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DIRECT MEASUREMENT OF THE DEPENDENCE OF RADON FLUX THROUGH STRUCTURE BOUNDARIES ON DIFFERENTIAL PRESSURE

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ABSTRACT

A relatively simple measurement technique was developed to estimate the fraction of radon flux through a specific portion of a structure boundary that is attributable to pressure-driven flow. The technique consists of directly measuring the differential pressure across a structure boundary, while concurrently measuring the radon-flux density for a portion of the boundary. Measurements are also made of several other related parameters (temperatures, barometric pressure, wind speed, and wind direction). The resulting data allow a simple regression of the measured radon-flux density on differential pressure. The zero pressure intercept of this regression represents zero driving force for pressure-driven flow and, therefore, the nonpressure-driven flow component of the total flux density.

This measurement technique was conducted in three houses in or near Grand Junction, Colorado. Two of these houses are considered to have low radon levels, while the third house exhibits somewhat elevated radon levels during the winter. Interpretation of data acquired from measurements at these houses indicates that, contrary to the commonly accepted theory, pressure-driven flow accounts for only a small fraction of the total radon entering these structures through the surfaces measured.

INTRODUCTION

Understanding the dynamics of radon entry into even a simple structure is not an easy task. However, two entry mechanisms are considered to be of importance for those cases where soil gas appears to be the major source of radon available for entry into a structure. These mechanisms are (1) diffusion of radon through the structure boundary and (2) pressure-driven flow of radon-laden soil gases through the structure boundary.

Diffusion accomplishes transport of radon atoms by a random-walk process from regions of high radon concentration to regions of lower radon concentration. The rate of diffusion depends on the difference in concentration between the two regions and the physical parameters (including porosity, permeability, and water saturation) of the media separating the two regions. The potential exists in most houses for diffusive transport of radon into the structure because the radon concentration in the soil gas is considerably higher than the radon concentration within the structure.

Pressure-driven flow is simply the movement of molecules in a fluid state from regions of high pressure to regions of lower pressure. The lower levels of most houses exhibit modest pressure differences between their interior volumes and the atmospheric and soil gases during the colder months of the year. These pressure differences, commonly on the order of several pascals (Pa), result from temperature differences between the structure's interior volume and outdoors, suction produced by combustion appliances operating within the structure, effects of wind, and changes in barometric pressure. The resulting depressurization of the structure volume creates a potential for flow of outside gases into the lower levels of the structure. The rate of flow depends on the driving force between the two regions (the differential pressure) and on the physical parameters of the media separating the two regions.

The overwhelming majority of authors considering radon-entry dynamics favor pressure-driven flow as the dominant radon entry mechanism (1, 2, 3, 4). However, some authors (5, 6) point to diffusion as an important transport mechanism.

It seems likely that both processes are acting to transport radon into structures and that factors specific to the structure under consideration determine the relative importance of the two mechanisms. Our understanding of the relative contributions of these two mechanisms would be greatly improved if there was a relatively simple method to directly measure the pressure-driven flow component of the total radon entering a given structure. This paper presents the progress to date in developing such a technique and the results of field measurements employing the technique in three houses in the Grand Junction, Colorado, area.

APPROACH

Even a relatively simple structure such as a house represents a complex network of potential entry pathways for radon from soil gases. Moreover, factors such as soil moisture and permeability, which may dramatically affect both pressure-driven flow and diffusive transport of radon, may change seasonally and add further complexity. Our approach was to greatly simplify the system under consideration. Rather than treat the structure and its surroundings as a multicompartment system as some authors have done (5, 7), we elected to consider only small portions of the structure boundary separating the structure interior from the surrounding soil.

The term "structure boundary" means the concrete walls and floor slab of the basements under study. We believe the importance of pressure-driven flow in transporting radon across the boundary can be directly ascertained by examining the radon-flux density from a small portion of the structure boundary and concurrently measuring the differential pressure across this same boundary portion. Performing a regression of the observed radon flux on the measured differential pressure and determining the zero pressure intercept of such a regression line represents the nonpressure-driven flow component of the observed radon flux.

Measurements were conducted only in houses with poured concrete basements for three reasons. First, a basement house represents a better characterized and simpler system than either a crawl-space house or a slab-on-grade house. Second, a basement with a floor slab and walls provides two distinctly different structure boundaries that are bounded by soil on the exterior surface. Third, these structure boundaries are more readily accessible in an unfinished basement than in the finished living spaces above a crawl space or a slab-on-grade house.

