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BENCHMARK AND APPLICATION OF THE RAETRAD MODEL

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ABSTRACT

Field measurements were used to benchmark a simple new predictive correlation between soil gas permeability and soil grain size, moisture, and porosity. The correlation was incorporated with a previous diffusion correlation into the new RAETRAD code, that calculates radon generation and two-dimensional transport in soils, and radon entry into structures. RAETRAD generalizes the one-dimensional RAETRAN model, combining advective and diffusive radon transport with radon emanation, decay, absorption, and adsorption. RAETRAD calculations suggest 0.3 liter/minute normalized radon entry rate for slab-on-grade homes on low-permeability soils (<10^{-8} cm^2), increasing to 7 liter/minute for sandy soils. Soil or fill properties in the first few feet dominate radon entry efficiency and limiting radium concentrations for prescribed indoor radon levels. For indoor radon concentrations of 2 pCi/liter, sandy soils may contain only 2-3 pCi/g radium compared to 10-20 pCi/g for more clayey 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

Radon generation and transport in soils and its subsequent entry into dwellings is a complex process requiring characterization of the soil conditions, meteorological conditions, and the structure. Radon emanates from radium-bearing minerals into the soil pore space, followed by diffusive and advective transport in both liquid and gas phases into the dwelling, entering via cracks, sumps, porous building materials, and other routes. The RAECOM

(Radon Attenuation Effectiveness and Cover Optimization with Moisture) (1) multiregion, one-dimension radon generation and transport code has been used widely to predict radon migration through porous media. RAETRAN (RAdon Emanation and TRANsport) (2) provides similar capabilities, but also includes advective transport mechanisms. These codes are easy to use and require very little input data; however, because they are one-dimensional, they have limited application for radon entry into structures.

The mathematics of the RAETRAN code have been extended to two dimensions. In addition, the pressure-driven flow equation now is solved in the code instead of externally as required with RAETRAN. The resulting position-dependent velocities have corresponding boundary conditions to those used for the radon generation and transport calculations. The resulting code, called RAETRAD (RAdon Emanation and TRAnsport into Dwellings) (3), retains the general simplicity of operation and minimal input requirements as the earlier RAECOM and RAETRAN codes. However, it provides a more detailed description of radon movement through porous materials such as soil and concrete and subsequent radon entry into structures coupled to the soils.

Key factors in the simplicity of the RAETRAD input data are the simple correlations for predicting gas permeabilities and radon diffusion coefficients for the porous materials. These correlations and their use are discussed in the next section. After that the RAETRAD code is briefly described, and finally is applied to typical Florida soils and structures to obtain radon entry efficiency factors and radon entry rates into dwellings, and to estimate example maximum soil radium concentrations for foundation fill materials.

AIR PERMEABILITY AND RADON DIFFUSION COEFFICIENT CORRELATIONS

Radon migration through soils and entry into dwellings depend strongly on values of radon diffusion coefficients and air permeabilities for the soils and for the applicable house construction materials. Simple correlations for the radon diffusion coefficient have been developed and have been widely used (4-5). The diffusion coefficient correlation that is incorporated in RAETRAD is (6):

$$D - D_a p \exp(-6mp - 6m^{14p}) \tag{1}$$

where

D	=	pore average radon diffusion coefficient (cm^2s^{-1})
d_a	=	diffusion coefficient for Rn in air (0.11 cm^2s^{-1})
p	=	soil porosity
m	=	fraction of moisture saturation.

Predictive correlations for gas permeability have been proposed previously (7-8). A recently improved permeability correlation for shallow soils (6) was incorporated into RAETRAD:

$$K = \left(\frac{p}{110}\right)^2 d_a^{4/3} \exp(-12m^4) \qquad (2)$$

where

K	=	air permeability in porous material (cm^2)
d_a	=	arithmetic average particle diameter (cm).

