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Project Summary

Site-Specific Protocol for Measuring Soil Radon Potentials for Florida Houses

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The full report describes a protocol for site-specific measurement of radon potentials for Florida houses that is consistent with existing residential radon protection maps. The protocol gives further guidance on the possible need for radon-protective house construction features. In applying the test results, the user should also consider the relative costs of using conservative radon controls and the EPA guidance on further reducing radon levels even in the range below 4 pCi L^{-1}.

The measurements included in the protocol were selected from sensitivity analyses of radon entry into the same reference house as was used to develop the radon protection maps. The sensitivity analyses also used the same RAdon Emanation and TRAnsport into Dwellings (RAETRAD) model, providing a common basis to that of the maps. The sensitivity analyses identified radium concentration, soil layer depth, soil density, soil texture, and water table depth as the independent parameters dominating indoor radon. Radium concentration and water table depth were most important. Soils up to 2.4 m deep contributed to indoor radon in uniform-radium scenarios, and soil layers about 0.6 m thick significantly affected radon in cases of nonuniform radium distributions.

A conservative upper limit for radon potentials was defined as the 95% confidence limit for radon in the reference house, corresponding to the radon protection map definition. The number of samples needed to represent a site was determined from equivalent regional map precisions to be 20 samples per 4,000 m^2 (1 acre). The samples are taken at four depth increments extending to 2.4 m. Equivalent precisions for a smaller parcel of land can use fewer total samples.

The site-specific protocol involves drilling five boreholes in each 4,000 m^2 parcel of land. Twenty soil samples obtained from the borings are used for radium measurements. The soil borings are also used for density and textural estimates unless default values are chosen. A soil radon measurement detects the potential presence of anomalous elevated-radium materials at depth. The site water table depths are defined from soil survey data or site observations. The site measurements are analyzed by a special-purpose computer code called RAETRAD-F to determine the upper limit for indoor radon concentrations in the reference house. Using the same category definitions as for the residential radon protection map, the RAETRAD-F code determines whether the site is in the low, intermediate, or elevated map category for radon protection purposes.

This Project Summary was developed by EPA's 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

The Florida Department of Community Affairs (DCA) has developed prescriptive building standards to reduce radon-related health risks. The standards require passive radon barriers and active sub-slab ventilation to reduce radon entry from soils that can cause elevated radon levels. Regions requiring these radon controls are identified by radon protection maps that show where soils require no special controls, passive radon controls, or passive and active radon controls. Despite the convenience and low cost of using the maps, it is sometimes desirable to directly measure the radon potential category of a site. Although not generally required, site-specific analyses can give valuable guidance on alternative planning or anomalous site conditions. Alternative planning decisions should also consider the relative costs of using conservative radon controls versus testing, as well as the EPA guidance on further reducing radon levels even in the range below 4 pCi L^{-1}.

The full report builds on a previous study of methods for measuring site-specific radon potentials as a consistent alternative to the radon protection map. It examines more closely the fundamental parameters controlling radon potential and identifies from model simulations the minimum measurements to characterize radon potential. The measurement requirements are used to define a field sampling and measurement protocol for characterizing site radon potentials with the appropriate level of sampling and replication. The measurements are analyzed by the RAETRAD model to find a reference-house radon potential that is consistent with the residential radon protection map.

Model Simulations

Model simulations of radon generation and movement from soils into houses were used to estimate the dependence of indoor radon levels on different site parameters. The simulations focused on long-term average values to avoid the temporal radon fluctuations from varying soil and house conditions. Radon potentials for open land used the same reference house and approach as the soil radon potential maps to remove house variables from the definition of radon potential. The hypothetical reference house was simulated on the individual soil profiles that occur in different regions, with radon generation and movement from the soils into the reference house. This approach determines the geographic soil contributions to indoor radon without the complicating effects of individual house properties.

The radon simulations also used soil and geology definitions that were consistent with the prior radon map analyses. For example, soil radium distributions were defined to be uniform throughout the strata in an upper layer about 2.5 m thick, and they were also defined to be uniform throughout a lower, geology-dominated zone that was also about 2.5 m thick. Soil water distributions throughout both zones were determined from drainage properties and water table depths.