METHODS AND INSTRUMENTATION

The basic requirements of this study were measurements of radon flux and differential pressure at several locations in the basements of the studied houses. Additionally, monitoring a number of associated parameters more fully describes the system under investigation and ensures that the measurements being made do not adversely affect the natural situation. These associated measurements consist of the radon concentrations in the soil gas adjacent to the structure boundary, in the outside air, and in the basement: various temperatures: and barometric pressure, wind speed, and wind direction. Figure 1 depicts some of these measured parameters.

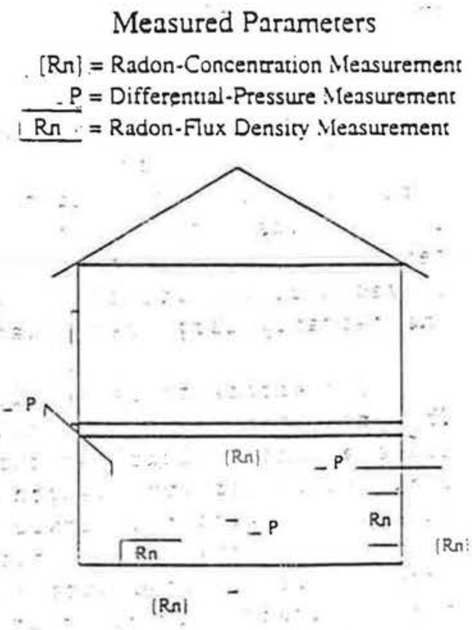

Figure 1. Some Measured Parameters

RADON MEASUREMENTS

Both active and passive continuous radon monitors were employed in this study. The two types of monitors differ principally in the means of delivering the gas sample to the scintillation chamber and in the size of the scintillation chamber. Both types of monitors have a zinc-sulfide-coated scintillation chamber connected to a photomultiplier tube, which is powered by a Ludlum model 2000 scaler. Modifications to the scaler produce a logic-level pulse as output in addition to the standard light-emitting diode (LED) display and printed output. This modification permits the photomultiplier pulses counted by the scaler to be transmitted directly to the data logger. The data logger counts the number of pulses per sampling interval and applies a calibration equation to compute radon concentration.

Active Monitors

An active continuous radon monitor was used for all radon measurements except soil-gas measurements. This monitor uses a 7.5-centimeter-diameter photomultiplier tube looking into a 1-liter scintillation chamber. A small pump delivers the sample through a filter into the scintillation chamber at a flow rate of 0.8 liter per minute (L/min). Whenever possible, an external pump immersed in the atmosphere to be sampled supplies the air sample to the radon monitor to minimize the possibility of contaminating the sample by a leak in the delivery system. The sensitivity of the active continuous monitors is approximately 220 counts per hour per picocurie per liter [cph/(pCi/L)].

Passive Monitors

A passive continuous radon monitor was developed to measure soil-gas radon concentration. Early attempts to use the active version of the continuous radon monitor demonstrated how sensitive soil-gas radon concentration and sub-slab differential pressure are to even slight perturbations. Extraction of extremely small flow rates of soil gas resulted in significant depletion of the sub-slab radon concentration and depressurization of the sub-slab soil in the region of the measurements. A closed-loop recirculation system was also tried, but the system produced unacceptably large perturbations.

To overcome these problems, a passive in-soil radon monitor was assembled. The probe portion of the monitor contains a Hamamatsu R-1010, 13-millimeter-diameter photomultiplier tube that looks into a scintillation chamber made of a 51-millimeter (mm) length of 1/2-inch copper tubing coated with zinc sulfide. A number of small holes drilled in the wall of the chamber at the end opposite the photomultiplier tube allow soil gases to enter. This assembly is inserted into a 17.5-mm inside diameter (I.D.) stainless steel tube, approximately 60 cm in length, that is used as the probe housing. The lower end of the housing is fitted with a tapered plug. Just above the plug, a number of small holes drilled in the wall of the probe allow soil gases to reach the scintillation chamber. A rubber stopper seals the open end of the probe housing against light entry and gas exchange; a high voltage-signal cable passes through the stopper. A light seal forms at the lower end of the probe by its insertion into the soil. A hole is drilled in the concrete for measurements under a concrete slab, the probe is inserted, and the area between the probe housing and concrete is sealed with caulking material.

The small volume of the scintillation chamber produces a relatively low sensitivity [2.5 cph/(pCi/L)], and the instrument exhibits a good high-voltage plateau. When used for determining soil-gas concentrations with a counting interval of 1 hour, the coefficient of variation based on counting statistics is within a few percent for typical values of radon concentration in soil gas.

