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Project Summary

Site-Specific Characterization of Soil Radon Potentials

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The Florida Department of Community Affairs is developing construction standards for incorporating radon-resistant building features in areas of elevated soil radon potential. Although statewide maps have been developed to show the regions where the features are required, there is also a need for simple methods to assess the radon potential of specific building sites. The report gives results of the development and evaluation of a mathematical basis for using simple site measurements to estimate soil radon potential. The approach utilizes a lumped-parameter model of radon generation and entry. Site-specific soil radon potential is defined as the rate of radon entry into a reference house, consistent with previous definitions used for the statewide radon maps. The model shows that, in the simplest case, soil radon potential is reduced to a simple function of two measurable parameters: the soil surface radon flux and the soil moisture (as a fraction of saturation). The flux gives the radon generation rate of the soil profile, and the moisture is a surrogate for radon transport parameters, including air permeability and radon diffusion coefficient.

Field tests of soil radon flux and moisture measurements were conducted at 26 house sites in Polk County, Florida, to evaluate their utility in predicting site-specific radon potentials. Radon fluxes also were measured from bare concrete surfaces, where they were accessible, to better estimate non-advective radon entry rates. Gamma-ray intensity also was measured in the yards, but it failed to correlate well with the radon fluxes. The measured soil radon fluxes and moistures showed localized trends that compared well with mapped radon potentials in some cases, but not in others. For the 26 sites, the radon potentials estimated from site-specific measurements averaged twice the potentials from the generalized radon maps. A large geometric standard deviation (GSD = 4.7) was associated with individual sites.

The site-specific estimates also were compared with prior indoor radon measurements. When the reference-house ventilation rate was attributed to the houses, the calculated/measured radon ratios averaged 1.06 ± 0.72. Slightly greater bias but improved precision (0.87 ± 0.56) was obtained using concrete-surface radon flux measurements in addition to the site radon potential measurements. The empirical measurements suggest that the precision of site-specific evaluations is marginal, leaving an uncertainty of about a factor of 2 in site-specific estimates. Although potentially useful for some applications, the site-specific measurements studied here do not greatly improve the radon potential estimates over the regional estimates already available from radon maps.

This project summary was developed by the National Risk Management Research Laboratory's Air Pollution Prevention and Control Division, Research Triangle Park, NC, to announce key findings of the research project that is

fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Radon (^{222}Rn) gas generated by naturally occurring radium (^{226}Ra) in soils can enter buildings through their foundations. With elevated entry rates and inadequate ventilation, radon can accumulate indoors to levels that pose significant risks of lung cancer with chronic exposure. The Florida Department of Community Affairs (DCA) and the EPA have jointly developed radon-resistant building standards to help reduce radon entry from soils. The standards address improved understructure sealing, altered air pressures, and other engineered features developed under the DCA's Florida Radon Research Program (FRRP). Statewide radon potential maps also have been developed to identify regions where the radon-resistant features are needed. This report examines the feasibility of estimating soil radon potentials from simple measurements to help determine more accurately the radon protection needed at a specific building site.

Soil radon potential is defined using the same reference house as was used previously for the maps. A lumped-parameter model simplifies the theoretical basis, and indicates minimum parameters and surrogates for characterizing the site radon potential. Field tests of the methods include measurements of selected parameters and surrogates at 26 house sites that were already being studied under the FRRP. Soil radon potentials estimated from the field measurements were compared with mapped regional estimates, and were also compared with data from measured radon levels in the houses at the sites.

Previous Estimates of Radon Potential

Radon indices and simple models have been proposed previously for estimating soil radon potential. These have depended variously on house ventilation rates, emanating soil radium concentrations, soil air permeability, soil radon concentrations, soil porosity, soil radon migration distance, soil water permeability, and soil equivalent uranium concentration. A more detailed approach numerically analyzes advective radon transport into houses. This approach utilizes soil air permeability, soil radon generation rate (radium concentration, density, and radon emanation coefficient), foundation crack geometry, and house air pressures. It defines radon potential as the rate of radon entry into a house in picocuries per second. A review of site measurement methods shows the need for detailed radon source and transport measurements, including soil density, particle size, texture classification, moisture, permeability, diffusion coefficient, radon emanation coefficient, radium concentration, and radon concentration profiles. These properties are used in a radon source potential index that depends also on site drainage conditions, site groundwater conditions, and site climatology.

