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RADON ENTRY INTO DWELLINGS THROUGH CONCRETE FLOORS

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ABSTRACT

Indoor radon entry commonly is modeled as advection from pressure-driven flow through foundation cracks and openings. However recent diffusive-advective model analyses suggest that diffusion through intact concrete floor areas also may be significant. Diffusive radon entry is characterized further by new measurements of the porosities, radon diffusion coefficients, and air permeability coefficients of concrete. The measurements include concretes from typical Florida slab-on-grade housing, and others from industrial mixes that were selected to inhibit radon movement.

Measured radon diffusion coefficients ranged from 9×10^{-6} cm^2 s^{-1} for the industrial concretes to 0.003 cm^2 s^{-1} for floor-slab concretes. Air permeabilities generally were below 1×10^{-11} cm^2. The diffusion measurements included concretes made from Type I, II, and V cements, and exhibited a correlation with the water/cement (W/C) ratio of the concretes. The correlation had the form $D = 1.8\times10^{-6} \exp(11.1\ W/C)$. The average diffusion coefficient measured for the floor slab concretes (1.6×10^{-3} cm^2 s^{-1}) suggested that diffusion may account for indoor concentrations up to 2 pCi L^{-1} in cases of soil-gas radon concentrations of 3,000 pCi L^{-1}. Radium concentrations of 5 pCi g^{-1} in the concrete similarly may contribute more than 1 pCi L^{-1} of indoor radon. Combined diffusion through an intact slab and through a perimeter floor crack slightly exceeded advective radon entry for a reference house on sandy soil, and exceeded advective entry rates by more than 100 times for the house on clayey and silty clay loam soils.

This paper has been reviewed in accordance with the U. S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

Indoor radon entry from soil gas has been modeled most commonly as advective transport by pressure-driven air flow through foundation openings or cracks. The flow is caused by the typically negative indoor pressure compared with that in the soil and the outdoor atmosphere. Recently, attention has been directed toward the importance of diffusion as a significant mechanism for radon entry. In particular, Tanner (1) identified radon diffusion as the dominant entry mechanism when foundation soil permeabilities are less than 7×10^{-12} m^2. Rogers and Nielson (2) also identified diffusion through concrete floors and the contiguous soil as a significant mechanism for radon entry for many soils under typical long-term average foundation pressure gradients. Loureiro et al. (3) have compared theoretical diffusive and advective radon transport in soils to estimate conditions when diffusion is insignificant.

While the diffusive radon flux through concrete floors is much smaller than the advective flux through cracks in the floor, the predominance of the intact floor area over the crack area may compensate for the difference in fluxes. Thus, it is desirable to examine the diffusive properties of concretes used in dwelling floors to better assess this mode of radon entry. It also is instructive to characterize the relative importance of radon generated within the concrete to determine whether aggregates or other concrete components may contribute significantly to indoor radon concentrations.

This paper identifies the main properties of concrete that influence radon migration into dwellings. It reports measured values of these parameters for concretes typical of Florida residential floors and also for industrial concretes specifically selected to restrict radon migration. It then examines the relation of the measured properties to other physical properties of the concretes. Finally, it examines the relative importance of the concrete properties, including radium concentrations, to radon entry into dwellings. The radon entry analyses are based on an approximate indoor radon balance equation and on a complete numerical analysis of combined diffusive-advective radon entry.

CONCRETE CHARACTERISTICS IMPORTANT TO RADON TRANSPORT

The simplified equation describing radon generation and transport in concrete (ignoring radon adsorption) is given by (2,4):

$$\frac{\partial C}{\partial t} = D\nabla^2 C + \frac{K}{\mu}\vec{\nabla}P \cdot \vec{\nabla}C - \lambda C + \frac{R\rho E\lambda}{p} \qquad (1)$$

where

C = pore radon concentration (pCi cm^{-3})
D = radon diffusion coefficient (cm^2 s^{-1})
K = permeability coefficient (cm^2)
μ = viscosity of air (Pa•s)
∇ = three dimensional gradient operator
P = atmospheric pressure (Pa)
λ = radon decay constant (2.1×10^{-6} s^{-1})
R = radium concentration (pCi g^{-1})
ρ = bulk density (g cm^{-3}, dry)
E = radon emanation coefficient
p = porosity

The diffusive component of radon transport in equation (1) is based on Fick's law, which defines diffusive radon flux as:

$$F = -Dp\nabla C \qquad (2)$$

where

F = bulk radon flux (pCi cm^{-2} s^{-1}).

