12/23-12/31	192	0.8	1.9	0.18	1.1	10.7	0.6	0.53	0.4	1.5
1/7-1/14/83	165	1.1	2.5	0.28	0.8	15.5	0.6	0.59	0.6	1.6
Average		1.0	2.4	0.23	1.1	11.3	0.6	0.53	0.5	1.4
Vents Open										
11/19-11/25/82	138	0.7	1.4	0.40	1.2	11.1	1.8	0.55	0.3	0.6
11/26-12/2	141	0.5	1.1	0.31	2.3	12.7	3.9	0.65	0.2	0.6
12/11-12/17	156	0.6	1.2	0.29	1.1	8.2	2.0	0.49	0.2	0.6
12/31/82-1/7/83	162	0.7	1.4	0.22	0.9	16.1	1.0	0.61	0.4	1.2
Average		0.6	1.3	0.30	1.3	12.1	2.1	0.57	0.3	0.7

[a] 1 pCi = 0.037 Bq.

[b] Only 9 of 10 vents sealed during first week; all 10 sealed during other two weeks.

Table 3. Summary of results from detailed monitoring in house SF-B, located in Lafayette, CA.

		RADON				WEATHER		VENTILATION			
Dates	Hrs. Meas.	Outdoor (pCi l^{-1})[a]	Indoor (pCi l^{-1})	Crawl Space (pCi l^{-1})	Soil Flux (pCi $m^{-2}s^{-1}$)	Wind Speed ($m\ s^{-1}$)	ΔT (°C)	Crawl Space (h^{-1})	Indoor (h^{-1})	Radon Entry Rate (pCi $l^{-1}h^{-1}$)	f
Vents Sealed											
3/10-3/17/83	172	0.0	2.1	6.2	0.36	2.4	6.2	0.3	0.33	0.6	1.2
3/18-3/25	191	0.1	2.2	6.1	0.27	1.3	8.9	0.2	0.30	0.6	1.6
Average		0.0	2.2	6.1	0.31	1.8	7.5	0.3	0.31	0.6	1.4
Vents Open[b]											
3/27-4/1	142.5	-0.1	2.0	3.0	0.25	1.9	9.4	0.6	0.35	0.6	1.7
4/2-4/7	143.5	0.0	0.8	1.6	0.21	1.4	9.1	0.9	0.30	0.2	0.7
4/8-4/14	154.5	0.0	0.9	1.5	0.20	1.3	12.4	0.8	0.34	0.3	0.9
Average		0.0	1.2	2.0	0.22	1.5	10.3	0.8	0.33	0.4	1.1

[a] 1 pCi = 0.037 Bq.

[b] One of six vents sealed during these three weeks.

Table 4. Summary of results from detailed monitoring in house P-C, located in Portland, OR.

House/vents		ΔT → L WS → L $\frac{\Delta B}{\Delta t}$ → L	L L H	L H L	L H H	H L L	H L H	H H L	H H H	Median Values ΔT (°C)	WS (m s^{-1})	$\frac{\Delta B}{\Delta t}$ (Pa h^{-1})
SF-B/sealed	indoor (pCi l^{-1})	1.3±0.10	1.1±0.10	0.7±0.07	0.6±0.06	1.0±0.05	1.1±0.06	1.1±0.09	0.9±0.06	10.7	0.7	+10
	crawl space (pCi l^{-1})	2.9±0.12	2.4±0.14	2.4±0.11	2.0±0.16	2.5±0.11	2.4±0.10	2.5±0.15	2.4±0.14			
	entry rate (pCi $l^{-1}h^{-1}$)	0.5±0.05	0.5±0.05	0.3±0.03	0.3±0.03	0.6±0.04	0.6±0.04	0.7±0.06	0.5±0.06			
SF-B/open	indoor (pCi l^{-1})	0.8±0.08	0.7±0.10	0.5±0.07	0.3±0.05	0.8±0.05	0.7±0.05	0.6±0.06	0.5±0.09	12.7	1.1	-7
	crawl space (pCi l^{-1})	1.6±0.09	1.6±0.15	0.9±0.13	1.0±0.13	1.6±0.10	1.5±0.09	1.0±0.16	1.1±0.16			
	entry rate (pCi $l^{-1}h^{-1}$)	0.3±0.04	0.3±0.05	0.2±0.04	0.1±0.02	0.4±0.03	0.4±0.04	0.3±0.04	0.3±0.06			
P-C/sealed	indoor (pCi l^{-1})	1.9±0.25	2.6±0.35	1.9±0.13	2.4±0.13	2.3±0.13	2.2±0.10	2.0±0.10	2.2±0.16	7.4	1.2	-7
	crawl space (pCi l^{-1})	7.4±0.42	7.1±0.62	6.5±0.36	6.3±0.25	5.8±0.38	5.4±0.24	5.1±0.79	5.4±0.21			
	entry rate (pCi $l^{-1}h^{-1}$)	0.4±0.07	0.6±0.06	0.6±0.05	0.8±0.07	0.7±0.04	0.7±0.03	0.6±0.10	0.8±0.07			
P-C/open	indoor (pCi l^{-1})	1.0±0.17	1.7±0.38	1.4±0.20	1.6±0.41	1.1±0.06	1.0±0.06	0.9±0.10	1.2±0.31	11.2	1.4	+24
	crawl space (pCi l^{-1})	2.5±0.39	2.4±0.41	2.2±0.37	1.9±0.40	1.8±0.11	1.8±0.11	1.6±0.20	1.9±0.64			
	entry rate (pCi $l^{-1}h^{-1}$)	0.3±0.07	0.5±0.09	0.4±0.10	0.5±0.14	0.3±0.02	0.3±0.02	0.3±0.04	0.4±0.13			