Equations (1) and (2) reveal that soil gas permeability and radon diffusion coefficients both can be estimated from soil moisture, porosity, and average particle diameter. In turn, the particle diameter averages can be estimated from standard soil classifications such as the 12 categories used by the U.S. Soil Conservation Service (SCS) (9). Furthermore, the appropriate soil moisture near a dwelling can be estimated from the soil classification and soil matric potential (10).

As an example of the above methodology, measurements were made of the in-situ moisture, gas permeability, porosity, and soil particle sizes for several soils in Florida. Soil samples were obtained at depths of 60 to 75 cm from several locations around the state. The data for the soils are given in Table 1. The soil gas permeabilities were estimated from Equation (2) using the field soil data. The resulting correlation-predicted permeabilities and measured field permeabilities are also given in Table 1. In general, the agreement is within the experimental uncertainties. Two-thirds of the predictions were within a factor of 2 of the field-measured gas permeabilities.

From the particle size and moisture information in Table 1, soil matric potentials were estimated using the methodology described in Reference 10. The estimated matric potentials ranged from 1×10^4 Pa to 3.4×10^4 Pa. A matric potential of 5×10^4 Pa was selected as a reasonably conservative dry-side average for conditions in the locations sampled in Florida. Using the 5×10^4 Pa matric potential and soil particle size distribution parameters from the soil samples, soil moisture, permeabilities, and diffusion coefficients were estimated for the broader range of soils defined by the U.S. Soil Conservation Service classifications (9). These data are given in Table 2, and were used in the example radon migration and house entry analyses performed by RAETRAD.

TABLE 1. COMPARISON OF IN-SITU SOIL GAS PERMEABILITIES WITH CALCULATED VALUES

Location	Clay wt.%	Silt wt.%	Sand wt.%	Density (g/cm^3)	Moist. Sat'n.	Measured Permeability (cm^2)	Calculated Permeability (cm^2)	Ratio of Calc.Perm./ Meas.Perm.
Ocala	5.9	7.4	86.7	1.54	0.17	$7.0x10^{-8}$	$1.1x10^{-7}$	1.57
Leesburg	74.6	24.8	0.6	1.45	0.86	$3.6x10^{-12}$	$1.5x10^{-12}$	0.42
Leesburg	1.7	5.4	92.9	1.51	0.12	$1.4x10^{-7}$	$1.4x10^{-8}$	0.99
E Orlando	2.0	3.9	94.0	1.48	0.12	$1.0x10^{-7}$	$1.2x10^{-7}$	1.20
N Orlando	1.9	3.0	95.1	1.50	0.19	$2.4x10^{-7}$	$9.6x10^{-8}$	0.40
SW Orlando	2.1	3.1	94.8	1.75	0.49	$4.2x10^{-8}$	$5.0x10^{-8}$	1.19
SW Orlando	1.2	2.2	96.5	1.52	0.13	$9.0x10^{-8}$	$1.2x10^{-7}$	1.33
Kissimee	0.9	1.9	97.2	1.52	0.15	$7.2x10^{-8}$	$1.5x10^{-7}$	2.08
Lakeland	2.2	2.9	94.9	1.56	0.10	$6.8x10^{-8}$	$1.1x10^{-7}$	1.62
NE Tampa	2.2	5.1	92.7	1.69	0.40	$1.1x10^{-7}$	$7.5x10^{-8}$	0.68
Tampa	2.0	8.8	89.2	1.67	0.73	$4.5x10^{-10}$	$6.7x10^{-10}$	1.49
S Tampa	3.2	4.9	92.0	1.52	0.13	$8.6x10^{-8}$	$1.3x10^{-7}$	1.48