Equations (1) and (2) show that the concrete parameters dominating radon transport are D, K, and p. The D and K parameters are influenced in turn by the concrete free moisture content, m, and its mean pore radius, r_p. The measurements reported herein focus on these parameters. The parameters influencing radon generation in concrete are R, E, ρ, and p. Of these parameters, the influences of only R and E are examined here in the radon entry calculations with RAETRAN (4) and RAETRAD (2).

Four samples (F-1 through F-4) of residential concretes typical of new Florida dwellings were tested. These samples had a water-to-cement (W/C) ratio of about 0.6. Two additional samples (T-1 and T-2) were obtained of concretes intended to have relatively low radon transport constants (D and K). These samples had W/C ratios slightly less than 0.4. Bulk densities and effective porosities of the T-1 and T-2 samples were measured. For the (F-1 through F-4) samples, bulk densities were measured and porosities were estimated from the bulk densities by assuming a specific gravity of 2.71. All six of the samples were taken from separately poured test cylinders, and thus may vary in curing conditions and finishing from their construction counterparts. The physical properties of the concretes are given in Table 1.

TABLE 1. PHYSICAL PROPERTIES OF CONCRETE SAMPLES

Sample ID	Concrete Type	Water/Cement Ratio	Density (g cm^{-3})	Porosity
F-1	I	0.60	2.15	0.20
F-2	I	0.60	2.14	0.21
F-3	I	0.61	1.99	0.26
F-4	I	0.61	2.00	0.26
T-1	II	0.39	2.40	0.11
T-2	V	0.38	2.35	0.13

PERMEABILITY COEFFICIENT

Permeability coefficients were measured on samples T-1 and T-2 using the transient method, as described previously (5). The permeability coefficient of sample F-4 was measured using a 10 cm diameter by 5 cm long concrete sample that was tightly secured in a steel sample holder. Simultaneous measurements were then made of the air flow through the sample and the pressure drop across the sample. The permeability then was deduced using the one-dimensional form of Darcy's Law:

$$K = \frac{Q\mu L}{A \Delta P} \tag{3}$$

where

Q = air flow rate through the sample ($cm^3\ s^{-1}$)
L = sample length (cm)
A = sample cross-sectional area (cm^2)
ΔP = pressure drop across sample (Pa).

Measurements of air permeability for samples T-1, T-2, and F-4 all were less than $1 \times 10^{-11}\ cm^2$, and did not exhibit a strong dependence on porosity or on the W/C ratios. This suggests that the mean pore radius for the higher porosity samples may not be significantly larger than for the lower porosity samples, but that there simply may be more pores. These permeabilities are sufficiently low that radon advective flow through the intact bulk concrete is negligible, even for very high foundation pressure gradients.

DIFFUSION COEFFICIENT

Radon diffusion coefficients were measured on all concrete samples using the standard procedure for porous materials (6). For initial measurements, the samples were equilibrated with laboratory air, and had pore water contents that corresponded to the capillary retention by the concrete pores (7). In addition, for samples T-1 and T-2, diffusion measurements were made on water-saturated samples and at lower water contents, including zero pore water. The various water contents were achieved by vacuum-saturating the samples, with subsequent vacuum pumping to reduce water contents to the desired levels (measured gravimetrically). The results of the diffusion measurements are shown in Figure 1. There is considerable uncertainty in the water contents of samples F-1 through F-4.

The measurements at zero pore water provide estimates of the Knudsen diffusion coefficient and the associated effective pore radius for samples T-1 and T-2 (8). The total diffusion coefficient for the sample pores combines the Knudsen diffusion coefficient and the diffusion coefficient of the pore fluid with the relationship (7,8):

$$\frac{1}{D} = \frac{1}{D_K} + \frac{1}{D_C} \tag{4}$$

where

D_K = Knudsen diffusion coefficient ($cm^2\ s^{-1}$)
D_C = diffusion coefficient of the pore fluid ($cm^2\ s^{-1}$).