RADON-FLUX MEASUREMENTS

Radon-flux density measurements were made using a modification of the flow method described in Collé et al.(8). The device consists of a metal can that is 0.44 meter (m) in diameter and 0.16 m in height and has one 3-cm-diameter hole in the side of the can. A small aquarium pump, mounted on the inside of the can, permits continuous sampling of the air within the can. The open end of the can is placed against the surface where the radon-flux density will be measured, and the can edges in contact with the concrete are sealed with a caulking material. The pump delivers a steady flow of 0.2 L/min from the can to a continuous radon monitor. The hole in the side of the can permits room air to replace the volume of gas delivered to the radon monitor. When operated at a flow rate of 0.2 L/min, there is no measurable (< 0.1 Pa) pressure difference between the can and the room. The ventilation rate of the can at this flow rate is approximately 0.5 hour^{-1}. Figure 2 is a schematic diagram of the flux can applied to a concrete surface.

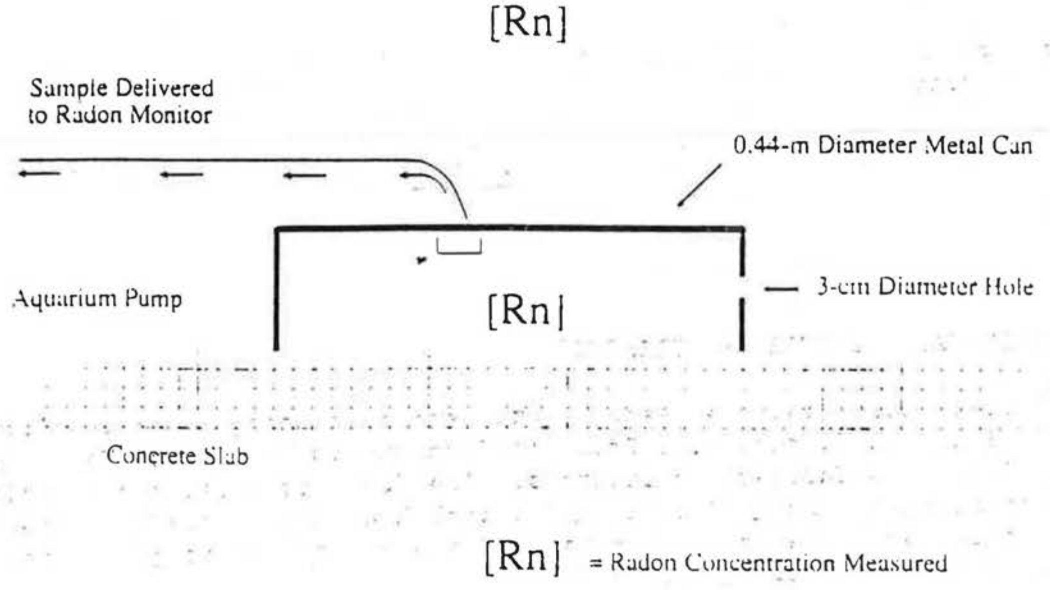

Figure 2. Schematic Diagram of the Radon-Flux Can Apparatus Applied to a Surface

The can acts as a partial accumulator and allows the radon concentration to build up within the can to a concentration that is a function of the radon flux into the can, the concentration of radon in the air backfilling the can, and the rate of air flow through the can. A simple mass balance approach, neglecting the radioactive decay of radon, yields the following expression for the measured radon-flux density:

$$J = \frac{Q_s C_s + E}{A} = \frac{Q_m C_m - Q_r C_r}{A} \qquad (1)$$

where:

J = radon-flux density from the surface of interest,
Q_s = flow rate of soil gases into the can,
C_s = radon concentration of the soil gases,
E = contribution of radon from direct emanation,
A = area of the can,
Q_m = flow rate of sample into the continuous radon monitor,
C_m = radon concentration measured by the continuous monitor,
Q_r = flow rate of room air into the can, and
C_r = radon concentration of the room air.

Because the rate of air flow out of the can is equal to the rate of air into the can, $Q_m = Q_s + Q_r$. If the assumption is made that Q_s is small compared to Q_r, that is to say that $Q_m = Q_r$, then the net radon-flux density from the surface being measured may be approximated by:

$$J = \frac{Q_s C_s + E}{A} = \frac{Q_m (C_m - C_r)}{A} \qquad (2)$$

Therefore, the following equation was used to calculate the measured radon-flux density:

$$J = \frac{Q_m (C_m - C_r)}{A} \qquad (3)$$

DIFFERENTIAL-PRESSURE MEASUREMENTS

Differential-pressure measurements were made using several Validyne model DP 103-10 Differential Pressure Transducers coupled to Validyne model CD-15 Sine Wave Carrier Demodulators. The CD-15 produces a ± 10-volt signal corresponding to the ± 87.2-Pa (0.350-inch H_2O) full-scale pressure range of the transducer. The stated accuracy of the transducer is ± 0.25 percent full scale or approximately ± 0.2 Pa.