TABLE 2. MOISTURES, DIFFUSION COEFFICIENTS, AND PERMEABILITIES OF STANDARD SCS SOILS AT 0.5-BAR MATRIC POTENTIAL*

SCS Soil Classification	Moisture Saturation Fraction	Radon Diffusion Coefficient† (cm^2/s)	Soil Gas Permeability‡ (cm^2)
Sand	0.084	$3.7x10^{-2}$	$2.4x10^{-7}$
Loamy Sand	0.173	$3.0x10^{-2}$	$2.1x10^{-7}$
Sandy Loam	0.375	$1.8x10^{-2}$	$1.2x10^{-7}$
Sandy Clay Loam	0.390	$1.7x10^{-2}$	$1.1x10^{-7}$
Sandy Clay	0.481	$1.3x10^{-2}$	$5.9x10^{-8}$
Loam	0.591	$8.0x10^{-3}$	$1.9x10^{-8}$
Clay Loam	0.667	$4.9x10^{-3}$	$5.8x10^{-9}$
Silt Loam	0.771	$1.8x10^{-3}$	$5.8x10^{-10}$
Clay	0.808	$1.1x10^{-3}$	$1.8x10^{-10}$
Silty Clay Loam	0.888	$2.5x10^{-4}$	$8.9x10^{-12}$
Silt	0.917	$1.3x10^{-4}$	$2.5x10^{-12}$
Silty Clay	0.923	$1.1x10^{-4}$	$1.6x10^{-12}$

*At 1.6 g/cm^3 bulk dry density; 0.407 porosity.
†Estimated from Equation 1.
‡Estimated from Equation 2.

THE RAETRAD CODE

RAETRAD solves the two dimensional radon balance and air pressure balance equations in cylindrical geometry. The two-dimensional rate balance equation for radon in the gas component of the soil pore space is given by:

$$D_a \left[\frac{d^2C_a}{dr^2} + \frac{1}{r}\frac{dC_a}{dr} + \frac{d^2C_a}{dz^2} \right] - \lambda C_a - \frac{k_a \rho \lambda}{(1-m)} C_a$$

$$+ \frac{K_p}{p(1-m)} \left[\frac{dP}{dr}\frac{dC_a}{dr} + \frac{dP}{dz}\frac{dC_a}{dz} \right] + \frac{R\rho\lambda E_{air}}{p(1-m)} \quad (3)$$

$$- R\frac{m\lambda}{(1-m)k_d} + T_{wa} = \frac{dC_a}{dt}$$

where

D_a	=	radon diffusion coefficient in air, including tortuosity
C_a	=	radon concentration in the air-filled pore space
r	=	radial distance from center of house
z	=	vertical depth from ground surface
λ	=	radon decay constant
k_a	=	air-surface adsorption coefficient for radon
ρ	=	bulk dry density
m	=	fraction of moisture saturation
K_p	=	pore gas permeability
p	=	total porosity
P	=	pore gas pressure
R	=	radium concentration in the solid matrix
E_{air}	=	component of emanation coefficient that is a direct pore air source of radon
k_d	=	equilibrium distribution coefficient for radium in solid-to-pore-liquid
T_{wa}	=	transfer factor of radon from pore water to pore air

The T_{wa} transfer factor from pore water to pore air is obtained from combining Equation (3) with a similar rate balance equation for radon in pore water (8). The derivatives of the atmospheric and soil air pressures are obtained by solving the following equation using the same approach as for the radon transport equation:

$$K\left[\frac{d^2P}{dr^2} + \frac{1}{r}\frac{dP}{dr} + \frac{d^2P}{dz^2}\right] = \frac{dP}{dt} \tag{4}$$

The boundary conditions for Equation (4) are the indoor air pressure applied to the inside surface of the dwelling floor, and the outdoor air pressure (typically averaging zero) applied to the outdoor soil surface. If the dwelling is at a negative pressure compared to the outdoors, then air movement proceeds from the outdoor soil surface downward through the soil and then inward and upward towards the structure as shown in Figure 1. Radon entry into the slab-on-grade dwelling in Figure 1 is assumed to be through a perimeter crack, such as may occur between the slab and foundation footings.