Table 5. Detailed monitoring data sorted into eight bins according to wind speed, temperature difference, and rate of barometric pressure change. Each entry reflects the mean ± standard error of all three-hour measurements for which each sorting parameter was higher or lower than the median value indicated.

No. of Samples	Temperature (°C)[a]	D (10^{-7} cm^2 s^{-1})[a]
1	3.5	0.30
4	11.4±1.7	0.65±0.20
6	25.1±1.2	1.61±0.20

[a] Mean value ± one s.d.

Table 6. Diffusion coefficient of ^{222}Rn through a polyethylene sheet for different temperatures. Results are averaged for clear and black sheeting and for thicknesses ranging from 0.10-0.25 mm.

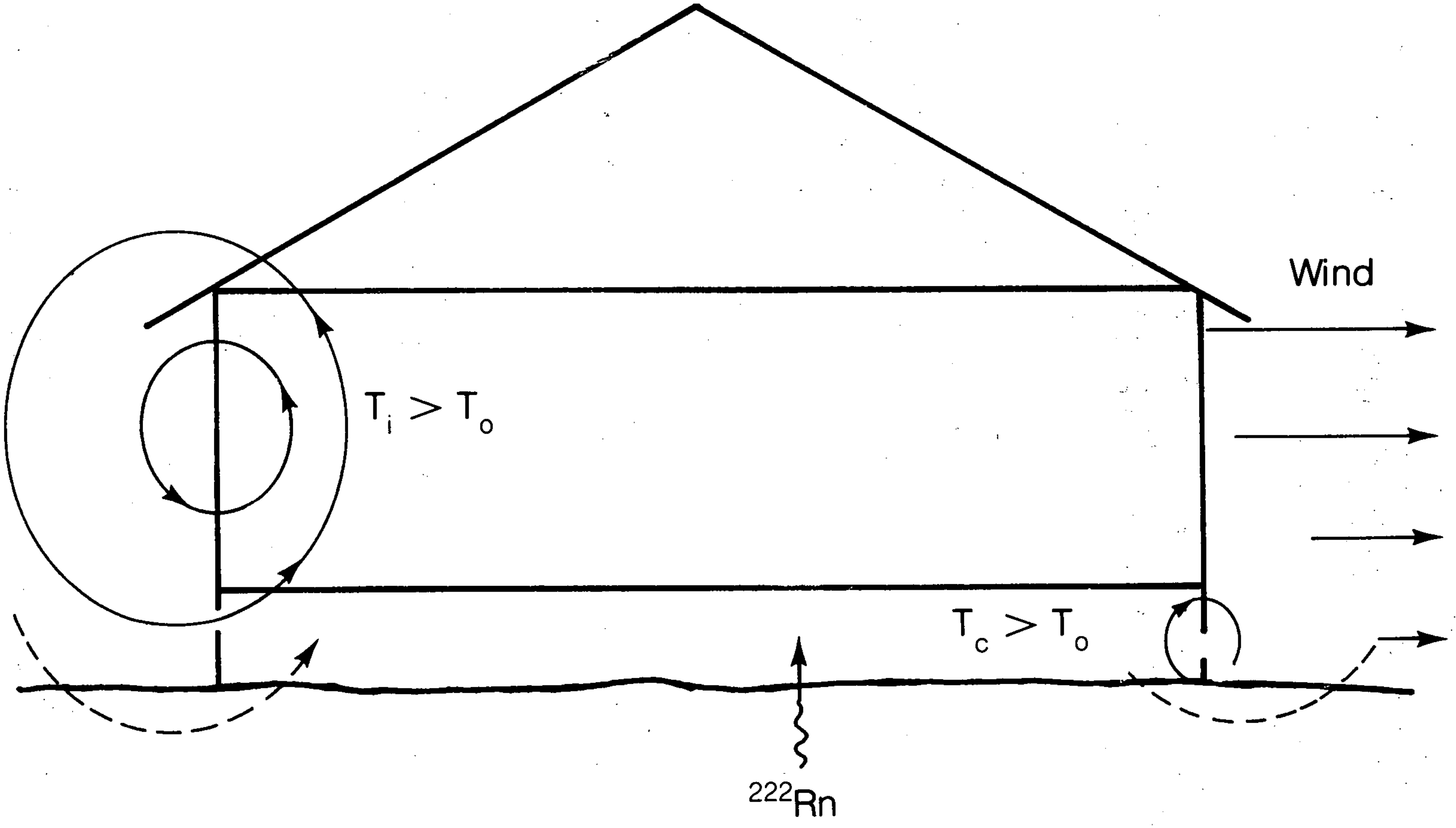
		Sulfur Hexafluoride		Weather		Ventilation				
Date	Hr. Meas.	Indoor (ppm)	Crawl Space (ppm)	Wind (m s^{-1})	ΔT (°C)	Crawl Space (h^{-1})	Indoor (h^{-1})	Entry Rate (cm^3 h^{-1})	Fraction of Release Rate	Comment
7/25/83	14	1.7	3.5	2.6	8.1	2.7	0.61	420	0.48	vents open
7/26	20	2.0	3.5	2.3	7.7	2.7	0.60	470	0.53	
7/30	20	1.8	3.0	2.7	8.5	3.2	0.64	430	0.48	
7/31	20	2.1	3.5	2.0	8.3	2.8	0.59	490	0.55	
Total	74	1.9	3.4	2.4	8.2	2.9	0.61	460	0.51	
7/27	17	2.0	9.6	2.5	9.5	1.0	0.65	520	0.59	vents sealed
7/28	19	2.4	9.7	1.9	9.3	1.0	0.61	560	0.63	
7/29	20	2.6	10.8	2.3	8.4	0.9	0.60	590	0.67	