A more detailed modeling approach characterizes radon entry from house and soil parameters, including radon movement by both advection and diffusion. Using the RAETRAD model, this approach uses detailed soil radium distributions; radon emanation fractions; and soil density, moisture, permeability, and diffusion coefficients with house air pressure and crack distributions. Soil radon potential is defined on an annual basis (in millicuries per year) to emphasize the long-term average nature of equivalent steady-state radon entry rates and exposures.

Reference House

The site-specific soil radon potential is defined as the annual rate of radon entry from soils into a hypothetical reference house that is defined to represent Florida slab-on-grade houses. The reference house provides a constant, typical interface between the indoor exposure volume and the varied soil conditions that control radon potential. Although house and soil parameters cannot be completely separated for modeling radon entry, the use of a reference house avoids the large differences in radon potential that would otherwise result from differences in house design, construction, ventilation, and occupancy.

The present reference house corresponds to the house defined previously for radon potential mapping. The house is an 8.6 x 16.5 (28 x 54 ft), slab-on-grade single-family dwelling. Its volume is based on that of a median U.S. family dwelling, and is similar to that of typical Florida houses. Its area is estimated from its volume using a nominal 2.4-m (8-ft) ceiling height. Its ventilation rate is about half the normal median U.S. house ventilation rate, based on measurements in Florida houses. A perimeter floor crack approximates a floating-slab shrinkage crack to permit advective radon entry from pressure-driven air flow. The stem wall and footing penetrate 61 cm (2 ft) into the natural terrain, and enclose an additional 30 cm (1 ft) of above-grade fill soil beneath the slab. The indoor pressure is -2.4 Pa, typical of pressures from thermal and wind-induced pressures in U.S. houses, and also typical of the average pressures measured in 70 Florida houses under passive conditions. Concrete slab air permeabilities, radon diffusion coefficients, and other properties are estimated from data measured on Florida floor slabs.

Soils beneath the reference house are modeled as uniform, isotropic soils with a bulk density of 1.6 g cm^{-3}. A 30-cm layer of sandy fill soil is located beneath the slab, below which the site-specific soil is represented by its textural class and its associated water content at a matric potential of -30 kPa. From these properties, the soil air permeability and radon diffusion coefficient are calculated from empirical relationships.

Lumped-Parameter Model

The mathematical definition of site-specific radon potential utilizes a lumped-parameter model, which is based in turn on the detailed RAdon Emanation and TRAnsport into Dwellings (RAETRAD) model. The lumped-parameter model was developed primarily from RAETRAD sensitivity analyses, which identified the most significant house and soil parameters. The analyses suggested simplified approximations to express average indoor radon levels as a function of radon source strength and house radon resistance and ventilation parameters. Radon source strength was defined in terms of the sub-slab radon concentration. House radon resistance was defined from floor openings, pressure driving forces, and slab diffusivity. The lumped-parameter model uses a simplified relation between indoor radon and the radon entry rate:

$$C_{net} = C_{in} - C_{out} = 3.6\, Q / (\lambda_h V_h) \quad (1)$$

where
- C_{net} = net indoor radon concentration from sub-slab sources (pCi L^{-1})
- C_{in} = total indoor radon concentration (pCi L^{-1})
- C_{out} = outdoor background radon concentration (pCi L^{-1})
- 3.6 = unit conversion (pCi L^{-1} h^{-1} per pCi m^{-3} s^{-1})
- Q = radon entry rate (pCi s^{-1})
- λ_h = rate of house ventilation by outdoor air (h^{-1})
- V_h = h A_h = interior house volume (m^3)
- h = mean height of the interior volume of the house (m)
- A_h = house area (m^2).

The radon entry rate in equation (1) is defined in the lumped-parameter model for the reference house as:

$$Q = A_h C_{sub} [f_c (v_{dc} - v_{ac} \Delta P) + v_{slab} + v_{sc}] \quad (2)$$

where C_{sub} = sub-slab radon concentration (pCi L^{-1})
f_c = area of floor openings as a fraction of total floor area (dimensionless)
v_{dc} = equivalent velocity of radon diffusion through floor openings, dependent on the radon diffusion coefficient of the soil (0.0143 mm s^{-1})
v_{ac} = equivalent velocity of radon advection through floor openings, dependent on the air permeability of the soil (mm s^{-1} Pa^{-1}) = exp(-3-0.045e^{6S})
S = soil water saturation fraction (dimensionless)
ΔP = indoor air pressure (Pa)
v_{slab} = equivalent velocity of radon diffusion through the slab, dependent on the radon diffusion coefficient of the slab (mm s^{-1}) = 2.9×10^{-7} exp(11.4W)
W = water/cement ratio of the slab concrete (dimensionless)
v_{sc} = radon entry velocity adjustment for house size and crack location (mm s^{-1}) = $3.5 \times 10^{-5} (x_{crk}/x_h) + 4.6 \times 10^{-5}/x_h$
x_{crk} = location of dominant floor crack opening from house perimeter (m)
x_h = house width (m).

