1991-27

RADON ENTRY MODELING - SLAB ON GRADE

by: Kirk K. Nielson
Vern C. Rogers
Rogers & Associates Engineering Corp.
Salt Lake City, Utah 84110-0330

ABSTRACT

Radon generation and transport into soils and subsequent entry into dwellings is a complex process requiring characterization of soil conditions, meteorological conditions as well as the structure. Radon entry into slab on grade dwellings has been modeled in the RAETRAD code and applied to conditions in florida as part of the Florida Radon Research Program. RAETRAD solves the two-dimensional radon balance and air pressure balance equations in cylindrical geometry. Key factors in the simplicity of RAETRAD are the simple correlations for predicting gas permeabilities and radon diffusion coefficients for the porous soil and house slab materials.

Use of RAETRAD reveals that diffusive transport effects are significant and may even dominate for typical long-term average house pressure differentials. Results of the calculations for a fixed indoor radon concentration reveals increasing limiting soil radium concentrations with decreasing foundation soil air permeabilities.

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

The Florida Department of Community Affairs (DCA) is developing radon protective standards for new construction (Sanchez et al. 1990; SBCCI 1990) that are to be integrated into a statewide uniform building code. The standards will help reduce public health risks from exposure to indoor radon (^{222}Rn). 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. This process has been modeled for slab on grade structures in Florida geological and environmental conditions as part of the technical support for the radon protection standards.

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 1990 identified radon diffusion as the dominant entry mechanism when foundation soil permeabilities ar less than $7x10^{-12}$ m^2. Rogers and Nielson 1990 also identified diffusion through concrete floors and the contiguous soil as a significant mechanism for entry for many soils under typical long-term average foundation pressure gradients. Loureiro et al. 1990 have modeled theoretical diffusive and advective radon transport through soils into swellings to estimate conditions when diffusion is insignificant. Consequently, radon entry modeling into dwellings must consider diffusive transport as well as advective transport.

THE RAETRAD MODEL

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) (Rogers and Nielson 1984) multiregion, one-dimension radon generation and transport code has been used widely to predict radon migration through porous media. RAETRAN (RAdon Emanation and TRANsport) (Nielson and Rogers 1989) 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) (Rogers and Nielson 1990), 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.

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:

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

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

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

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 (Rogers and Nielson 1991a). 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:

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

where

K = air permeability in porous material (cm^2).

The boundary conditions for Equation (2) 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.

