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RADON-222 and ^{222}Rn PROGENY CONCENTRATIONS MEASURED IN AN ENERGY-EFFICIENT HOUSE EQUIPPED WITH A HEAT EXCHANGER*

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Abstract—Radon-222 and ^{222}Rn progeny concentrations, barometric pressure and pressure differentials between inside and outside were measured continuously in the basement of a recently constructed energy-efficient house in metropolitan Denver, CO. Although the monitoring equipment was developed primarily for underground mines, it proved to be applicable for house monitoring. Results indicate that for tightly sealed houses, forced-flow transport does not significantly contribute to the ^{222}Rn present even when the pressure within the house is less than the outside pressure by 0.8 Pa (.006 mm Hg). Calculations of ^{222}Rn levels using diffusion as the primary transport mechanism are in agreement with observed data. The diffusion coefficient of ^{222}Rn in the walls and floor surrounding the basement is higher than values previously reported. Ventilation by means of a heat exchanger reduces the ^{222}Rn levels in accordance with measured air exchange rates, regardless of the pressure differential between inside and outside.

INTRODUCTION

EXPOSURE of the public to natural background radiation may be increased considerably through energy-conserving measures such as reducing ventilation in buildings. Inhalation of ^{222}Rn progeny indoors contributes a large portion of the biologically significant dose associated with natural background radiation (Na81; Ne83). The exposure is increased when energy-efficient structures are built in regions of high natural soil radioactivity or when construction materials originate from these regions.

* Reference to specific equipment is made for identification only and does not imply endorsement by the organizations represented by the authors.

In 1981, the Colorado Energy Research Institute began a program to evaluate the extent of this problem. Initially, a screening study examined 30 new electrically heated houses in the Denver area. The measurements showed that ^{222}Rn progeny concentrations were higher than anticipated (Mo83). This paper reports the results of measurements taken within an inhabited house that typifies new energy-efficient construction in the United States.

Radon-222 can enter the house by diffusion, which is driven by concentration gradients, or by forced flow, which is controlled by pressure differentials. In a review article, Bruno concluded that the main source of ^{222}Rn in houses is forced-flow transport from the soil (Br83). He speculates that the driving force would come from the stack effect and that wind forces generate the required negative pressure differential. He did not report any data that would verify the existence or determine the magnitude of such phenomena. Scott reported that no measurable pressure drop between the inside and outside of the house has been observed, unless a fan was used to create pressure differences (Sc83). Bruno states that the contribution to indoor ^{222}Rn from building materials is much smaller than from surrounding soil. This was based on reported values of effective diffusion coefficients measured from samples of building materials having a surface area less than 1 m^2. Other review articles, such as Collé *et al.* offer similar conclusions (Co81).

An experiment was designed to determine the pressure differences required to regulate the transport of radon into a recently constructed house. Radon-222, ^{222}Rn progeny, barometric pressure, and inside-outside pressure differential were measured continuously for two months (28 January 1983 to 12 March 1983).

A heat exchanger was installed in the basement, and measurements were made to test the capability of this system to reduce indoor ^{222}Rn levels. The heat exchanger was also used to regulate air exchange rates. Knowing the air exchange rates and ^{222}Rn concentrations, it was possible to determine the effective diffusion coefficient for the entire basement *in situ*. This provides a realistic evaluation of diffusion velocities since inhomogeneities and cracks are automatically included. A comparison of these results with previous determination of diffusion coefficients by other workers is presented. The contributions to indoor ^{222}Rn by diffusion and forced flow are discussed. Nazaroff has reported on a study using heat exchangers but they did not measure pressure differentials (Na81a).

MATERIALS AND METHODS

Radon-222 was measured by a 0.5 liter scintillation cell operating at a flow rate of 5 l min^{-1}; having a sensitivity of 2.17 counts per minute (cpm) per pCi l^{-1}. Radon-222 progeny activities were measured using both continuous β and continuous α methods (Dr77). The flow rate through the continuous β detector was 5 l min^{-1}. This system has a sensitivity of 0.0001 working level cpm^{-1}. The average γ-ray background count was 57.3 cpm. The continuous α monitor is commercially available and has a sensitivity of 0.0003 working level cpm^{-1} at a flow rate of about 1 l min^{-1}.* There is no significant background count for this α detecting system.

Absolute barometric pressure was measured with a barometer** and the differential pressure between the basement and outside air was measured with a Barocel.*** The outside probe of this device was shielded from the wind. The analog signals from these transducers were converted to digital signals for the data acquisition system.

Radon-222, working level (WL), barometric pressure and differential pressure were measured simultaneously by a data acquisition system assembled from commercial nuclear instrument modules. The transducers were sampled for 60 min and the data printed. Sampling resumed after a delay of 40 min, making a total of 100 min for the sampling interval.

Gamma-ray analyses of soil and concrete samples were performed to obtain the concentration of Th and U. The emanation coefficient for ^{222}Rn was determined to be 0.1 ± 0.03 using the closed can method.

The house is located in a residential community just west of Denver, CO. The structure is a conventional single-floor frame structure over a full basement. The roof is surfaced with asphalt shingles. The outside walls are of particle board with a partial covering of brick veneer. Heating is provided entirely by electricity.