The differential pressure measurements were made by drilling a 3/8- to 1/2-inch-diameter hole in the floor slab or basement wall. A length of

1/4-inch-diameter stainless steel tubing was inserted a distance of approximately 20 cm into the soil beyond the thickness of the concrete. Caulking material was used to fill the space between the tubing and the concrete to form a gas seal. The open end of this tubing was then connected to the signal-in side of the pressure transducer. In all cases, the reference side of the pressure transducer was left open to the basement room.

DATA LOGGING

A Campbell Scientific CR-10 data logger continuously recorded the values provided by the various sensors. A pulse-counting module provided inputs for as many as eight radon monitors. A portable weather station equipped with wind direction and speed sensors, as well as a barometric pressure transducer, was coupled to the data logger to provide relevant weather data. All temperature measurements were made using type-T thermocouple wire. The data logger was programmed to sample each of the input channels at 10-second intervals and tabulate and record an average value for a 1-hour sampling period.

FIELD MEASUREMENTS

Field measurements were conducted in basements of three houses in or near the vicinity of Grand Junction, Colorado. No known uranium mill tailings deposits are associated with any of these houses. All three houses are situated on soils derived from the Mancos Shale, which underlies most of the Grand Junction area. These soils are dominated by the clay-sized fraction: a significant portion of the clay-sized fraction consists of smectitic clays. The smectitic clays produce large shrink-swell potentials that affect not only the soils' engineering properties but also the permeability and porosity characteristics.

House-1 has a full basement, approximately 22 by 43 feet, finished with plywood paneling or paint on the wall surfaces and asphalt tile on the floor. The basement is divided into five rooms, one of which is a bathroom. The measurements were conducted in the largest of these rooms, measuring 12 by 28 feet, during October. This house was unoccupied during all of the measurements. Radon-flux density measurements were made at two locations. The first location was over an open joint in the floor slab approximately 3 mm wide; the second location was on one of the exterior walls at a height of approximately 1 meter. The average radon concentrations for this structure for the last 6 years are 1.8 pCi/L in the upstairs area and 2.8 pCi/L in the basement.

House-2 has a partial basement measuring 28 by 29 feet. The remaining portion of the house is located over a crawl space. The basement has been partially finished by the addition of two interior walls that separate the basement into two rooms. The measurements were conducted in the smaller of the two rooms, measuring 14 by 15 feet, during August and September. This house was occupied during the period of the field measurements. The exterior basement walls and floor slab are bare concrete. Radon-flux measurements were made at two locations on the floor slab. The first location was over a crack approximately 0.5 mm wide: the second location was over an undisturbed portion of the floor slab. A flux can was also located on one of the exterior walls at a height of approximately 1 meter. The average radon concentrations measured in this house during the past 6 years are 0.9 pCi/L in the upstairs area and 2.8 pCi/L in the basement.

House-3 has a partial basement measuring approximately 16 by 38 feet. The remaining portion of this house rests on slab-on-grade and over crawl space. The basement is unfinished with bare concrete floor and walls. Radon-flux measurements were made at two locations on the basement floor slab during the months of December and January. This house was occupied during all of the measurements. The first location was over a 30-cm by 30-cm opening in the floor slab that presumably was intended for a lavatory. The hole exposes soil directly beneath the slab (no aggregate is present). The second flux measurement was made over undisturbed concrete floor at a distance of approximately 1 m from the closest edge of the first location. No flux measurements were made on the walls and no long-term average radon measurements are available for this house.

RESULTS AND DISCUSSION

This investigation was not intended as a comprehensive study of the role of pressure-driven flow as an entry mechanism for radon into houses but as an evaluation of the usefulness of the measurement technique. These three houses were selected for field measurement because of availability and their range of radon levels. Initial measurements were conducted over concrete surfaces with structural cracks and undisturbed sections of slab. Plans are underway to test this measurement technique on sections of the floor-wall joints at House-2 and House-3.