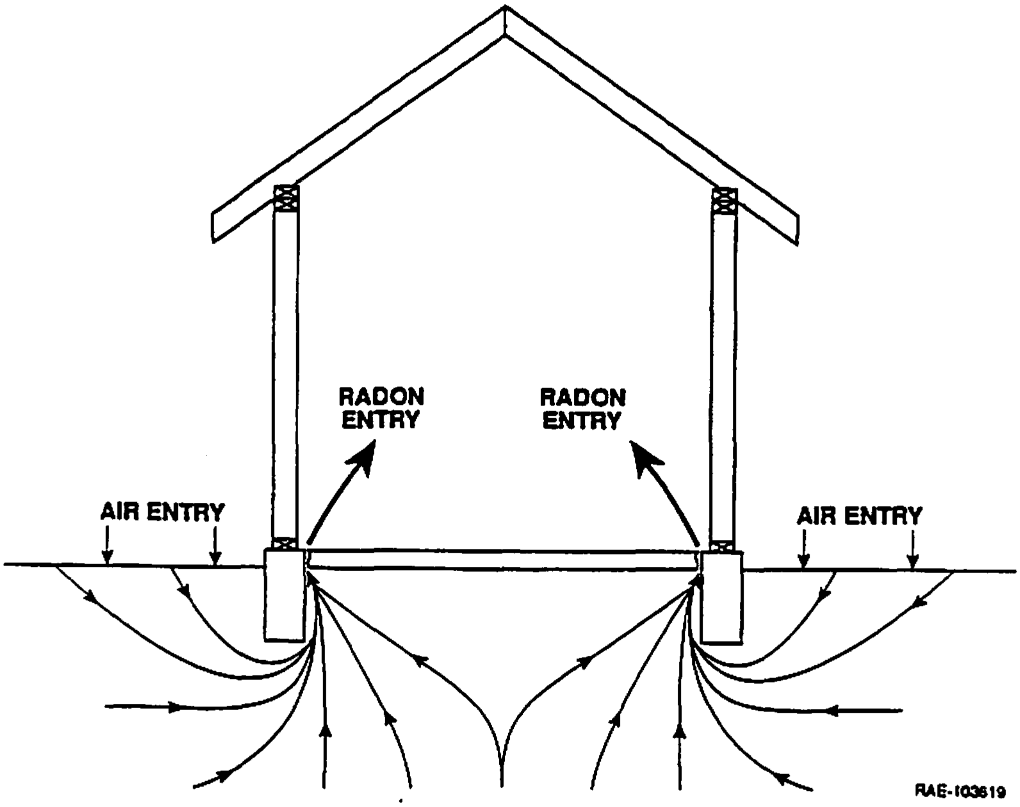

Figure 1. Flow lines and peripheral air entry locations for a structure.

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

1. Radon concentration in soil air pores as a function of position.
2. Average radon concentration under the dwelling slab.
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.

AIR PERMEABILITY AND RADON DIFFUSION COEFFICIENT CORRELATIONS

Two key parameters that strongly influence radon transport through soils and subsequent dwelling entry are the radon diffusion coefficients and the soil air permeabilities. Simple correlations for the radon diffusion coefficient have been developed and have been widely used (Nielson et al. 1988, NRC 1989). The diffusion coefficient correlation that is incorporated in RAETRAD is (Rogers and Nielson 1991b):

$$D = D_a p \exp(-6mp - 6m^{14p}) \tag{3}$$

where

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

The soil air permeability correlation that was incorporated into RAETRAD is (Rogers and Nielson 1991b):

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

where

d_a = arithmetic average particle diameter (cm).

Equations (3) and (4) 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) (Dunn et al. 1980). Furthermore, the appropriate soil moisture near a dwelling can be estimated from the soil classification and soil matric potential (Nielson and Rogers 1990).

APPLICATION OF RAETRAD

As an example of the use of RAETRAD, soil air permeabilities and radon diffusion coefficients were estimated for the broad range of soils defined by the U.S. Soil Conservation Service Classifications. A matric potential of 5×10^4 Pa was selected as a reasonably conservative dry-side average for conditions throughout Florida. These data are given in Table I. The RAETRAD code then was applied to the soils and soil conditions given in Table I. A slab-on-grade structure was coupled to the soils. Model dwelling parameters are given in Table II. 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.

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 model calculations 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 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).

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.

TABLE I. 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	3.7×10^{-2}	2.4×10^{-7}
Loamy Sand	0.173	3.0×10^{-2}	2.1×10^{-7}
Sandy Loam	0.375	1.8×10^{-2}	1.2×10^{-7}
Sandy Clay Loam	0.390	1.7×10^{-2}	1.1×10^{-7}
Sandy Clay	0.481	1.3×10^{-2}	5.9×10^{-8}
Loam	0.591	8.0×10^{-3}	1.9×10^{-8}
Clay Loam	0.667	4.9×10^{-3}	5.8×10^{-9}
Silt Loam	0.771	1.8×10^{-3}	5.8×10^{-10}
Clay	0.808	1.1×10^{-3}	1.8×10^{-10}
Silty Clay Loam	0.888	2.5×10^{-4}	8.9×10^{-12}
Silt	0.917	1.3×10^{-4}	2.5×10^{-12}
Silty Clay	0.923	1.1×10^{-4}	1.6×10^{-12}

---

*At 1.6 g/cm^3 bulk dry density; 0.407 porosity.
†Estimated from Equation (2).
‡Estimated from Equation (4).