The RAETRAD model was used to simulate radon generation and transport from the soil profiles into the reference house. RAETRAD is a steady-state, numerical-analytical computer code that simulates (a) radon generation and decay in soil regions around a house and in the house understructure (e.g., floor slab, footings); (b) diffusive and pressure-driven advective movement of radon through the soils and the house understructure; and (c) radon accumulation in a single-chamber house. RAETRAD's multiphase radon source and transport equations explicitly represent the solid soil particles, pore water, and air-filled pore space.

The reference house corresponds to the one used previously for radon potential maps, giving the site-specific analyses a common basis for estimating equivalent radon potentials. The house is a 143-m^2 (1,540-ft^2) rectangular, slab-on-grade structure with the approximate characteristics of Florida single-family dwellings. The dominant characteristics affecting indoor radon include the indoor air pressure, the indoor-outdoor air exchange rate, and the type and quality of foundation design and construction. The house has a floating-slab floor design, causing a shrinkage crack about 0.5 cm wide at the slab perimeter. Other properties of the house are listed in Table 1.

Surface and deep soils were defined for sensitivity analyses to have a sandy texture, a density of 1.6 g cm^{-3}, and a porosity of 0.407. Soil air permeability and radon diffusion coefficients were defined by RAETRAD from porosity, water content, and mean particle diameters using empirical correlations. Soil water contents were defined by the distance of each 30-cm soil layer above a 5.2-m deep water table. Soil radon emanation fractions were defined from an empirical trend with radium concentrations for consistency with previous radon map calculations.

Radon Sensitivity Analyses

Sensitivity analyses with the RAETRAD model determined which site parameters strongly affect radon potentials and which have smaller influences. Five main parameters were analyzed: soil texture, depth, radium, density, and water table depth. The depth parameter was applied only to radium distributions since water contents and their dependent parameters already varied with depth from the water table. For consistency with previous analyses, surface and geologic soil zones comprised the depth parameters for the radon simulations. Soil gas radon was also analyzed as a possible surrogate for deep-soil radium concentration to detect potential high-radium anomalies beneath the sampling depth range.

Sensitivity analyses determined the net radon concentration in the reference house while individually varying each of the five independent parameters. Analyses first were performed in which the entire soil column consisted of one of the 12 Soil Conservation Service (SCS) textural classifications. The resulting changes in calculated moistures, diffusion coefficients, and permeabilities caused decreased radon concentrations for the fine-textured soils, as shown in Figure 1.

A semi-quantitative approach helped interpret the sensitivity analyses. The relative sensitivity of each parameter was estimated from a log-log plot of radon versus the parameter of interest. Although the textural classifications had no direct numeric scale for such a plot, they were assigned integer values for comparison purposes, starting at 1 for sand and increasing to 12 for silt. The slopes of the lines on the plot, near the parameter value of interest, correspond to the power-curve ($y = ax^b$) dependence of each parameter. This approach helped rank the relative importance of each parameter for site-specific measurements. Figure 2 compares the sensitivity of soil texture with that of the other parameters.

The sensitivity to surface soil emanating radium concentrations was found to be highest, with a power-curve exponent of $b = 0.81$ at Ra·E = 1 pCi g^{-1} of emanating radium. As shown in Figure 2, this sensitivity increases at higher radium concentrations, approaching $b = 1.0$ and potentially raising indoor radon levels above 20 pCi L^{-1} as the emanating radium concentration approaches 5 pCi g^{-1}. The sensitivity of the deeper, geologic soil radium level is smaller, with an exponent of $b = 0.13$ at Ra·E = 1 pCi g^{-1} of emanating radium. Its sensitivity also increases at higher radium concentrations but remains lower than that for surface soils because of the decreasing sensitivity of radon sources that are farther from the house foundation.