Only the parameters C_{sub} and v_{ac} in equation (2) are site-dependent; therefore reference-house values were substituted for all of the others, leading to a simplified relationship for defining the site-specific soil radon potential:

$$Qss = 1.68 C_{sub} [0.019 + \exp(-3 - 0.045\, e^{6S})] \quad (3)$$

where Q_{ss} = site-specific soil radon potential (pCi s^{-1}).

Although the indoor radon concentration for a reference house can be directly estimated from Q_{ss} in equation (1), indoor radon concentrations for specific houses are better estimated by using as many defining parameters in the lumped-parameter model as are known. Using the definitions associated with equation (2) to define the radon entry rate for equation (1), indoor radon concentrations can potentially be better estimated from house-specific data.

Surrogate Estimates of Model Parameters

Many model parameters are difficult to measure directly, and therefore are seldom quantified. However, most can be estimated from related parameters that are directly measurable. The site-specific value for the soil water saturation fraction (S) can be readily estimated from measured soil moisture contents as:

$$S = 0.01 M_v / \in = 0.01 p M_w / \in \quad (4)$$

where M_v = soil moisture (volume percent)
$\in$ = total soil porosity (dimensionless) = 1 - p/p_g
p = soil bulk dry density (g cm^{-3})
p_g = soil specific gravity (nominally 2.7 g cm^{-3})
M_w = soil moisture (dry weight percent).

Using the reference-house slab parameters and assuming that the radon-generating soil profile is deep (unconstrained by a water table or bedrock), C_{sub} can be approximated as:

$$C_{sub} = (90 + 5{,}900\, J_s) / (1.13 + 35 \sqrt{D_s}) \quad (5)$$

where J_s = radon flux at the soil surface (pCi m^{-2} s^{-1})
D_s = radon diffusion coefficient of the soil pore space (cm^2 s^{-1}).

Field Tests

Sensitivity analyses with the lumped-parameter model have demonstrated a relatively strong dependence of radon potential on C_{sub},λ_h, W, ΔP, S, h, and f_c, and a smaller dependence on v_{dc}, x_h, x_{crk}. Field measurements therefore were directed at quantifying the important parameters. Where the parameters could not be adequately measured, default values typical of the reference house were used.

Site-specific field measurements were conducted during March 17-22, 1993, to evaluate the sensitivity, precision, and utility of selected parameters for estimating site-specific radon potential. The measurements were conducted in the yards of 26 houses in Polk County, FL, for which indoor radon data were already available. The protocol at each site included measurements on all four sides of the house of soil moisture, gamma-ray activity, and radon flux. In addition, radon flux was measured from a bare concrete surface where suitable locations were accessible.

The site protocol concentrated on rapid, inexpensive measurements that could most directly estimate the site-specific radon potential, Q_{ss}. As indicated by equation (3), the sub-slab radon concentration (C_{sub}) and the soil water saturation fraction (S) were of primary interest. The soil moisture, M_v, was measured using a time-domain reflectometer probe, which characterized the top 30 cm of soil. The value of S was calculated from equation (4), assuming a soil porosity of $\in$=0.407.

Although prior FRRP measurements of C_{sub} were planned, these data were generally unavailable, and consisted of only single measurements in a few cases. Therefore, the soil surface radon flux measurements at each site became the primary estimator of C_{sub}, using equation (5) as the basis. The flux measurements were made using the small-canister method, which gives equivalent results to EPA Method 115. The radon fluxes were sampled over a 24-hour period, after which the charcoal canisters were retrieved, sealed, and submitted for laboratory assay of radon activity. The value of D_s required for calculating C_{sub} was estimated from the same porosity and moisture using the predictive correlation:

$$D_S = D_o \in \exp(-6 \in S - 6 S^{14\in}) \quad (6)$$

where D_o = diffusion coefficient for radon in air (0.11 cm^2 s^{-1}).

The radon flux measurements on bare concrete slab surfaces, when accessible, estimated more directly the radon entry through the intact portions of the concrete slabs. The flux measurements directly estimate v_{slab} for use in equation (2) as:

$$v_{slab} = J_{slab} / C_{sub} \quad (7)$$

where J_{slab} = radon flux from the concrete slab surface (pCi m^{-2} s^{-1}).