TABLE II. MODEL DWELLING PARAMETERS FOR CALCULATING INDOOR RADON ENTRY RATES

House area	141 m
House Volume	344 m^3
House air exchange	$2.8 \times 10^{-4}\ s^{-1}$ ($1\ h^{-1}$)
Indoor radon	74 Bq m^{-3} (2 pCi^{-1})
House pressure	-2.4 Pa
Floor thickness	0.1 m
Concrete floor porosity	0.2
Concrete slab permeability	$1 \times 10^{-16}\ m^2$
Concrete slab diffusion coefficient	$5 \times 10^{-8}\ m^2\ s^{-1}$
Concrete slab radium	11 Bq kg^{-1} (0.3 pCi g^{-1})
Outdoor radon	0 Bq m^{-3}
Floor effective crack width	0.01 m
Footer width	0.3 m
Footer depth	0.9 m
Footer permeability	$1 \times 10^{-15}\ m^2$
Footer diffusion coefficient	$5 \times 10^{-8}\ m^{-2}\ s^{-1}$
Footer porosity	0.407
Footer radium	11 Bq kg^{-1} (0.3 pCi g^{-1})

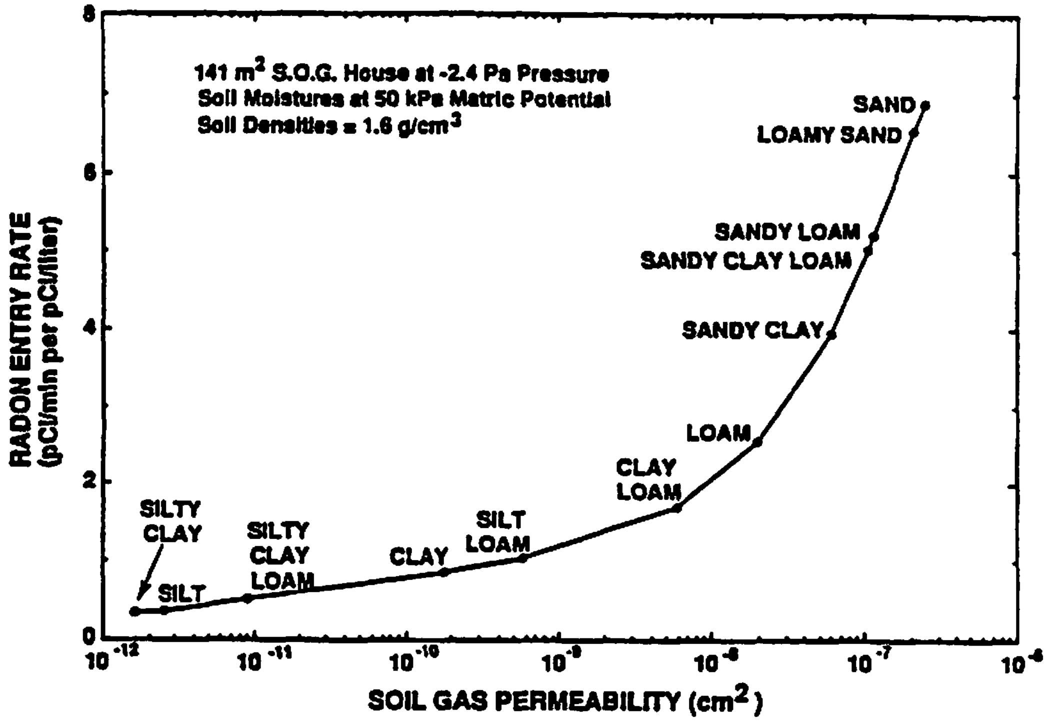

Figure 2. Normalized radon entry rates computed by RAETRAD for a slab-on-grade structure (Figure 1) on uniform soils.