Using the prior, predictive correlation for the diffusion coefficient in soil pores to represent D_C (9), and using equation (4) to estimate the total diffusion coefficient give the two curves shown in Figure 1. The curves agree with the data for T-1 and T-2 to within the experimental diffusion measurement

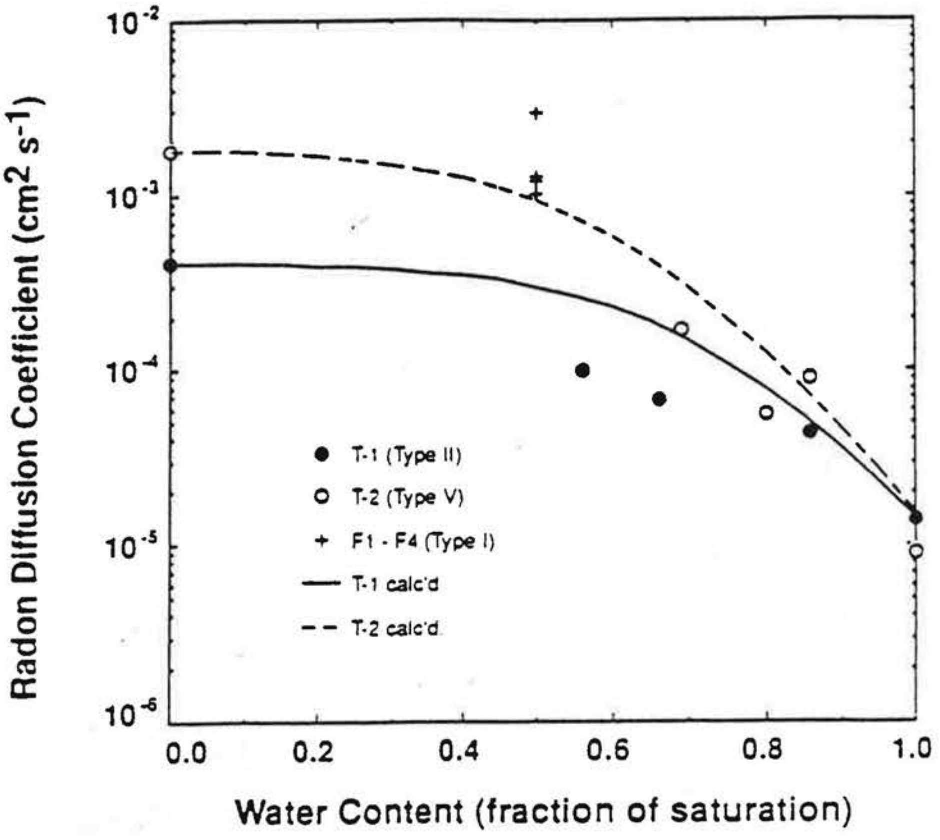

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Figure 1. Measured radon diffusion coefficients for the six concrete samples, with comparisons to soil-based water-dependence trends for samples T-1 and T-2.

uncertainty. If it is assumed that the mean pore radius in samples F-1 through F-4 scales with the mean pore radius in sample T-2 according to the ratio of the sample porosities, then similar diffusion coefficient predictions can be made for samples F-1 through F-4 that have similar degrees of accuracy as the curves for samples T-1 and T-2.

It is also of interest to plot the concrete diffusion coefficients for samples equilibrated with ambient air as a function of their W/C ratios. The diffusion data, shown in Figure 2, correlate well with the W/C ratios to yield the least-squares fitted expression:

$$D = 1.8 \times 10^{-6} \exp(11.1\ W/C). \qquad (5)$$

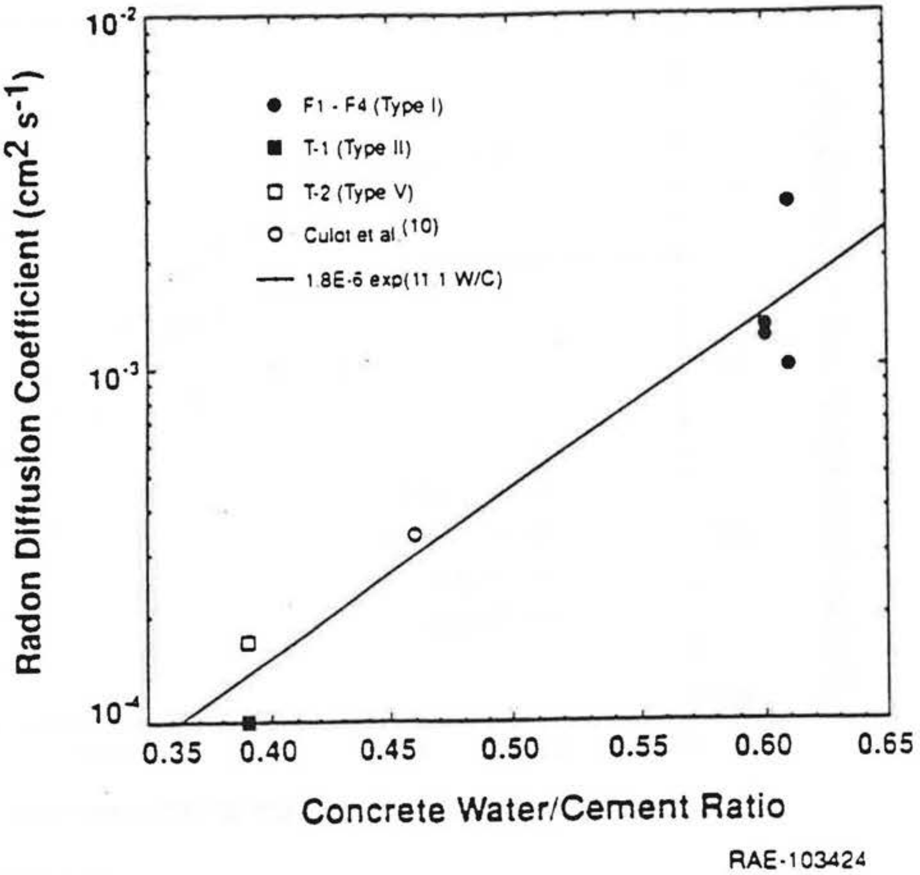

Figure 2. Regression of ambient-moisture radon diffusion measurements on the water/cement ratio of the initial concrete mixture.

The correlation coefficient associated with this fit is $r = 0.96$. Also included in Figure 2 and in the determination of equation (5) is the radon diffusion coefficient for concrete reported by Culot et al. (10). Equation (5) is also an excellent predictor for the value reported by Culot, and suggests an important dependence of the radon diffusion coefficient on the W/C ratio of the concrete.

SIGNIFICANCE OF RADON DIFFUSION THROUGH CONCRETE FLOORS

The significance of indoor radon entry by diffusion through concrete floors can be estimated from a simplified approximation of the indoor radon balance equation. The approximation assumes that all indoor radon enters via the concrete foundation area, and that the indoor volume is uniformly diluted at the continuous rate of λ_v with clean air having an insignificant radon concentration:

$$J \cdot A = C V \lambda_v \qquad (6)$$

where

J = radon flux entering the house foundation (pCi m^{-2} s^{-1})
A = house foundation area over which radon entry occurs (m^2)
C = steady-state indoor radon concentration (pCi L^{-1})
V = indoor volume (L)
λ_v = ventilation rate of indoor volume (s^{-1}).

For a simple slab-on-grade house geometry typical of Florida construction, equation (6) can be simplified further by introducing the indoor height as the ratio of the house volume to its area. This leads to the expression:

$$C = 10^{-3} J / (h \lambda_v) \qquad (7)$$

where

h = height of indoor volume (m)
10^{-3} = L per m^3 conversion.

Based on the approximate separability of diffusive and advective radon entry into dwellings, equation (7) can be used directly to estimate the component of the indoor radon concentration that results from diffusion through the concrete floor slab. The diffusive radon flux through the slab was estimated by repeated analyses with the RAETRAN code (4), in which a 10-cm slab separated an indoor radon concentration of 2 pCi L^{-1} from 5 m of sandy foundation soil that had varying source strengths corresponding to deep-soil radon concentrations of 100 pCi L^{-1} to 10,000 pCi L^{-1}. Various diffusion coefficients also were used for the slab, which had a fixed porosity of $p=0.23$, corresponding to the average porosity of the Florida concrete samples (F-1 to F-4). The radium concentration in the concrete first was assumed to be 1 pCi g^{-1}, and to have a radon emanation coefficient of 0.25.