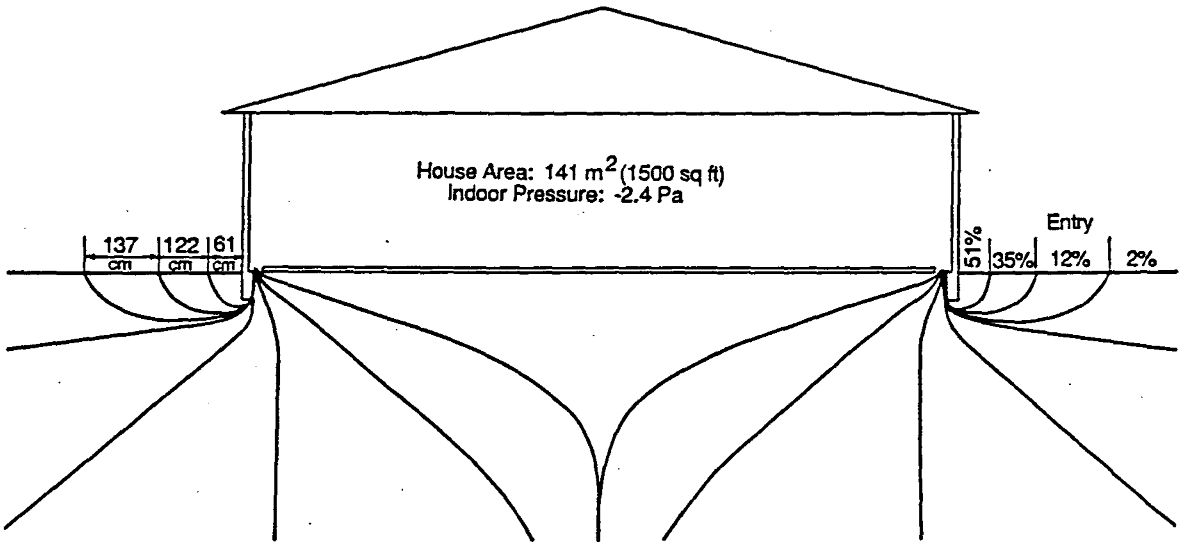

Figure 1. Flow lines and peripheral air entry locations for a structure on a 61-cm deep foundation in sandy soil ($K = 2.4 \times 10^{-7}$ cm^2).

After the pressure field is determined, RAETRAD solves the radon generation and transport equations to obtain values for the following parameters (3):

1. Radon concentration in soil air pores as a function of position.

2. Average radon concentration under the dwelling slab (if applicable).

3. Diffusive, advective, and total surface radon fluxes.

4. Radon entry rates through dwelling floors, walls, and cracks in contact with the soil.

5. Average indoor radon concentration.

6. Air entry rates from the soil.

7. Normalized radon entry rate.

The normalized radon entry rate is defined as the radon entry rate divided by the area-weighted average sub-slab radon concentration in the soil pores.

APPLICATION OF RAETRAD

The RAETRAD code was applied to the soils and soil conditions given in Table 2. A slab-on-grade structure was coupled to the soils as shown in Figure 1, and it was assumed that radon entered the dwelling through a perimeter crack between the 10-cm thick concrete slab and a 60-cm deep foundation footing. The dwelling is assumed to be at a -2.4 Pa pressure compared to the atmosphere. The radon emanation coefficient of the soil is 0.25. Other parameters used in the analyses are shown in Figure 1.

Normalized radon entry rates computed by RAETRAD for the dwelling on each of the SCS soils are shown in Figure 2. They increase with increasing soil permeability mainly for coarse-grained soils. The normalized entry rate becomes less dependent on permeability for permeabilities less than about 10^{-8} cm^2, because diffusion processes dominate the radon entry rate into the dwelling for the low-permeability soils. For these examples, the normalized radon entry rate varies from about 0.3 to 7 pCi/minute per pCi/liter.