The small charcoal canisters were found to have marginal sensitivity for the lower fluxes from concrete surfaces. Therefore, an alternative method used approximately 230 cm^3 of granular activated carbon spread over a paper napkin mounted in a 30-cm diameter wooden compression frame and covered with a polyethylene sheet. The frame was sealed to the concrete surface with rope caulk. After a 24-hour deployment, the charcoal was retrieved and sealed into metal cans for assay of radon. The method was calibrated against the small-canister samplers using a thin-sample radon source. The large-area method measured fluxes equal to those from small canisters, but with 13 times greater sensitivity.

The gamma ray measurements were intended for possible correlation with the soil radon flux measurements, or as potential surrogates for surface soil radium concentration. The measurements were made 1 m above the soil surface using a 5 x 5-cm sodium iodide scintillation probe.

Test Results and Analysis

The site-specific measurements were first analyzed for simple empirical correlations with the measured soil radon fluxes. The measurements also were used to predict site-specific radon potentials, which in turn were compared with the FRRP indoor radon concentration data. The gamma ray measurements showed greater differences among the different house sites than the radon flux measurements, which in turn showed greater differences than the moisture measurements. All of the variations among house sites were significant at the $p<0.01$ level in analyses of variance.

Since radon flux expectedly varies with radium in uniform soils, a linear flux vs. gamma relationship was sought by least-squares linear regressions. The regression on individual gamma intensity measurements (γ in $\mu R\ h^{-1}$) gave a correlation coefficient of only r = 0.26 for the fitted line $J_s = -0.2 + 0.146\ \gamma$. A regression corresponding to $J_s = 0.23\ \gamma^{0.62}$ was obtained from log-transformed data. The regressions were strongly affected by some low flux points at high gamma intensity that were associated with wet soils. The high uncertainty in the flux vs. gamma relationship limits the usefulness of gamma intensity as a surrogate for soil radon flux.

A similar regression of soil radon flux on soil moisture gave similar scatter. This regression on individual moisture measurements had a correlation coefficient of r = 0.26 for the fitted line $J_s = 6.9 - 0.268M_v$. Log-transformed data gave the line $J_s = 28\ M_v^{-1.18}$. Low fluxes were associated with high soil moisture levels.

Measured radon fluxes also were regressed on $\gamma \cdot \sqrt{D_s} \cdot \tanh(x_s \sqrt{\lambda / D_s})$, where λ is the radon decay constant ($2.1 \times 10^{-6}\ s^{-1}$) and x_s is the soil thickness dominating the flux (i.e., above the water table). Since γ is a surrogate for radium concentration, this lumped parameter is the theoretical surrogate for radon flux, J_{sur}, for uniform soil. The measured radon fluxes were regressed on J_{sur}, which utilized radon diffusion coefficients from equation (6) and measured moistures. The regression had an improved correlation coefficient of r = 0.55 for the fitted line $J_s = -0.85 + 1.51\ J_{sur}$. Log-transformed data gave the least-squares fitted line $J_s = 0.6\ J_{sur}$. Although this relation better predicts radon flux, it still exhibits considerable uncertainty, which limits its potential use in predicting radon flux.

Estimation of Site Radon Potentials

Site-specific soil radon potentials were estimated using equation (3). Measured soil moistures were used to determine S from equation (4), and measured radon fluxes were used to determine C_{sub} from equation (5). The calculated site-specific soil radon potentials were averaged by neighborhood groupings for area-based comparisons with the mapped soil radon potentials. Figure 1 illustrates the resulting geometric means and geometric standard deviations, and gives side-by-side comparisons with the median mapped radon potentials. For illustration purposes, average error bars also were applied to the three houses not associated with other neighborhood groupings. As illustrated, the Q_{ss} values were higher than the mapped radon potentials (Q_{map}) in six of the ten comparisons. In statistical analyses of the seven comparisons involving multiple houses, the Q_{ss} values averaged 0.8 standard deviations higher than the Q_{map} values. This average bias is not significant ($p<0.41$). The geometric mean of all 27 ratios of Q_{ss}/Q_{map} was 2.02, with a geometric standard deviation of 4.7 (GSD of the mean is 1.35). The positive bias in Q_{ss} may result in part from radon flux sampling near the houses, which can increase