The resulting radon fluxes from the slab were divided by an indoor height of 2.3 m and a ventilation rate of 1.4×10^{-4} s^{-1} (0.5 h^{-1}) to estimate the diffusive component of the indoor radon concentration (equation 7). The resulting indoor concentrations (Figure 3) start to exceed the 1 pCi L^{-1} level for elevated soil gas radon concentrations (several thousand pCi L^{-1}) only when concrete diffusion coefficients exceed 3×10^{-4} cm^2 s^{-1} or higher. Using concrete diffusion coefficients similar to the 3.4×10^{-4} cm^2 s^{-1} reported by Culot et al. (10), previous estimates of radon entry by diffusion were relatively small (2), but still were significant compared to advective radon entry. Using the higher diffusion coefficients measured with Florida floor-slab concretes (averaging 1.6×10^{-3} cm^2 s^{-1}), indoor radon concentrations of more than 2 pCi L^{-1} may result from soil radon sources of about 3,000 pCi L^{-1}. The assumption of separability of diffusive and advective entry made a difference of less than 5% in the entry rates. Even if a 1-cm perimeter floor crack is assumed for the house, diffusion rates through the intact part of the slab are affected by less than 25%, mainly from altered gradients near the perimeter.

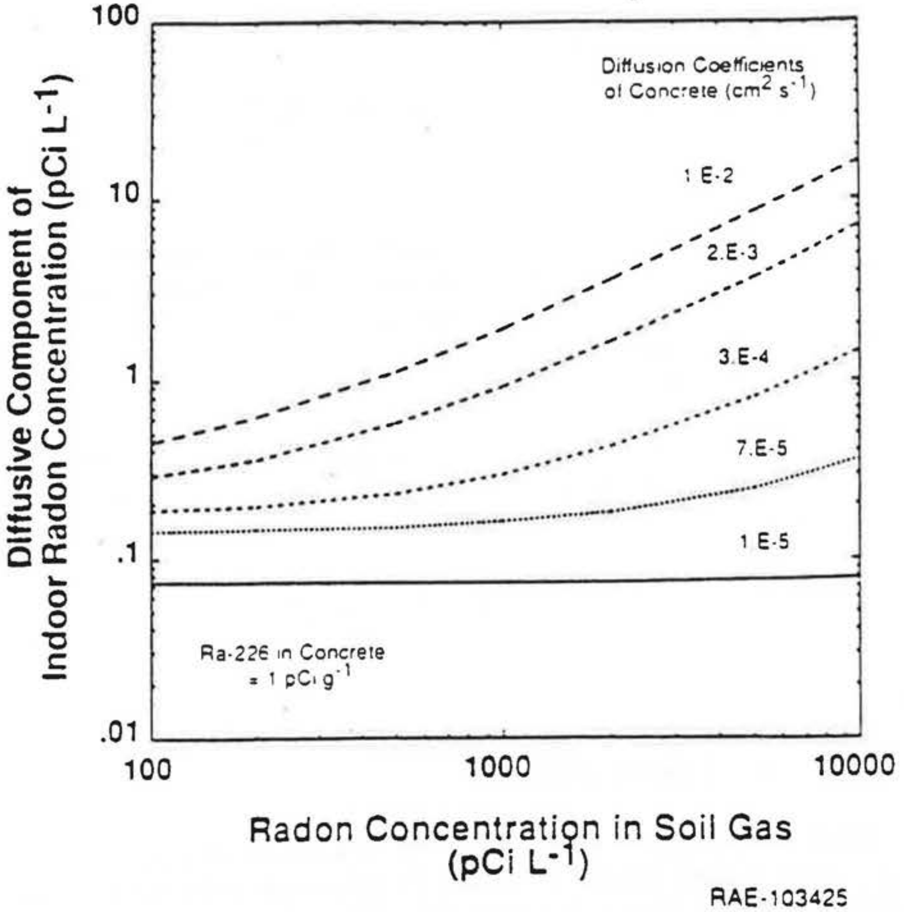

Figure 3. Diffusive contributions to indoor radon concentrations for varying soil radon sources and five different radon diffusion coefficients.