Total	56	2.4	10.1	2.2	9.0	1.0	0.62	560	0.63	
8/1	12	1.5	3.5	2.3	11.4	2.5	0.45	270	0.31	floor tightened vents open
8/2	20	1.9	3.9	1.9	9.7	2.5	0.41	310	0.35	
Total	32	1.7	3.7	2.1	10.3	2.5	0.53	300	0.33	
8/3	15	2.5	9.9	3.0	10.7	1.0	0.49	500	0.56	floor tightened vents sealed
8/4	20	2.7	10.0	2.5	9.6	0.9	0.46	480	0.54	
Total	35	2.6	10.0	2.7	10.1	0.9	0.47	490	0.55	

Table 7. Summary of results from the tracer-gas transport study conducted at an unoccupied house in San Leandro, CA.

House Condition	Measured	Calculated l=0.6m	Calculated l=1.0m	Calculated l=1.5m
SF-B	(F=0.27)[a]	(F=0.31)	(F=0.52)	(F=0.78)
vents sealed	1.4	1.0	0.7	0.4
vents open	0.7	0.6	0.4	0.2
P-C	(F=0.26)	(F=0.38)	(F=0.63)	(F=0.94)
vents sealed	1.4	1.0	0.6	0.4
vents open	1.1	0.6	0.4	0.2
San Leandro				
before tightening floor				
vents sealed	0.63			
vents open	0.51			
after tightening floor				
vents sealed	0.55			
vents open	0.33			

[a] pCi m^{-2} s^{-1}

Table 8. Summary of crawl-space transmission factors determined in this study. Data in the first column are based on measured radon flux or SF_6 injection rate; data in the last three columns are derived from eqn (1) assuming a diffusion length, l, as indicated. The average flux of radon from the soil (pCi m^{-2} s^{-1}) is given in parenthesis in each case.