The sensitivity to soil density is moderate at the low-density end of the curve in Figure 2, but it diminishes at higher soil densities. The strong dependence at low densities is dominated by the emanation

***Table 1**. Reference House Parameters Used in Radon Entry Simulations*

Parameter	*Value*	*Parameter*	*Value*
Footprint dimensions	*8.6 x 16.5 m*	*Slab water/cement ratio*	*0.55*
Interior volume	*350* m^3	*Floor slab thickness*	*10 cm*
External ventilation	*0.25* h^{-1}	*Floor slab porosity*	*0.22*
Floor crack width	*0.5 cm*	*Slab* ^{226}Ra *emanation*	*0.07 pCi* g^{-1}
Floor crack location	*Slab perimeter*	*Exterior footing depth*	*61 cm*
Fill soil thickness	*30 cm*	*Slab air permeability*	1×10^{-11} cm^2
Indoor air pressure	*-2.4 Pa*	*Slab Rn diffusion*	8×10^{-4} cm^2 s^{-1}

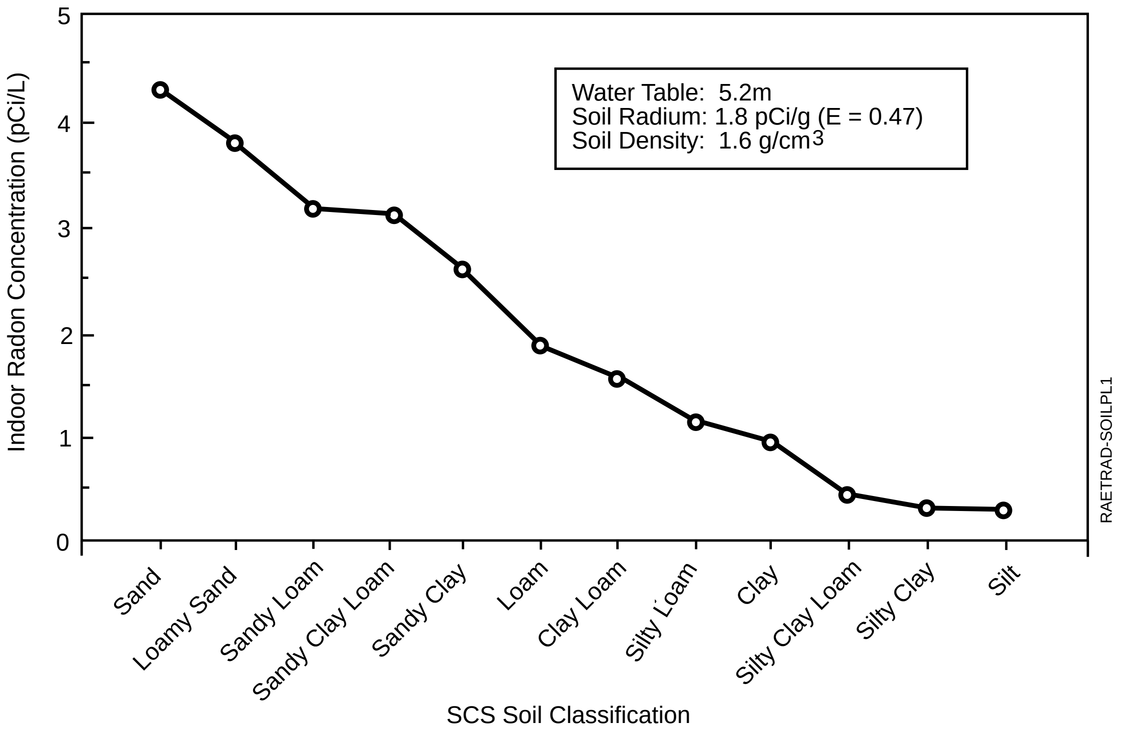

Figure 1. Sensitivity of indoor radon to soil textural class.

of radon into progressively smaller pore volumes, causing higher radon concentrations in soil pore spaces. At higher soil densities, however, the competing effects of reduced permeability and diffusion, caused by increased capillary water retention, reduce the rate at which radon escapes the pores to enter the reference house.

The sensitivity to water table depth is shown in Figure 2 to be strong for shallow water tables. However, the high sensitivity is unimportant in the shallow depth region because the water effectively blocks radon entry at high moistures. Water table sensitivity decreases to a negligible effect at depths of about 2.4 m, however, and has an exponent of $b = 0.77$ at a nominal 1 m depth.