Measurements were made in the basement area which had poured concrete walls and floor. All visible cracks or gaps between floor, walls and pipes were carefully sealed. During this experiment, the basement was not heated. Spaces between the floor joints were filled with six inches of glass fiber insulation. Wood interior framing was installed but no walls had been

* Working Level Meter, Model WLM300, EDA Instruments, Inc., 1 Thorncliffe Park Drive, Toronto, Ontario M4H 1G9, Canada.

** Barometer, Model 2041-19.2/25.7 HA-1, Yellow Springs Instrument Company, Yellow Springs, OH 45387.

*** Barocel Model 590D, Datametrics, Inc., 340 Fordham Rd., Wilmington, MA 01887.

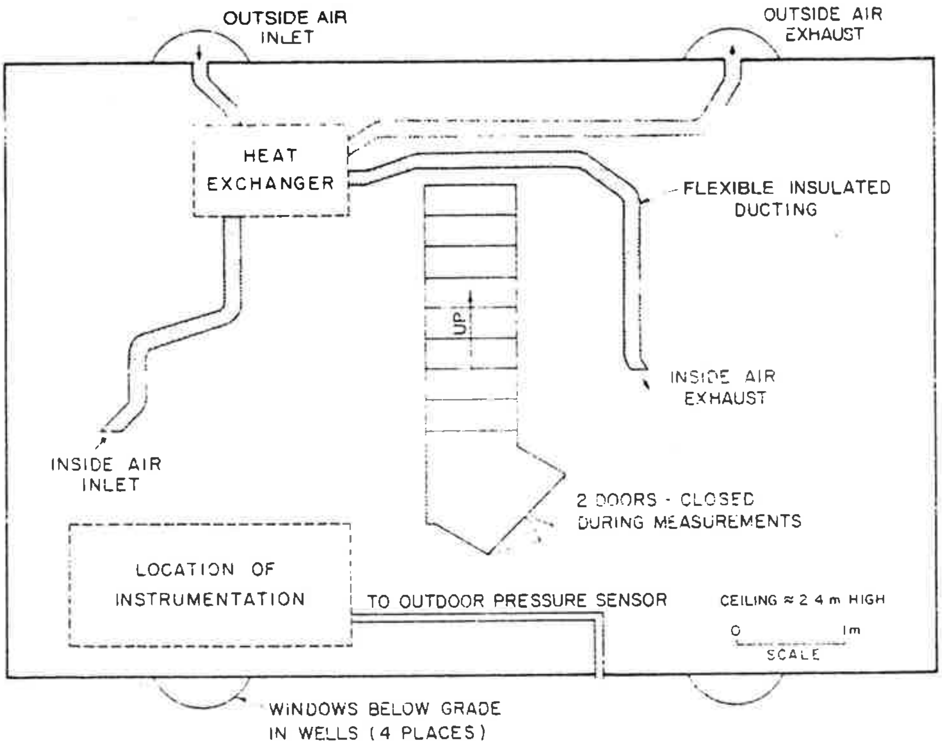

FIG. 1. Schematic diagram of the basement showing the location of the heat exchanger and monitoring instrumentation.

erected which would have impeded air flow. The basement has four windows: two in the front and two in the rear. These windows are below grade and opened into window wells. A schematic diagram of the basement and experimental arrangements are shown in Fig. 1.

To connect the heat exchange (Sm83) to the two rear windows, the glass was replaced with plywood panels through which the inlet and exhaust ducts were installed. The separation between exhaust and inlet was approximately 20 feet. From each window, a six-inch-dia. insulated flexible duct was connected to the heat exchanger. This system was designed to provide a counter flow heat exchange between the incoming and outgoing air using two individually driven variable-speed centrifugal blowers. The unit prevented frosting by automatically shutting off one blower. This function was disabled for this test.

From the "warm" mode of the heat exchanger, two separate insulated ducts were installed at opposite ends of the basement. A metal damper was installed on the end of the inlet duct to the basement.

Approximately 60 inches (10 diameters) from the end of the duct carrying the warmed air from heat exchanger to the basement, the probe of a hot wire anemometer* was inserted in the center of the duct. The air velocity measured at this point was converted to a volumetric flow, F, and to air exchange rate, λ_v, for the total volume of the basement, V. The total ventilation rate, λ_t, is the sum of the induced ventilation, λ_v, and natural ventilation, λ_n.

Controls on the blowers and the damper on the inlet duct were used to adjust the ventilation rates to suitable values. In order to create positive or negative pressures within the basement, one of the heat exchanger fans was disconnected and sealed.

RESULTS

Plots of ^{222}Rn gas concentrations, WL, and pressure differential as a function of time are shown in Fig. 2. The total measurement period, approximately two months, was subdivided into six regions, which are indicated in the figures

* Anemometer Model 1610, TSI Incorporated, 2500 N. Cleveland Ave., St. Paul, MN 55164.