XBL 839-868

Figure 1. Schematic diagram of flows related to radon transport from soil, through a vented crawl space, and into a house. Radon migrating from the soil into the crawl space may be drawn by convective flow into the house, or it may enter the outside air, via wind or convective flow. The presence of the house may influence radon transport from the soil in several ways, as discussed in the text.

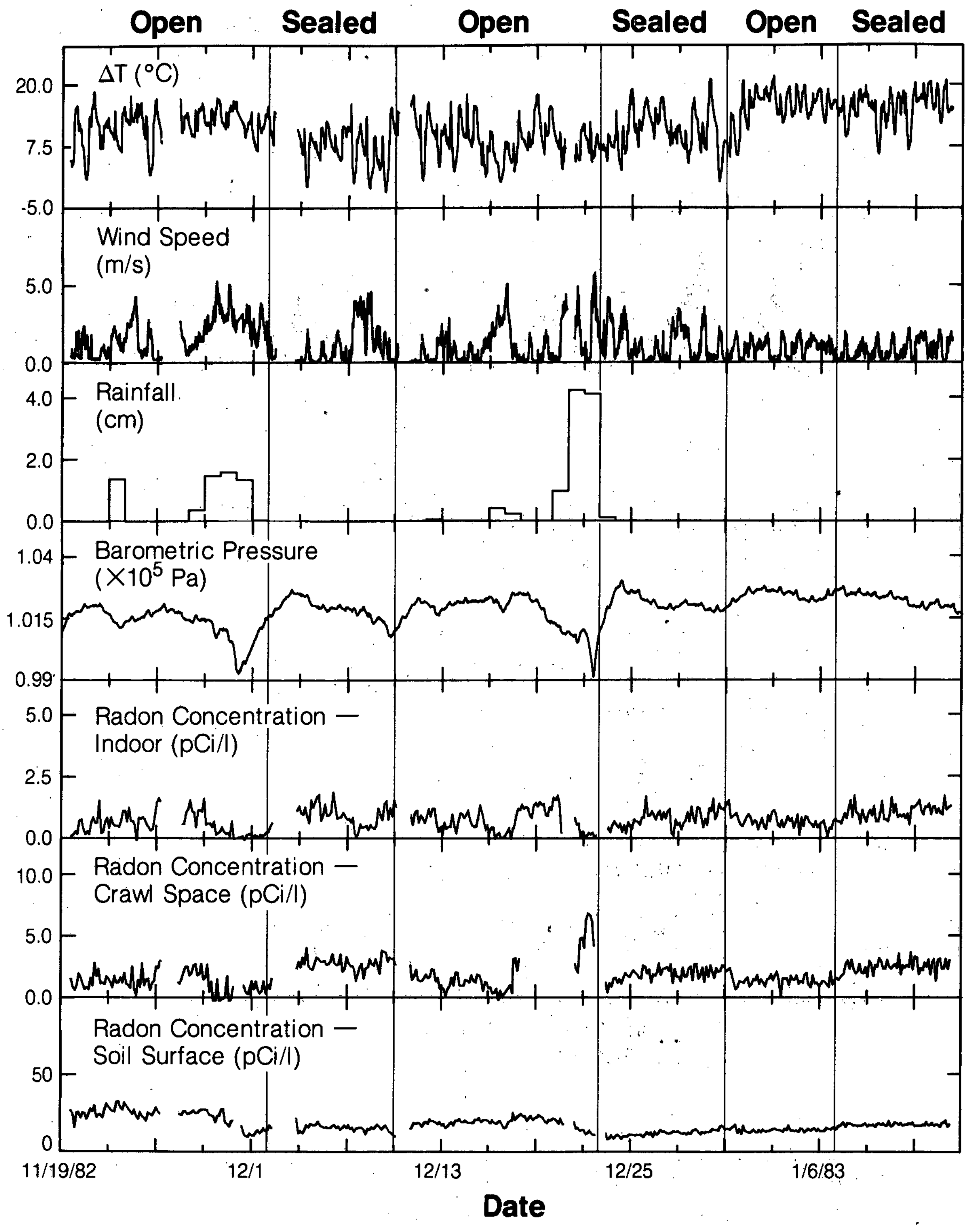


Figure 2. Measurements made over a two-month period at SF-B, in Lafayette, CA. During the periods denoted "sealed", the crawl space vents were covered with polyethylene sheets and tape.