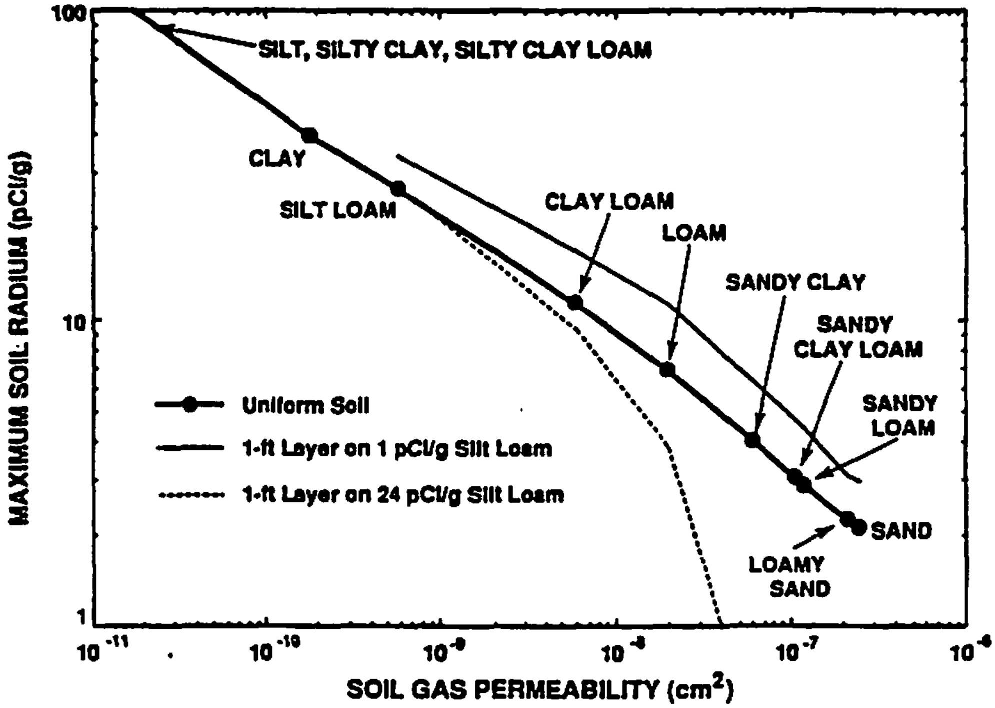

Figure 3. Maximum soil radium concentrations to maintain 2 pCi/liter radon in a slab-on-grade structure (Figure 1) on SCS soils that are uniform (solid line) or used for 1 30 fill layer over a silt-loam base soil (broken lines).

REFERENCES

Dunn, I.S., Anderson, L.R., and Kiefer, F.W. Fundamentals of Geotechnical Analysis. New York: Wiley & Sons, 1980.

EPA. A Citizen's Guide to Radon. Washington, D.C., U.S. Environmental Protection Agency and U.S. Department of Health and Human Services, report *OPA-86-004*, 1986.

Loureiro, C.O., Abriola, L.M., Martin, J.E., and Sextro, R.G. Three-Dimensional Simulation of Radon Transport Into Houses with Basements Under Constant Negative Pressure. *Environmental Science and Technology* 24:1338-1348, 1990.

Nielson K.K., and Rogers, V.C. Radon Transport Properties of Soil Classes for Estimating Indoor Radon Entry. Proc. 29th Hanford Symposium on Health and the Environment, Richland, Washington, October 15-19, 1990.

Nielson, K.K. and Rogers, V.C. Radon Generation, Absorption and Transport in Porous Media -- The RAETRAN Model. *EOS*, 70, 497 (1989).

Nielson, K.K., Rogers, V.C., and Gee, G.W. *Soil Science Society of America Journal*, 52, 898 (1988).

Rogers, V.C. and Nielson K.K. Correlations for Predicting Air Permeabilities and ^{222}Rn Diffusion Coefficients of Soils. *Health Physics*, 61:225-230, 1991a.

Rogers, V.C. and Nielson, K.K. Multiphase Radon Generation and Transport in Porous Materials. *Health Physics*, 60:807-815; 1991b.

Rogers, V.C. and Nielson, K.K. Benchmark and Application of the RAETRAD model. In: The 1990 International Symposium on Radon and Radon Reduction Technology. Vol. 3, *EPA/600/9-90/005C*, U.S. Environmental Protection Agency, Washington, D.C., 1990.

Rogers, V.C. and Nielson, K.K. Radon Attenuation Handbook for Uranium Mill Tailings Cover Design. U.S. Nuclear Regulatory Commission report, *NUREG/CR-3533*, April 1984.

Sanchez, D.C., Dixon, R. and Williamson, A.D. The Florida Radon Research program: Systematic Development of a Basis for Statewide Standards. Proceedings of the 1990 International Symposium on Radon and Radon Reduction Technology, Atlanta, GA, February 1990.

Tanner, A.B. The Role of Diffusion in Radon Entry Into Houses. In: The 1990 International Symposium on Radon and Radon Reduction Technology. Vol. 3, *EPA/600/9-90/005C*, U.S. Environmental Protection Agency, Washington, D.C., 1990.

U.S. Nuclear Regulatory Commission Regulatory Guide 2.64. Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers, June 1989.