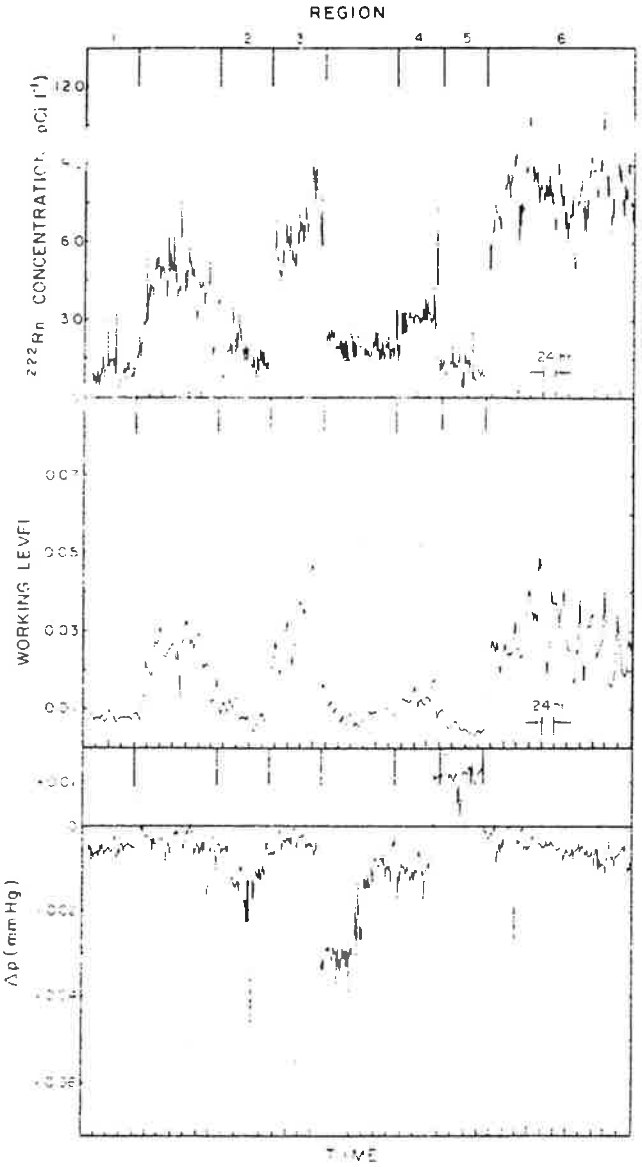

FIG. 2. Plots of ^{222}Rn gas concentration vs time: working level vs time; and pressure differential vs time. Positive values indicate that the pressure inside the house was greater than the outside pressure. The six time regions used in the statistical analysis are indicated at the top of the figure.

and identified according to date and ventilation conditions in Table 1. In each region, the induced air exchange rates, λ_v, and average pressure differential, Δp, were controlled by adjusting the inlet or exhaust vents of the heat exchanger.

The short-term fluctuations in ^{222}Rn concentration were random. By taking into account counting statistics, the uncertainty per counting interval is approximately equal to the observed variations between adjacent intervals.

Random variations in WL were less than those for ^{222}Rn because of higher count rates measured by the WL monitors. Temporal variations were recorded identically by both the α and β detectors even though the sampling inlets were more than six feet apart.

There are similar random variations in Δp. Large dips of short duration indicate pressure drops in the house due to gusty winds. These are especially evident in regions 2 and 6 in Fig. 2. Several smaller excursions of slight overpressures occurred at noon on warm sunny days when the outside temperatures reached or exceeded the inside temperature. These overpressures would cancel the stack effect mentioned by Bruno (Br83).

It can be shown from basic calculaltions that sudden changes in atmospheric pressure are propagated through soil gas with phase velocities of ~ 1 cm sec^{-1} (Sc83). Thus the soil gas pressure at the boundary of the basement rapidly reaches equilibrium with outside air. A measurement of the pressure differential between the basement and outside air is therefore equivalent to measuring the pressure differentials with the soil gas adjacent to the outside wall of the basement. This is not the case only for very strong winds whose duration is negligible compared to total.

Statistical methods were used to identify correlations between ^{222}Rn concentrations, potential α energy, barometric pressure, pressure differential, and ventilation rates. The analysis was performed in two stages. Stage one consisted of analyzing the short-term (diurnal) variations in the data during each of two background conditions. These represented periods of natural ventilation when both the inlet and outlet vents of the heat exchanger were turned off. The second stage consisted of comparing average values in each of the six regions shown in Fig. 2 where ventilation rates were controlled by the heat exchanger.

Figure 3 shows a plot of potential α energy (WL) and ^{222}Rn gas as a function of time during an eight-day period identified as region 6 in Table 1. Visually there was no apparent trend between ^{222}Rn gas and WL during this period. Figure 4 is a scatter plot of these data that shows working level vs ^{222}Rn gas concentration for each individual measurement. There was an

Table 1. Average values of the natural ventilation rate, λ_n, forced ventilation rate, λ_v, pressure differentials between inside and outside, ^{222}Rn gas concentration and working levels for six time periods during the experiment

		Ventilation		Air exchange				
Region	Date	Inlet	Outlet	λ_v (hr^{-1})	λ_n (hr^{-1})	ΔP (mmHg)	Radon (pCi l^{-1})	Working level
1	28 Jan–31 Jan	On	On	1.00	0.16	−0.005	1.11	0.008
2	7 Feb–11 Feb	On	On	0.50	0.16	−0.012	1.60	0.009
3	12 Feb–15 Feb	Off	Off	0.00	0.16	−0.004	6.7	0.032
4	21 Feb–24 Feb	On	On	0.25	0.16	−0.012	3.00	0.012
5	25 Feb–28 Feb	On	Off	1.00	0.16	+0.012	1.09	0.005
6	2 Mar–12 Mar	Off	Off	0.00	0.16	−0.007	7.8	0.028

apparent linear relationship when the ^{222}Rn concentration was less than about 7 pCi l^{-1}. However, a large spread in the values of working level was evident whenever the Rn gas concentration exceeded 7 pCi l^{-1}.