The sensitivity of soil layer thickness effects was analyzed using interleaved layers of low-radium and high-radium soils. When the thicknesses of the interleaved layers are small, the soil profile approaches homogeneity, and the bias caused by layer ordering becomes small. Based on these analyses, an approximate 61-cm (2-ft) thick soil layer contains adequate resolution for field sampling and measurement of soil radium concentrations and causes errors of only 17% due to layer-order differences. Two supplementary sensitivity analyses for soil air permeability and radon diffusion

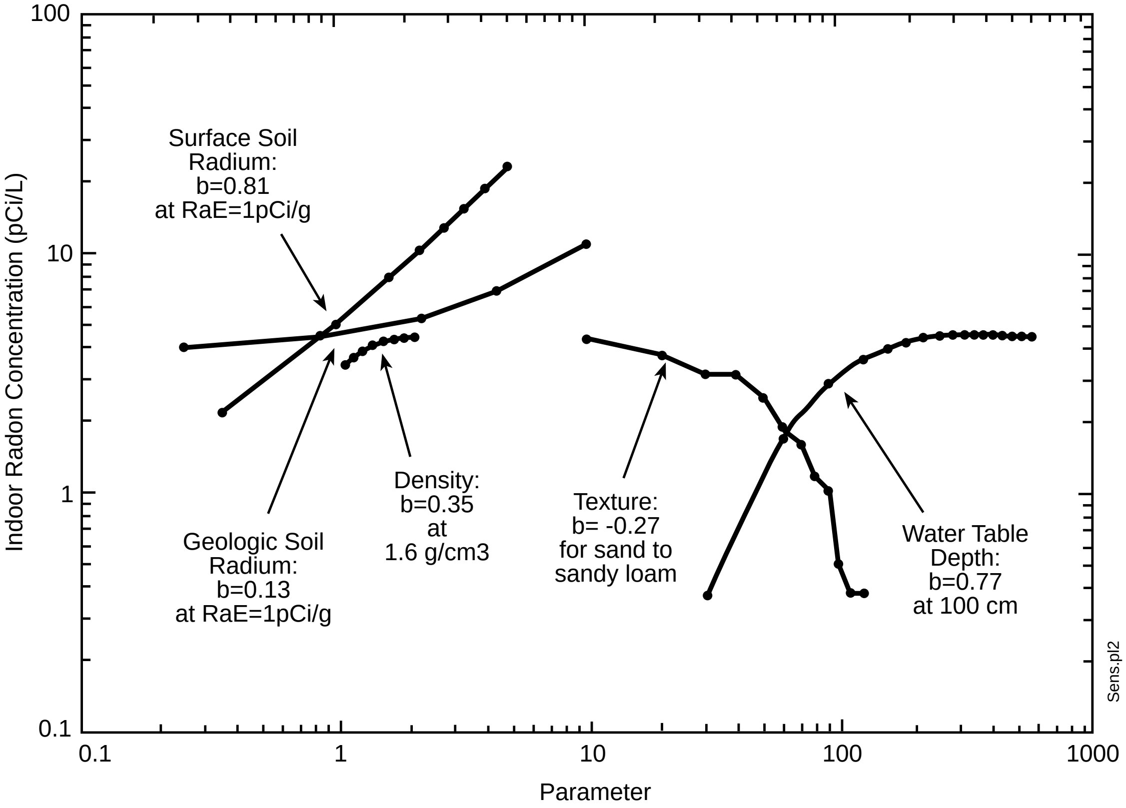

Figure 2. Comparison of parameter sensitivities.

coefficient both showed a square-root dependence (*b* = 0.5).

Mathematical Definition of Site-Specific Radon Potential

The radon potential for a residential building site is defined mathematically as it was for the residential radon protection map. It is the calculated radon concentration in the reference house that would not be exceeded if the house were placed on at least 95% of the land areas in a geographic region (map polygon). Stated more simply, it is the 95% confidence limit of radon concentration for the reference house. Although site measurements give a more representative estimate of radon in the reference house, site variations and measurement uncertainties define a distribution of possible radon concentrations. This distribution is defined to be log-normal, consistent with the mapped distributions, and is used to estimate the 95% confidence limit for radon that is consistent with the maps.

The equation for site-specific radon potential is defined from site-specific values of the log-normal radon distribution parameters. An annual-average radon concentration is first calculated for the reference house from seasonal values using the RAETRAD algorithm with the geometric means of the measured site parameters. A geometric standard deviation (GSD) is then calculated to represent the indoor radon variability associated with the distributions of the site-specific parameters. The radon concentration in the reference house at the 95% confidence limit is finally calculated from the estimated geometric mean and GSD to estimate the site-specific radon potential as:

$$C_{95} = C_{gm}G^{1.645} \tag{1}$$

where C_{95} = site-specific radon potential, at 95% confidence limit, for residences (pCi L^{-1})

C_{gm} = net radon concentration calculated for the reference house from geometric means of the site parameters (pCi L^{-1})

G = GSD of the indoor radon distribution (dimensionless)

1.645 = inverse of the normal distribution integral at 95% (standard deviations).