HOUSE-1

There is a strong degree of correlation between the measured flux and the differential pressure in House-1. Figure 3 shows a time plot of the naturally existing differential pressure across the floor slab and of radon-flux density measured directly above an open joint in the floor slab. The data were collected during the month of October. The radon flux lags behind the differential pressure by about 1 hour, primarily due to the ingrowth of radon-daughter activity within the radon monitor's scintillation chamber and the ventilation rate of the flux can. The occurrence of some negative differential-pressure values may represent situations where the sub-slab region is actually depressurized with respect to the basement, but it is more likely that these values represent a slight zero shift of the pressure transducer.

Figure 4 shows a regression of the data from the time plots of Figure 3. The radon-flux data have been shifted to compensate for the time lag seen in Figure 3. The correlation coefficient of 0.83 indicates a strong dependence of variations in radon-flux density on variations in differential pressure. More simply stated, pressure-driven flow is affecting the observed radon-flux density, but the slope of the regression line is comparatively low. The zero pressure intercept of 0.18 $pCi \cdot m^{-2} \cdot s^{-1}$ represents 80 percent of the average measured flux. Our interpretation is that approximately 80 percent of the radon flux transported through the measured portion of the slab occurs due to

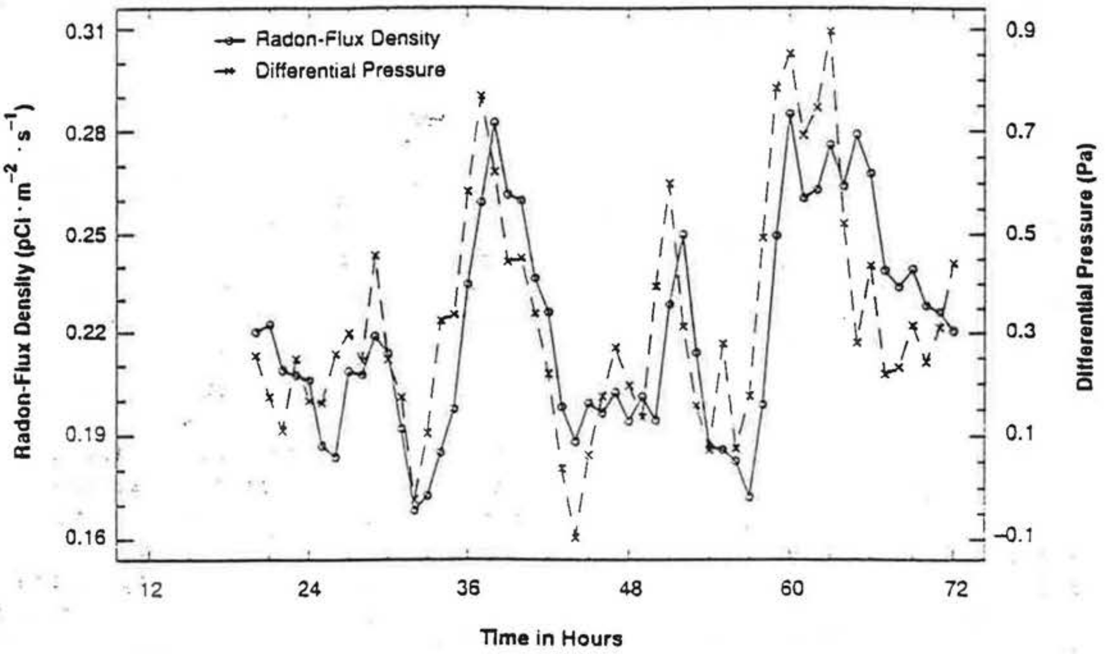

Figure 3. Time Plots of Measured Radon-Flux Density Through Open Joint in Floor and Differential Pressure Measured Across Floor (House-1)