A simple least-squares-regression technique was applied to several models relating WL to ^{222}Rn gas concentration. Although WL tends to increase with ^{222}Rn concentrations, the variations in the data for higher values of ^{222}Rn could not be explained by any model with an acceptable level of confidence.

Figure 5 shows a plot of ^{222}Rn gas concentration and atmospheric pressure as a function of

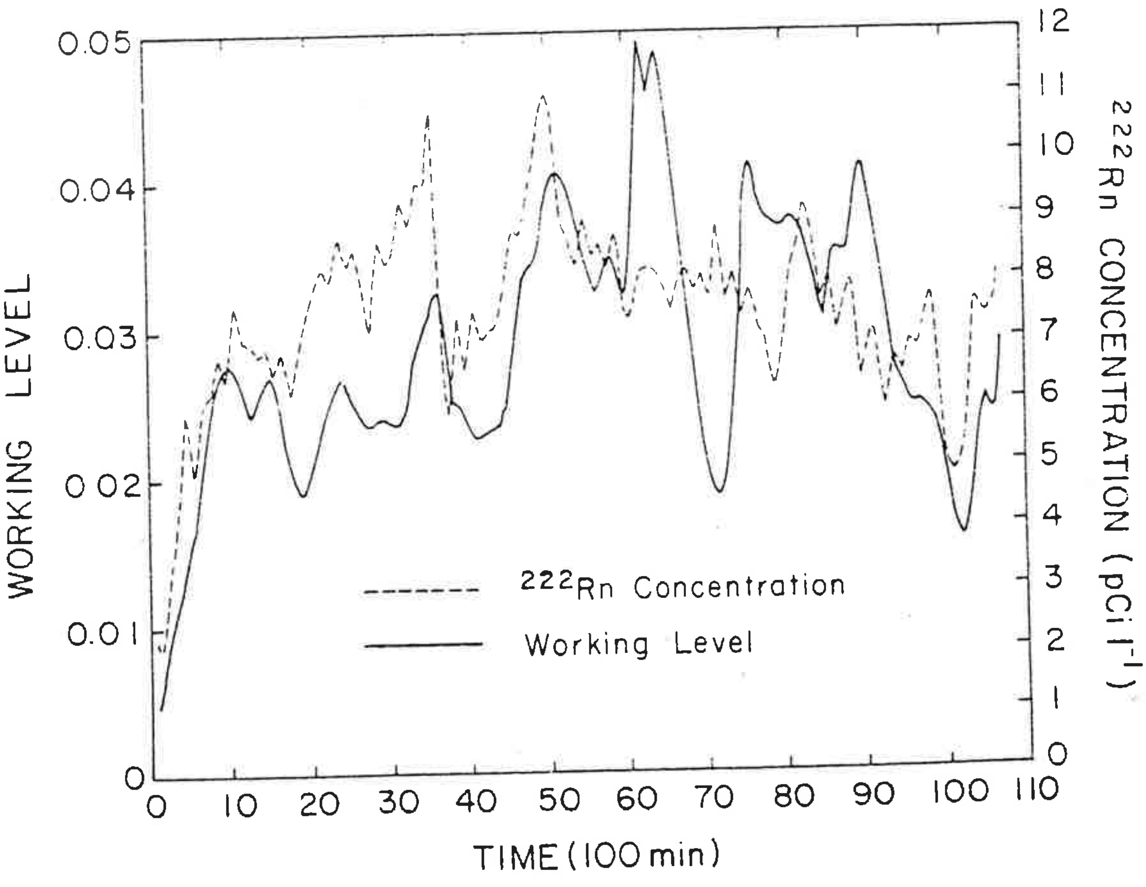

FIG. 3. Plots of ^{222}Rn gas concentration and working level vs time in region 6.