Further analyses with varying radium concentrations in the concrete slab are summarized in Figure 4. These used a radon diffusion coefficient equal to the average of the measurements on Florida concretes. As illustrated, 5 pCi g^{-1} radium in the bulk concrete may introduce more than 1 pCi L^{-1} of radon into the house, and 20 pCi g^{-1} of radium in the concrete may exceed the 4 pCi L^{-1} indoor level even in the absence of significant subslab radon sources. These analyses assume a radon emanation coefficient of 0.25; however, little is known about the radon emanation coefficients of concrete, or how they compare with those of the aggregate and other concrete components. If radon emanation coefficients for concrete are less than 0.25, the resulting radon source strengths and indoor radon concentrations will scale accordingly.

A set of complete advective-diffusive radon entry analyses by the RAETRAD code (2) provides a more direct comparison of radon entry through slab-on-grade foundations by diffusive and advective mechanisms. In these analyses, radon diffused through a 10-cm concrete floor slab that had a relatively low diffusion coefficient (5×10^{-4} cm^2 s^{-1}), and also moved by diffusion and advection through a 1 cm perimeter crack in the floor. The reference house was assumed to be located alternatively on five different soils, with textures including sandy, sandy clay loam, loam, clay, and silty clay loam. Water

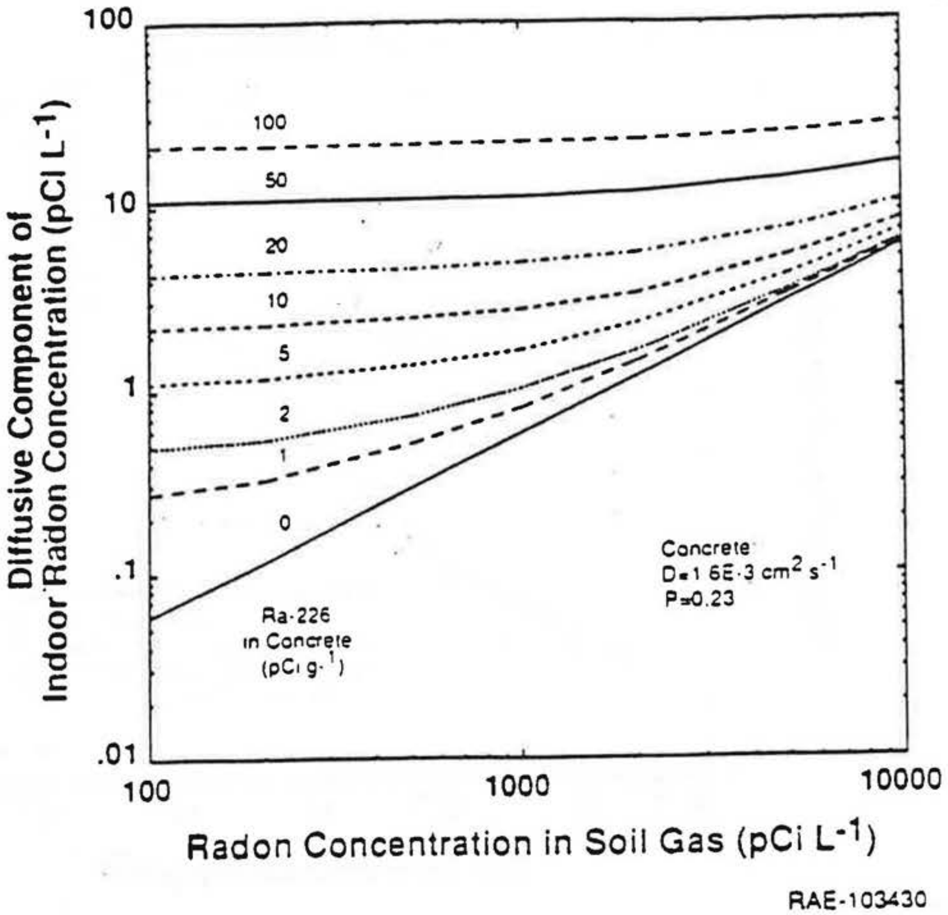

Figure 4. Diffusive contributions to indoor radon concentrations for varying soil radon sources and eight different concrete radium concentrations.

contents of the soils were defined as the drainage limits at -0.3 bar matric potential (11), and radium concentrations in the soils were varied to the maximum that could be tolerated for an indoor radon concentration of 2 pCi L^{-1}. The radium concentration in the concrete was kept constant at 0.3 pCi g^{-1}.