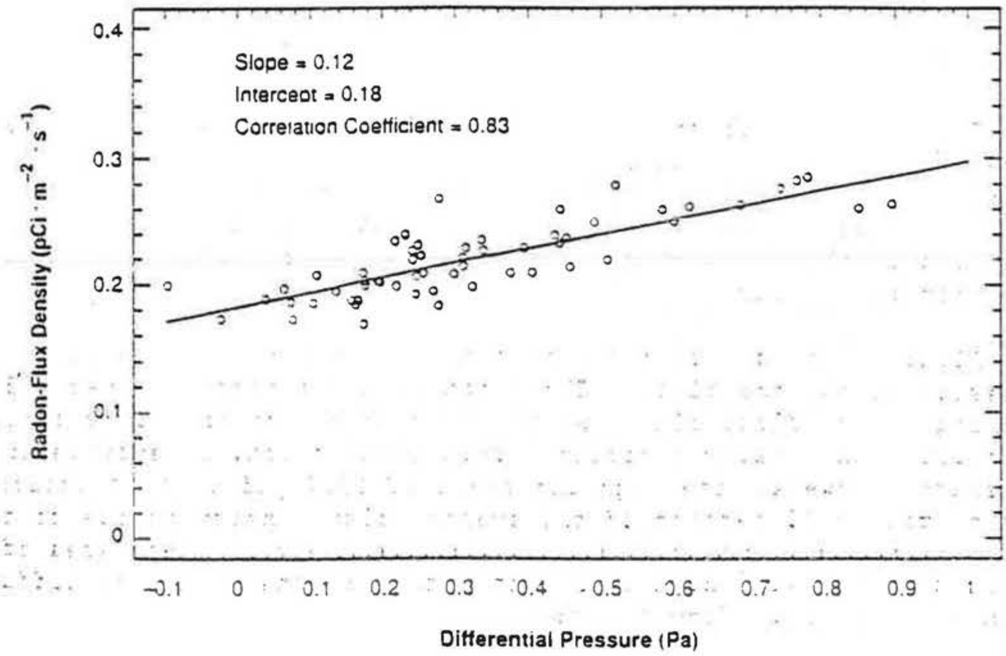

Figure 4. Regression of Measured Radon-Flux Density Through Open Joint in Floor on Differential Pressure Measured Across Floor (House-1)

a nonpressure-driven flow mechanism and only 20 percent occurs by pressure-driven flow. An obvious choice for this nonpressure-driven flow transport mechanism is diffusion.

HOUSE-2

Because the measurements were made in August and September, this house exhibited no significant depressurization of the basement relative to the underlying soil. In an effort to simulate wintertime conditions, a small box fan was installed in one of the basement windows to slightly depressurize the basement. The fan was run at a constant speed so that the pressure variations would be similar in magnitude to what would be expected during the winter. Figures 5 and 6 present the results of this experimental setup.

Figure 5 shows the regression of radon-flux density, measured over a small crack in the basement floor, on the differential pressure across the floor. Figure 6 shows a similar regression for radon-flux density measured over an undisturbed portion of the floor. Although some dependence of the measured radon flux on differential pressure is depicted on the graphs, the scatter about the regression line is quite large and, correspondingly, the correlation coefficients are extremely small. The zero pressure intercepts of 0.025 and 0.017 $pCi \cdot m^{-2} \cdot s^{-1}$ for Figures 5 and 6, respectively, represent approximately 80 percent of the average measured flux values. This indicates that pressure-driven flow adds only about 20 percent to the average nonpressure-driven flow component of the radon flux. The measured flux values are quite low for these two locations and are, in fact, comparable to values given in the literature for emanation from some typical concrete samples (8, 9).

HOUSE-3

This house exhibits significantly higher radon levels than either of the other two houses in this study. The average basement radon concentration during the measurements was approximately 8 pCi/L, compared to 3.6 and 1.6 pCi/L for House-1 and House-2, respectively. The radon concentration measured in the sub-slab soil gas averaged approximately 3,760 pCi/L during the measurement period.

Figure 7 shows a regression of the radon-flux density on the differential pressure across the floor. The radon flux was measured over a 30-cm by 30-cm opening in the floor slab. As might be predicted in this situation, the measured flux density exhibits a relatively strong dependence on differential pressure. However, the high intercept of 13.2 $pCi \cdot m^{-2} \cdot s^{-1}$ indicates that only approximately 20 percent of the average flux density is due to the pressure-driven flow component. Considering the relatively large area of exposed soil, it is not entirely unreasonable that this is the result of diffusive transport directly from the soil.