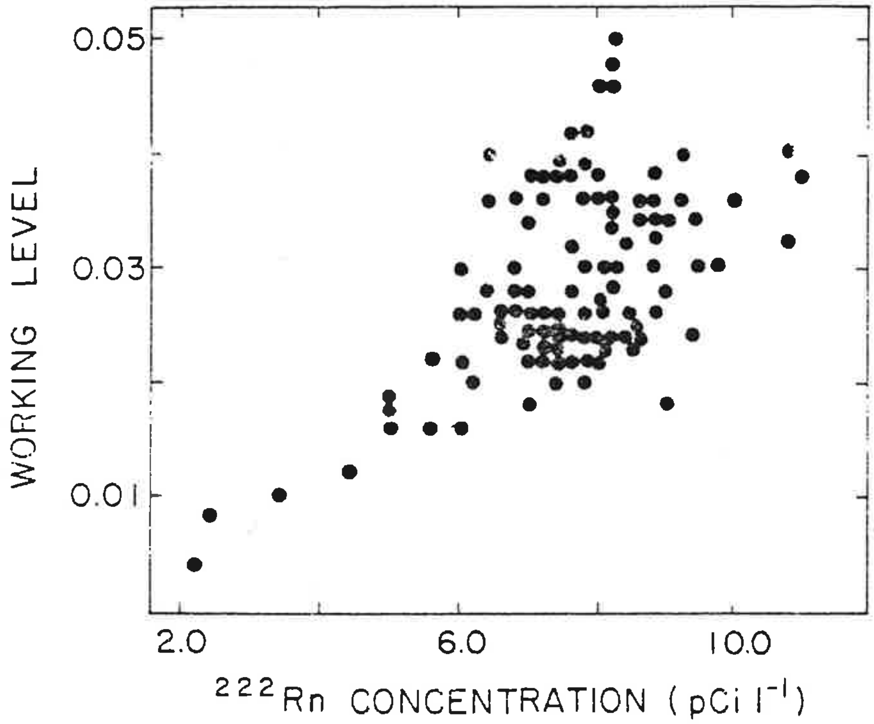

FIG. 4. Scatter plot of working level vs ^{222}Rn gas concentrations in region 6.

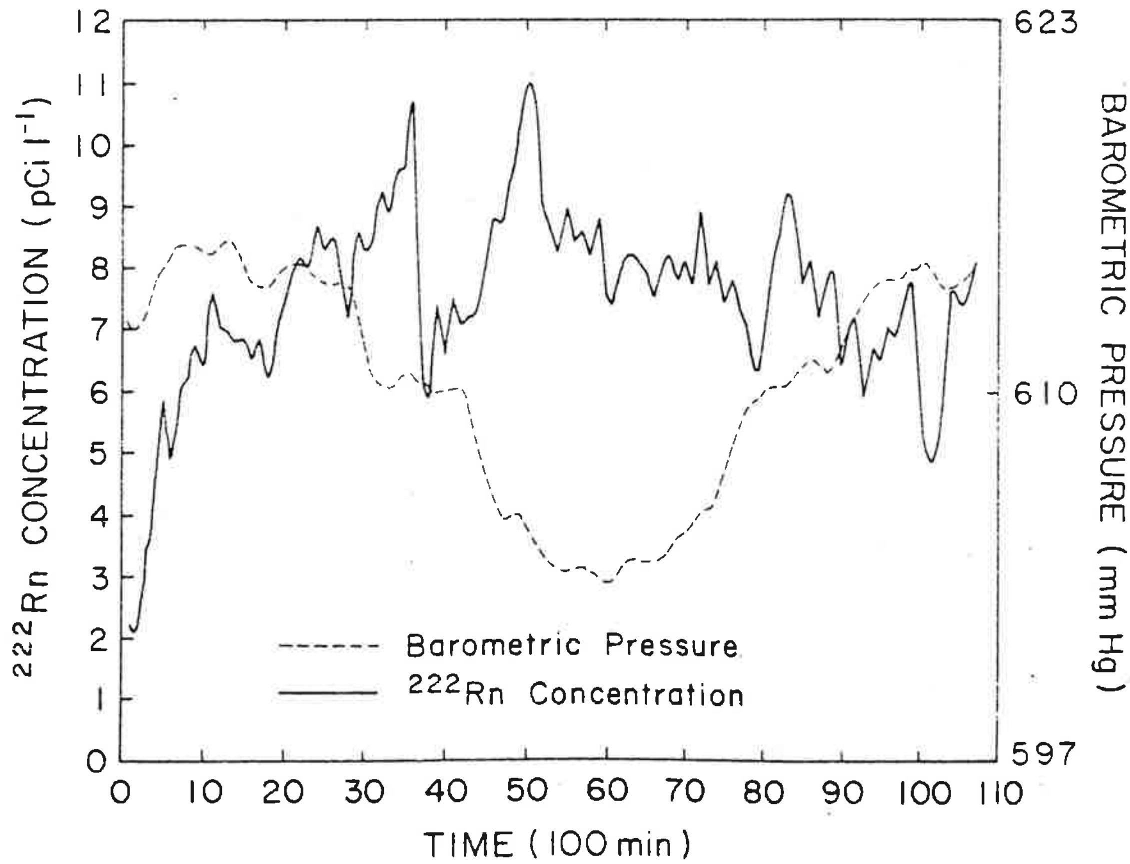

FIG. 5. Plots of ^{222}Rn gas concentration and atmospheric pressure vs time in region 6.

time for the same region. Figure 6 shows a plot of ^{222}Rn gas concentration and pressure differential as a function of time. Pressure differential was plotted on a log scale in order to accommodate the large excursions in Δp, which were often several orders of magnitude. The regression analysis failed to show any significant correlation between either pressure or pressure differential and ^{222}Rn concentration during the measurement period.

In the second stage of analysis, average values of the measured parameters were computed during the six time periods. Table 1 lists the average values of ^{222}Rn gas concentration, working level, pressure differential, and the induced ventilation rate, λ_v.

It is important to note that regions 1 and 5 have the same induced ventilation rate, λ_v, and also similar ^{222}Rn concentrations. However, in region 1, the pressure differential was negative with respect to outside (Δp = 0.8 Pa = 0.006 mm Hg). This implies that forced flow mechanisms were not responsible for controlling the transport of ^{222}Rn into this house.