Maximum soil radium concentrations can also be determined from the example analyses by assuming a maximum indoor radon concentration guideline and an indoor air exchange rate. A guideline of 2 pCi/liter and an exchange rate of 1 hr^{-1} applied to the example calculations gives the maximum soil radium concentrations shown in Figure 3. The maximum soil radium increases with decreasing soil permeability. Sandy soils permitted only 2-3 pCi/g radium before exceeding the 2 pCi/liter indoor radon concentration, while finer-grained soils could have 10-20 pCi/g due to their lower permeabilities and diffusion coefficients (Figure 3). Calculations were also made of the maximum soil radium concentrations for a layer of foundation fill material placed over the natural soil. Fill material properties generally obscured effects from the underlying soils when the fill layer thickness exceeded approximately 1 m. For thinner fill layers, high or low radium contents in the underlying soil affected the acceptable radium content of the fill material. As shown in Figure 3, the maximum soil radium for the fill material also becomes insensitive to the natural soil conditions for low-permeability fill materials (less than about 10^{-8} cm^2 permeability).

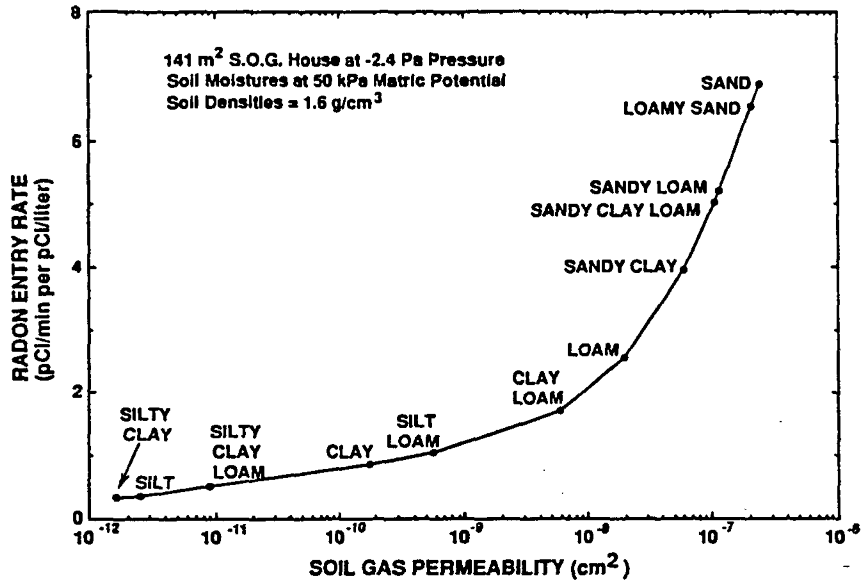

Figure 2. Normalized radon entry rates computed by RAETRAD for a slab-on-grade structure (Figure 1) on uniform soils defined in Table 2.