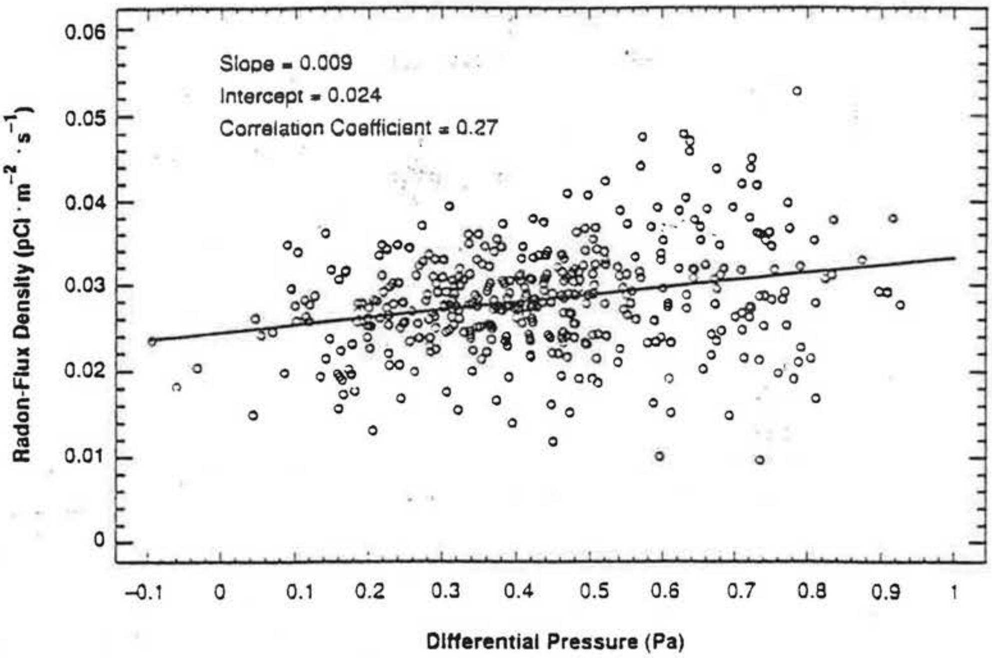

Figure 5. Regression of Measured Radon-Flux Density Through Cracked Portion of Floor on Differential Pressure Measured Across Floor (House-2)

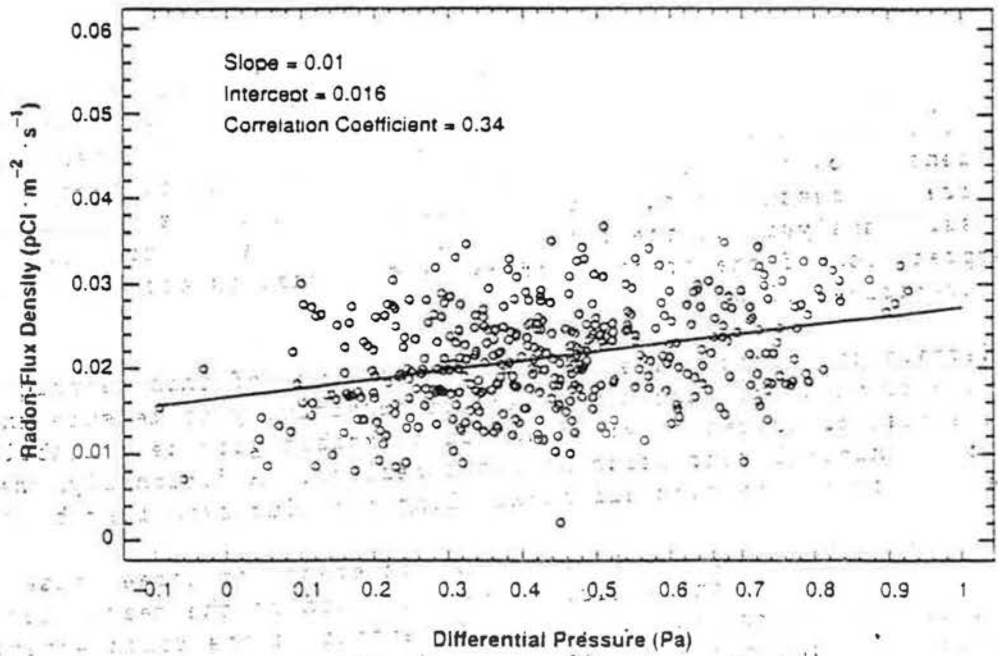

Figure 6. Regression of Measured Radon-Flux Density Through Undisturbed Portion of Floor on Differential Pressure Measured Across Floor (House-2)