Another test of this hypothesis is to establish the magnitude of the radon source term as a function of ventilation. Assuming that the source term for ^{222}Rn production is constant and that air exchange rates are much shorter than the rate of decay of ^{222}Rn, the concentration of ^{222}Rn in the house is related to the ventilation rate by

$$C = \frac{S}{\lambda_n + \lambda_v}, \tag{1}$$

where

C = ^{222}Rn concentration in the basement (pCi l^{-1}),
S = ^{222}Rn source term (pCi l^{-1} hr^{-1}),
λ_n = natural ventilation rate (hr^{-1}), and
λ_v = induced ventilation rate (hr^{-1}).

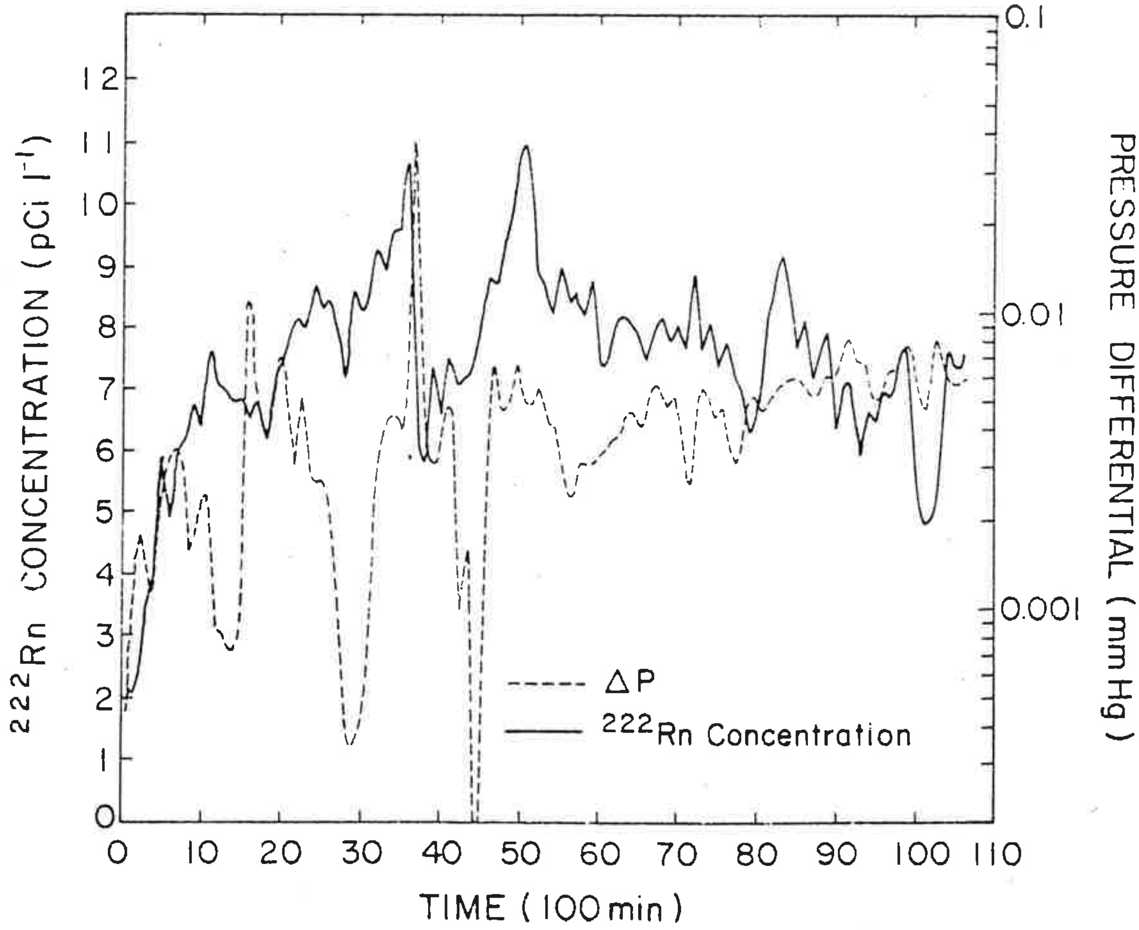

FIG. 6. Plots of ^{222}Rn gas concentration and pressure differential between inside and outside of house vs time in region 6.

In this expression, C and λ_v are variables that have been measured, while λ_n and S are assumed to be constants that need to be determined. A regression analysis using the six pairs of measured values in Table 1 indicated that this function fit the data with a coefficient of determination of $r^2 = 0.91$. Since we have already shown that the pressure differentials are not controlling radon concentrations, the only consistent conclusion is that the source term and natural ventilation rate are independent and constant. Therefore, the natural ventilation rate for this house was determined to be $\lambda_n = 0.16 \pm 0.03$ hr^{-1}, and the source term $S = 1.17 \pm 0.12$ pCi l^{-1} hr^{-1}.

Figure 7 shows a plot of $C\lambda_t$ vs λ_t obtained by Nazaroff (Na81b). The fact that the curve is a straight line with positive slope indicates that a forced flow component was present and that it was driven by air exchange rates. The individual points in Fig. 7 represent the measurements in Table 1 using $\lambda_t = \lambda_n + \lambda_v$. Since $C\lambda_t$ is constant we conclude that for this house forced flow transport does not contribute to the ^{222}Rn concentration. These results also indicate that a heat exchanger can successfully reduce the concentration of both ^{222}Rn and ^{222}Rn progeny.