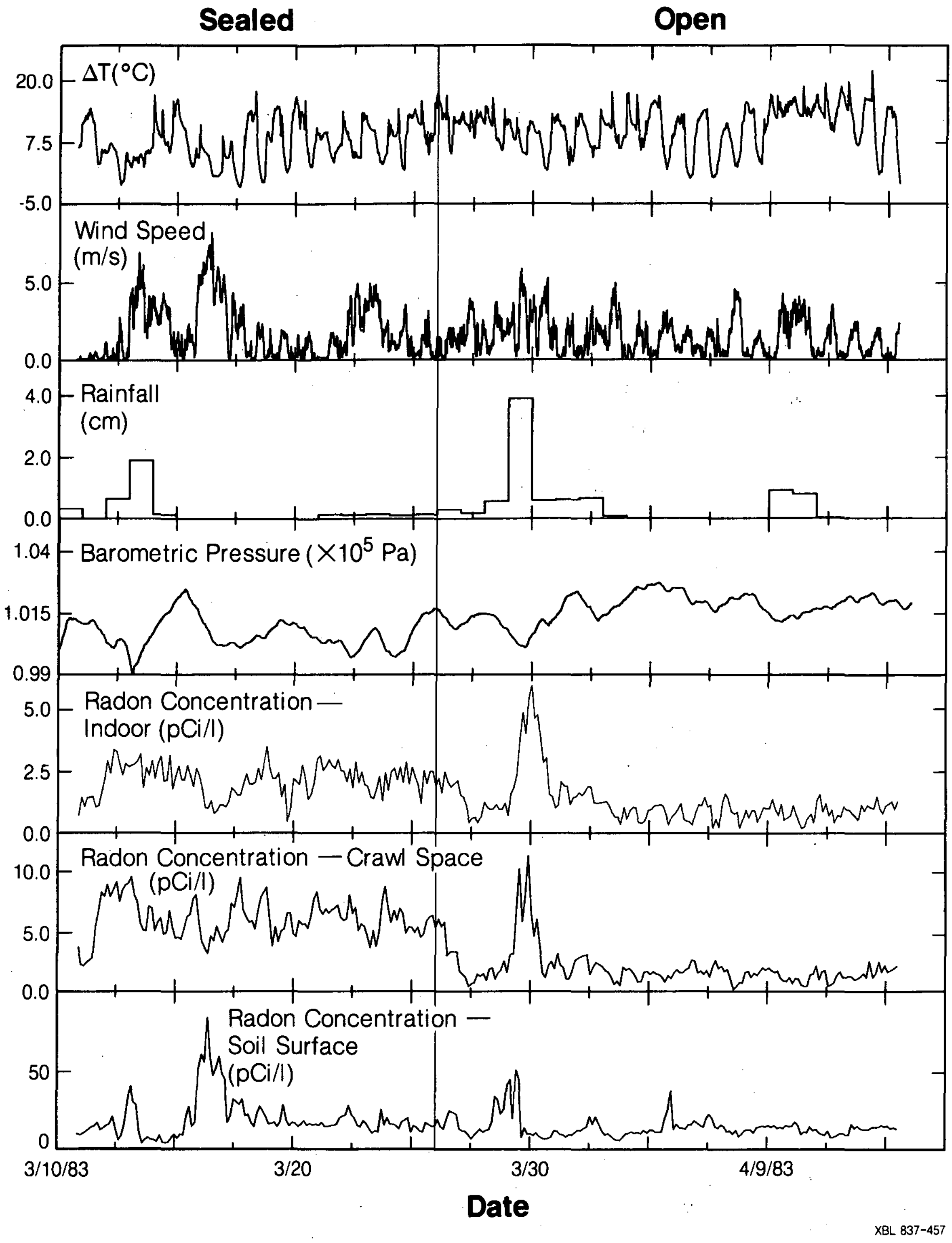
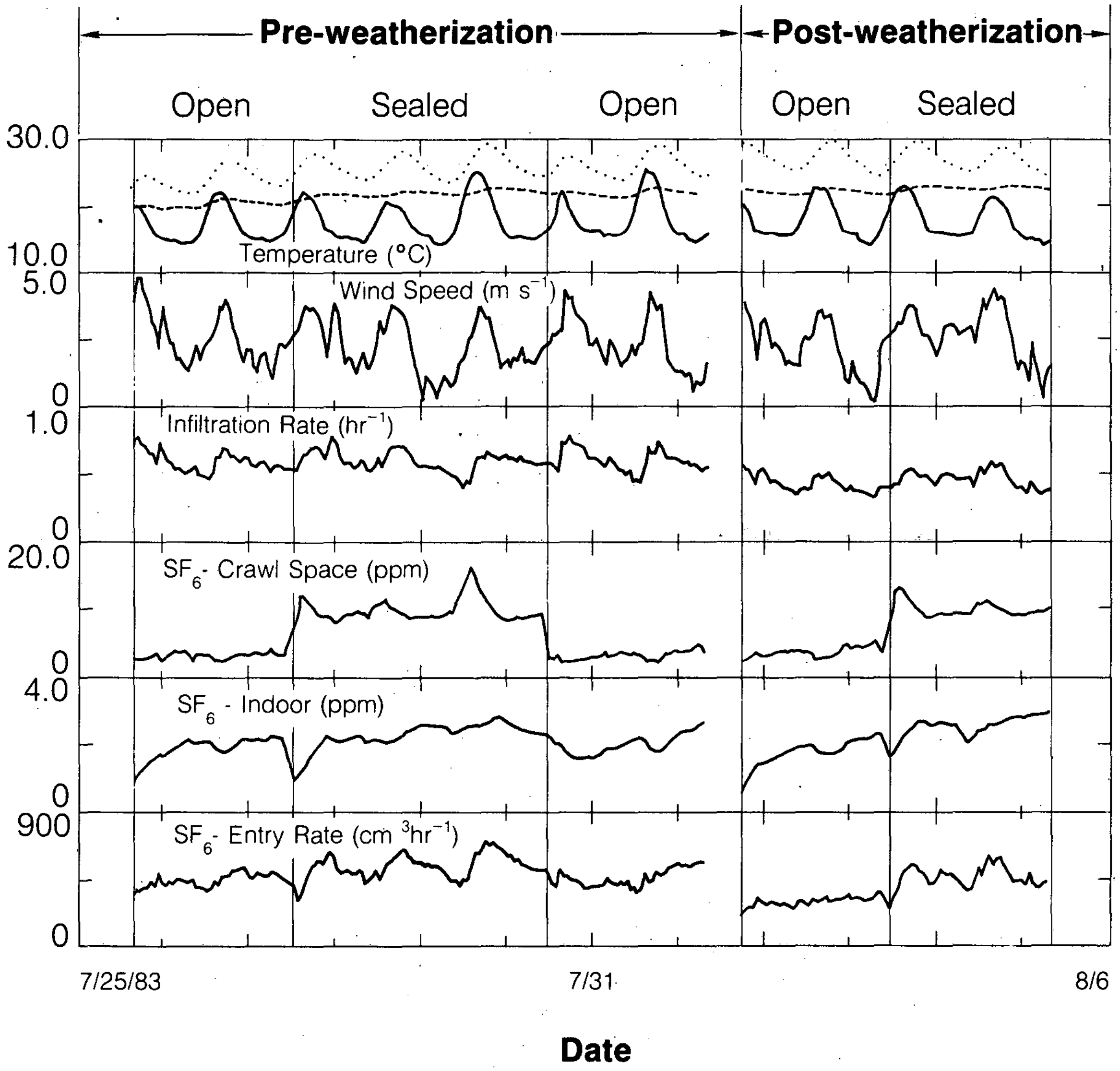


Figure 3. Measurements made over a five-week period at P-C, in Portland, OR. The crawl space vents were sealed during the first two weeks and open during the last three.



XBL 839-3240

Figure 4. Measurements during the 11-day tracer-gas transport study conducted at an unoccupied house in San Leandro, CA. As in Figures 2 and 3, "sealed" indicates that the crawl space vents were covered with polyethylene sheets. On August 1, leaks in the floor of the house were sealed using tape, polyethylene sheeting, and caulk. In the temperature plot, the solid line represents outdoor temperature and the dashed and dotted lines represent crawl space and indoor temperatures, respectively.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720