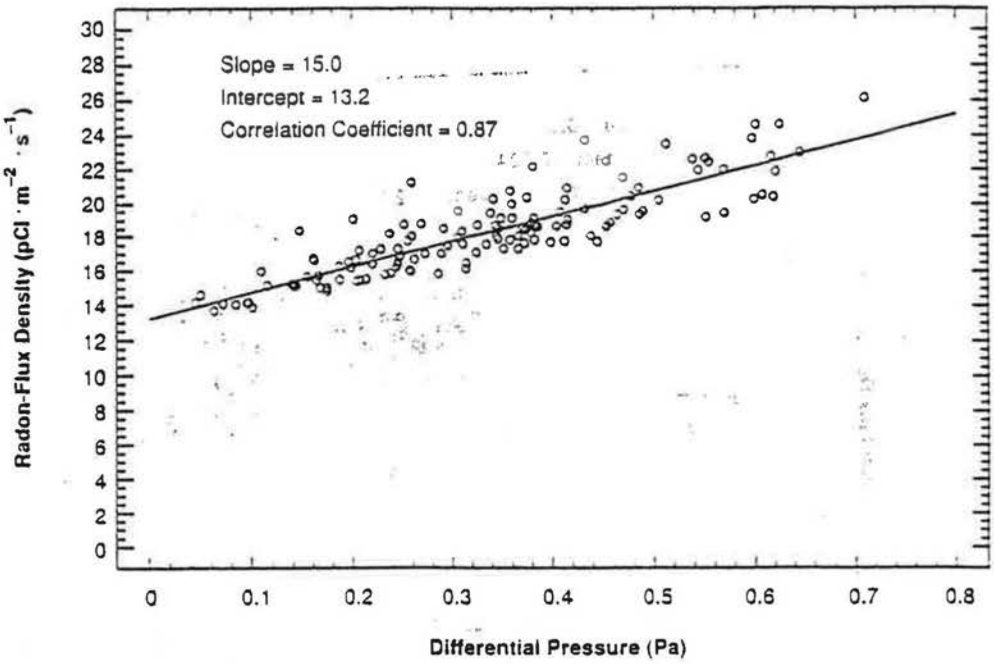

Figure 7. Regression of Measured Radon-Flux Density Through 30-cm by 30-cm Hole in Floor on Differential Pressure Measured Across Floor (House-3)

CONCLUSIONS

A relatively simple technique was developed to measure the pressure-driven flow component of radon flux passing through a selected portion of a structure boundary. The technique consists of directly measuring the radon-flux density over a selected portion of the structure boundary, while concurrently measuring the differential pressure across the same boundary. Regression analysis of the resulting data allows a quantitative interpretation of the fraction of radon flux that is attributable to pressure-driven flow.

Certain precautions are necessary in the use of this technique. The pressure transducers must have adequate sensitivity to measure the small differential pressures observed and must exhibit good zero stability to produce meaningful regression analysis results. Additionally, the radon concentration of the room air backfilling the flux cans must be known.

This technique was performed in the basements of three houses with low to slightly elevated radon levels. Interpretation of the measurement results indicates that, on the average, only 20 percent of the radon enters these structures through the boundaries tested because of pressure-driven flow.

ACKNOWLEDGMENTS

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REFERENCES

1. Bruno, R. C. Sources of indoor radon in houses: A review. Journal of the Air Pollution Control Association. 33: 105, 1983.

2. Nazaroff, W. W., Moed, B. A., and Sextro, R. G. Soil as a source of indoor radon: Generation, migration, and entry. In: W. W. Nazaroff and A. V. Nero. (eds.), Radon and its decay products in indoor air. John Wiley & Sons. New York, New York, 1988. p. 57.

3. Sextro, R. G., Nazaroff W. W., and Turk, B. H. Soil permeability and radon concentration measurements and a technique for predicting the radon source potential of soil. Paper presented at the 1988 Symposium on Radon and Radon Reduction Technology, Environmental Protection Agency, Denver, Colorado. October 17-21, 1988.

4. Nero, A. V., Gadgil, A. J., Nazaroff, W. W., and Revzan, K. L. Indoor radon and decay products: Concentrations, causes and control strategies. DOE/ER-0480P, U.S. Department of Energy, Office of Health and Environmental Research, Washington D.C., 1990. 138 pp.

5. Holub, R. F., Droullard, R. F., Borak, T. B., Indret, W. C., Morse, J. G., and Baxter, J. R. Radon-222 and Rn-222 progeny concentrations measured in an energy-efficient house equipped with a heat exchanger. Health Physics. 49: 267, 1985.

6. Tanner, A. B. The role of diffusion in radon entry into houses. Paper presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Environmental Protection Agency, Atlanta, Georgia. February 19-23, 1990.

7. Stoop, P., Aldenkamp, F. J., Loos, E. J. T., de Meijer, R. J., and Put, L. W. Measurements and modeling of radon infiltration into a dwelling. Paper presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Environmental Protection Agency, Atlanta, Georgia. February 19-23, 1990.

8. Collé R., Rubin, R. J., Knab, L. I., and Hutchinson, J. M. R., Radon transport through and exhalation from building materials: A review and assessment. NBS Technical Note 1139. U.S. Department of Commerce, National Bureau of Standards, Washington, D.C., 1981. 97 pp.

9. **Ingersol, J. G. A survey of radionuclide contents and radon emanation rates in building materials used in the U.S. Health Physics. 45: 363, 1983.**