Additional evidence for the lack of a forced flow component to the ^{222}Rn source term was provided by a simple calculation using Poiseuille's equation. Recognizing that the measured values of Δp were not very large for either positive or negative values, it is not likely that a flow would be induced except through rather large cracks in the concrete. This was modeled by assuming that random cracks in the concrete could be expressed as one hole of a given diameter, located in every square centimeter of surface. If, for example, the forced flow contribution to the total ^{222}Rn concentrations in the house were as large as 10%, the diameter of these hypothetical holes could not exceed 0.05 mm. This rough estimate of diameter does not disagree with the appearance of the basement since all major air cracks or gaps were sealed.

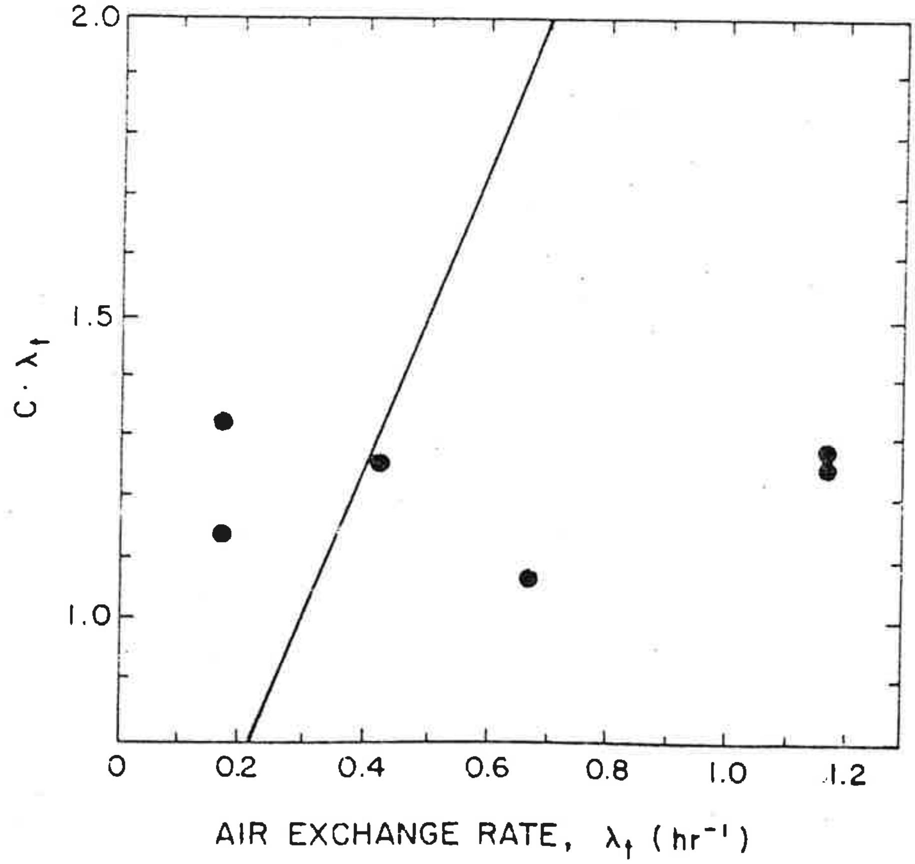

FIG. 7. Plot of ^{222}Rn source term $C\lambda_t$(pCi l^{-1} hr^{-1}) vs total air exchange rate, λ_t, in the basement.

whereas hairline cracks with separations ~ 0.05 mm were not sealed.

The absence of a forced-flow component to the ^{222}Rn source term provided a unique opportunity to determine the diffusion characteristics of the entire basement *in situ*. Previous measurements of the diffusion coefficient were subject to considerable uncertainty and the results did not always apply to real structures. Culot measured the diffusion coefficient by placing a detector on a section of concrete wall or floor (Cu76). This method only considers a small fraction of the total surface area and neglects random cracks or seams between sections. Another method is to make measurements using core samples of concrete (Jo78). This suffers from the same limitations. Results of measurements made by several authors are shown in Table 2.

A general time-dependent solution for ^{222}Rn infiltration from a slab or cylinder into a closed volume having ventilation rate, λ_n, has been described by Dallimore and Holub (Da83). This theory has been tested in small volumes by observing the buildup of ^{222}Rn as a function of time. From these measurements, it is possible to obtain both the diffusion coefficient and the porosity. Measurements of this kind are impractical in a house since the natural ventilation rate of even the tightest basements is rarely less than 0.1 hr^{-1}, which is much larger than the ^{222}Rn decay constant 0.0076 hr^{-1}, making it almost impossible to measure the buildup of ^{222}Rn.

A compromise has been developed that applies a steady state solution to the problem. Since the concentration of Ra is similar in both the soil and concrete (Table 3), the walls and floors of the basement are considered to be infinitely thick. The production rate of atoms into a unit interstitial volume within the concrete is

$$\phi = \frac{\mathrm{Ra}\rho E}{\epsilon}, \tag{2}$$

where

ϕ = production rate of ^{222}Rn (pCi cm^{-3}),
Ra = concentration of Ra in the concrete in pCi g^{-1},
ρ = bulk density of the soil (g cm^{-3}),
E = emanation coefficient of ^{222}Rn gas, and
ϵ = porosity of the concrete.