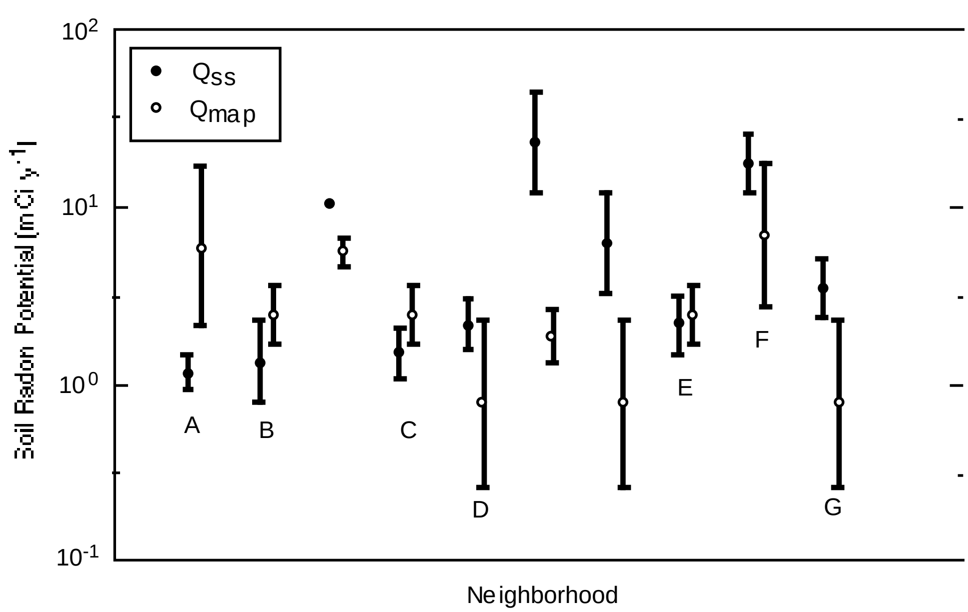

Figure 1. *Comparison of site-specific and mapped soil radon potential distributions for seven neighborhood groupings (A-G) and three isolated houses.*

the flux compared to an open-field sample that is away from the house foundation.

Comparison of Soil Radon Potentials with Indoor Radon Data

Indoor radon concentrations were estimated from the soil radon potential measurements for comparison with the FRRP indoor radon data. The indoor radon concentrations were estimated from equation (1) using the reference-house ventilation rate (λ_h = 0.25 h^{-1}) with individual estimates of house volumes. The ratios of calculated/measured indoor radon concentrations averaged 0.94 ± 0.65 for the 13 slab-in-stem-wall houses and 1.18 ± 0.80 for the 13 monolithic-slab houses. The overall average ratio for all 26 houses was 1.06 ± 0.72. Despite the relatively large scatter, this comparison demonstrates close average agreement of calculated and measured radon concentrations.

A separate comparison also utilized the measured radon fluxes from concrete surfaces, J_{slab}. Using equation (7), the fluxes defined v_{slab}, which was used in equation (2) with reference-house values for the other parameters. The ratios of calculated/measured radon concentrations averaged 0.97 ± 0.64 for the 10 slab-in-stem-wall houses, and 0.69 ± 0.35 for the five monolithic-slab houses where concrete surface fluxes were measured. The overall average ratio for all 15 houses was 0.87 ± 0.56, compared to 1.18 ± 0.89 for the corresponding houses by the previous approach. The lower variation from using the concrete fluxes shows that they improve the estimate of radon transport through slabs over the generic assumption of equation (2). This approach has slightly larger biases, but significantly improves the precision over the previous approach.

Discussion and Conclusions

The analyses in this report demonstrate a theoretical basis for measuring site-specific radon potentials from a variety of potential surrogate parameters. Although radon flux and soil moisture were the primary parameters evaluated, others (e.g., soil radium, soil radon, soil air permeability, and soil density) may also provide useful results. The flux and moisture measurements were chosen for their simplicity and low cost. However, their marginal precision leaves an uncertainty of about a factor of 2. This uncertainty can compromise the basic purpose of site-specific measurements, which is to reliably determine the potential for elevated radon at a particular building site.

The need for better precision and accuracy may require other measurements. For example, soil radium profiles measured from borehole samples support more detailed model analyses that determine radon potentials with greater precision and accuracy. Although more costly, radium profile measurements have demonstrated model and measurement agreement within 10-20%.

If site-specific measurements are considered for construction decisions, the planning should consider measurement costs, radon control costs, measurement uncertainty, and radon control uncertainty. Ample design safety margins should allow for measurement and control uncertainties. The safety margins also give benefits of reduced health risk from lower radon levels, thereby serving a greater purpose than simply assuring attainment of a ≤ 4 pCi L^{-1} indoor radon goal.

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The complete report, entitled "Site-Specific Characterization of Soil Radon Potentials," (Order No. PB96-140553; Cost: $17.50, subject to change) will be available only from:
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