The resulting radon entry rates for the diffusion and advection mechanisms are plotted in Figure 5, and illustrate the dominance of diffusive radon entry for this case. Although the diffusive and advective entry rates have the same order of magnitude for the sandy soils, they are more divergent for the low-permeability soils, differing by more than 2 orders of magnitude for the clay and silty clay loam soils.

In summary, the present radon diffusion measurements on Florida floor slab concretes exceed previous diffusion estimates for concrete, emphasizing the importance and sometimes dominance of the diffusive mechanism for indoor radon entry. The correlation of radon diffusion coefficients with the concrete W/C ratio suggests this ratio as a possible surrogate for estimating radon diffusion coefficients of concretes when better data are unavailable. Parametric model analyses indicate several pCi L^{-1} of

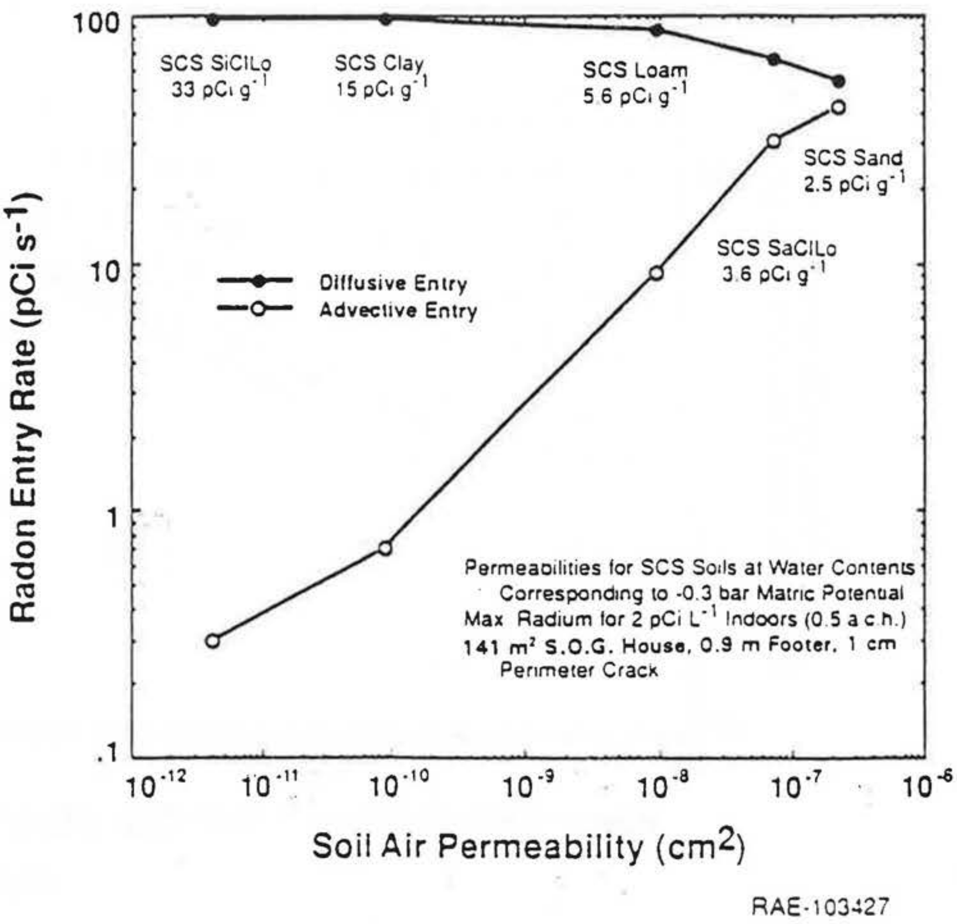

Figure 5. Comparison of diffusive and advective radon entry rates for a slab-on-grade house with a 1-cm perimeter floor crack.

indoor radon may result from diffusive entry from near-background soils, or from slightly-elevated radium concentrations (10-15 pCi g^{-1}) in the concrete.

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