Neglecting corner effects, the appropriate steady state solution for the concentration of ^{222}Rn in the basement is

$$C = \phi \left[1 - \frac{1}{1 + \frac{\sqrt{\lambda D}}{k\lambda_t}} \right], \tag{3}$$

where

C = concentration of ^{222}Rn gas in the basement (pCi cm^{-3}),
λ = radioactive decay constant for ^{222}Rn,
λ_t = ventilation rate in the basement = $\lambda_n + \lambda_v$,
$k = V/S\epsilon$,
V = volume of the basement (cm^3),
S = surface area of the walls and floor which contribute ^{222}Rn (cm^2),
ϵ = porosity, and
D = diffusion coefficient (cm^2 sec^{-1}).

Rearranging eqn (3) and taking into account that $k\lambda_t \gg (\lambda D)^{1/2}$ the diffusion coefficient is

$$D = \left[\frac{V\lambda_t C}{SE\mathrm{Ra}\rho}\right]^2 \Big/ \lambda. \tag{4}$$

Each of the quantities in the right side of eqn (4) can be independently determined with an accuracy of a few percent except for ERa, which usually can be measured to within 30%. It is interesting to note that porosity, which is the major cause of uncertainty in methods used by other authors, is not required for the solution of eqn (4).

Table 2. Diffusion coefficients and relaxation lengths for ^{222}Rn in concrete

Author	Ref.	D (cm^2 sec^{-1})	$R = \sqrt{D/\lambda}$* (cm)
Culot	Cu76	3.4×10^{-4}	7.6
Jonassen	Jo78	7.5×10^{-5}	4.0
Krisiuk	Kr71	4.8×10^{-4}	15.2
		1.1×10^{-3}	23.0
Holub	This paper	3×10^{-3}	43.0

λ = Decay constant for ^{222}Rn = 2.097×10^{-6} sec^{-1}

The diffusion coefficients obtained for this house (listed in Table 2) are three to 10 times higher than those listed by other authors. It appears that small cracks in the walls and floors have a permeability that is too small to allow ^{222}Rn transport by forced flow when Δp is on the order of 0.8 Pa. However, these voids reduce the tortuosity such that the effective diffusion coefficient becomes as much as 10 times greater than that estimated over small surfaces or core samples.

Various authors define an effective diffusion coefficient as the product of the diffusion coefficient, D, in eqn (4) by the porosity ϵ, such that $D_e = D\epsilon$. We have chosen not to use this concept for two reasons. First, measurements of porosity are difficult and often have large uncertainties. Second, D alone provides information on the thickness of material (soil or wall) that contributes to the diffusion of radon into a house since the relaxation length is (D/λ) and not (D_e/λ).

The concentrations of U and Th in soil and concrete samples obtained by γ-ray spectroscopy are shown in Table 3. At the conclusion of the experiment, the ^{212}Pb(ThB) concentration in the air was estimated by measuring the activity of ^{208}Tl on a filter 3 hr after the air flow was terminated. The concentration of ^{212}Pb(ThB) was estimated to be 0.12 pCi l^{-1}, assuming that equilibrium existed between ^{212}Pb(ThB) and ^{212}Bi(ThC) when the pump was stopped. Using the fact that Th and U concentrations in the concrete are similar (Table 3), the concentration of ^{220}Rn, assuming equilibrium with ^{212}Pb(ThB) for the sake of simplicity, can be estimated from the concentration of ^{222}Rn by using the ratio of the diffusion lengths. For example,

$$C_{\mathrm{Tn}} = \left[\frac{\lambda_{\mathrm{Rn}}}{\lambda_{\mathrm{Tn}}}\right]^{1/2} \cdot C_{\mathrm{Rn}} = \frac{1}{80} C_{\mathrm{Rn}}. \quad (5)$$

Table 3. Concentration of Th, U and K in soil and concrete samples

	Th (pCi g^{-1})	U (pCi g^{-1})	K %
Soil	1.5	1.4	2.5
Concrete floor	2.2	1.4	2.3
Concrete wall	1.1	0.8	3.7

The ^{222}Rn concentration at that time was about 7 pCi l^{-1}. Thus from the equation the Th concentration is approximately equal to 0.09 pCi l^{-1} which is in agreement with the value of 0.12 obtained from the sample filter.

CONCLUSIONS

Radon-222 is transported into houses by diffusion and forced-flow mechanisms. Sealing cracks and holes in concrete surfaces can be an efficient way of eliminating the forced flow component when pressure differentials between the inside and outside of the house are less than 1.0 Pa. The sealing process, however, does not eliminate the transport controlled by diffusion. In this house, radon concentrations in the basement averaged 8 pCi l^{-1} under natural ventilation conditions. The concentration of U in the soil and concrete was at 1.4 pCi g^{-1}.

The diffusion coefficient of the combination of walls and floor surrounding sthe basement has been measured. This method automatically takes into account inhomogeneities in the structure. Values of the diffusion coefficient computed by this method are three to 10 times higher than those obtained by previous authors (Table 2). This is probably due to cracks or fissures in the structure, which are too small to allow forced flow by pressure differentials but large enough to increase the total diffusion length.

A heat exchanger can be an effective way of reducing ^{222}Rn levels by a factor of about six in an energy-efficient house.

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