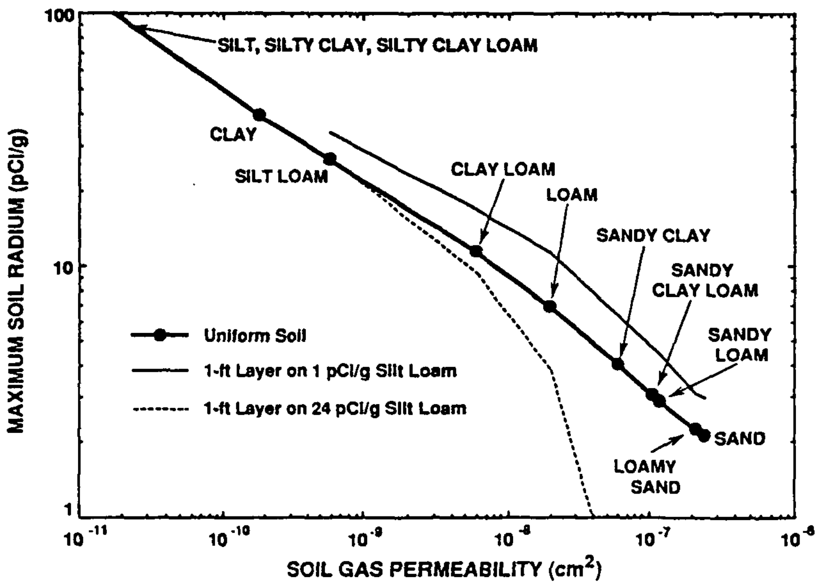

Figure 3. Maximum soil radium concentrations to maintain 2 pCi/liter radon in a slab-on-grade structure (Figure 1) on SCS soils that are uniform (solid line) or used for a 30 cm fill layer over a silt-loam base soil (broken lines). Soil properties are defined in Table 2.

Radon entry rates and maximum soil radium concentrations also vary according to the perimeter crack width. Figure 4 shows the variation of the radon entry rate with the perimeter crack width for a sandy soil. The perimeter crack width also may be used to approximate the effects of perimeter utility penetrations through the slab.

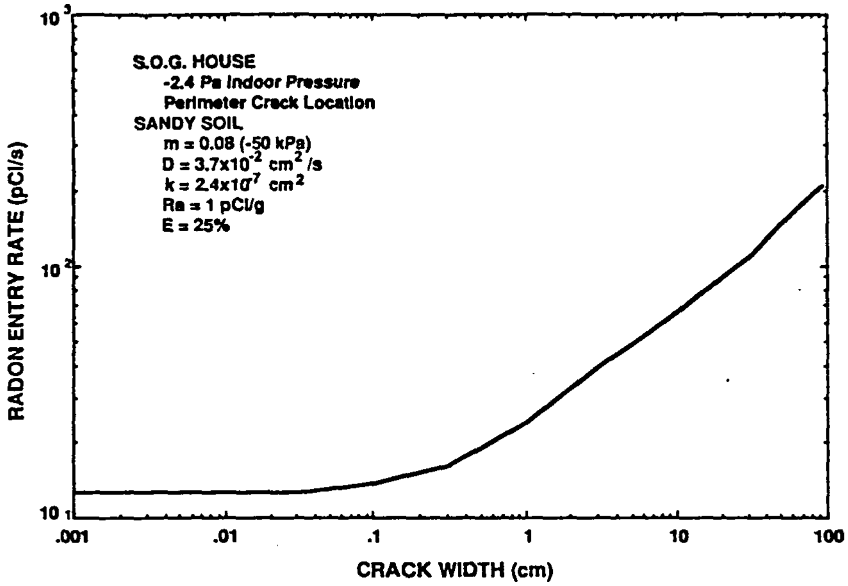

Figure 4. Variation of radon entry rates with the width of perimeter crack for the slab-on-grade structure (Figure 1) on SCS sandy soil.

As a benchmark for RAETRAD, an analysis was performed for a house-soil system in Florida for which some field data are available. The indoor radon concentration for a 203 m^2 slab-on-grade dwelling was measured to average about 10 pCi/liter.

The radium concentration in the top 30 cm of subslab soil is about 0.9 pCi/g, the soil moisture is about 15 percent of saturation, and the measured permeability is 8×10^{-7} cm^2. A subslab radon concentration of 4,200 pCi/liter indicates the presence of a deeper soil layer with elevated radium. This is represented by a 5 pCi/g soil radium layer beneath the top 31 cm layer characterized above. A radon emanation coefficient of 0.25 is also used in the analysis. The RAETRAD calculation gives a subslab radon concentration of 4,000 pCi/liter and an indoor radon concentration of 7 pCi/liter, for a house pressure differential of 1.0 Pa. The estimated indoor concentration is within 30 percent of the measured value of 10 pCi/liter.

ACKNOWLEDGEMENT

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