The GSD of the indoor radon distribution is estimated from a sensitivity-weighted sum of the variances of the individual parameters that contribute to the total uncertainty in the indoor radon calculation. Since the distributions are log-normal, the component uncertainties are GSDs, which require log-transformation for the usual quadratic addition of uncertainties, giving:

$$G = \exp\left\{\sqrt{\sum_i\left[\ln\left(g_i^{\,b_i}\right)\right]^2}\right\} \tag{2}$$

where g_i = GSD of parameter i

b_i = power-curve dependence of indoor radon on parameter i.

The b_i weighting factors give the correct weighting to the GSD of each parameter in proportion to the influence of the parameter on indoor radon concentrations.

The main parameters contributing to uncertainty in Equations 1 and 2 are the soil radium concentrations, the water table depths, and the soil density and texture. Soil air permeability and radon diffusion coefficient also have inherent uncertainties. Since the uncertainties from density, permeability, and diffusion vary less with site properties, they are represented in Equation 2 by a constant, composed of respective contributions of 0.001, 0.173, and 0.120.

The dependence on soil radium is approximately linear (b_i = 0.8 in Figure 2, but approaches unity at higher radium levels), and it is given a linear dependence (b_i = 1) for use in Equation 2. Similarly, the GSD for water table variations is assigned a b_i = 1 sensitivity, which corresponds to water table depths slightly shallower than 1 m. Equations 1 and 2 can be written in a combined form with these numerical values as:

$$C_{95} = C_{gm} \exp\{1.645\sqrt{0.294 + [\ln(g_{Ra})]^2 + [\ln(g_{wt})]^2}\} \qquad (3)$$

where 0.294 = combined variance from permeability, diffusion, and density (dimensionless)

g_{Ra} = GSD of site radium concentrations (dimensionless)

g_{wt} = GSD of indoor radon from varying site water table depths (dimensionless).

The minimum number of soil samples needed to characterize a site is dominated by the soil radium distributions, since the other parameters have more predictable variations. The number of soil samples must be sufficient to characterize both the geometric mean and the GSD of the soil radium distribution. The number must also be adequate to limit the uncertainty in the GSD to a value consistent with the radium variability associated with the radon protection map.

Soil radium concentrations in Florida are distributed log-normally, so their logarithms are normally distributed, and the standard deviations of their logarithms follow a chi-squared distribution. The minimum number of samples required to determine a geometric mean with a given degree of precision depends on the upper limit of the GSD. The required number of soil samples therefore can be expressed as a fractional uncertainty that represents the interval between the upper limit and the best estimate (geometric mean) as:

$$\sqrt{(n-1)/\chi^2_{p,n-1}} - 1 = u \qquad (4)$$

where n = number of samples

$\chi^2_{p,n-1}$ = chi-squared value for n-1 degrees of freedom and for (1-p) confidence

p = probability of exceeding a given chi-squared value

u = fractional uncertainty required (consistent with radon protection map).

Solving Equation 4 for n gives:

$$n = 1 + (1+u)^2 \chi^2_{p,n-1}, \qquad (5)$$

which must be solved iteratively because the $\chi^2_{p,n-1}$ values also depend on n. For a 4,000-m^2 (1-acre) area, statewide radium concentrations had typical uncertainties in the 25 to 35% range. Using an uncertainty limit of 25% (u = 0.25) for the site-specific soil radium data, a 90% confidence limit for the radium GSD (p = 0.1), and solving for the 95% confidence limit on the transformed radium data gives a minimum value of n = 19. For practical purposes, the minimum n is rounded to 20. Thus, at least 20 soil radium samples must be collected and analyzed for a 4,000-m^2 (1-acre) site to have similar confidence in the site-specific radon potential as in the radon protection map.

The sensitivity analyses also give information on how the 20 soil samples should be distributed. For example, the maximum depth from which soil generally influences indoor radon is about 2.4 m (8 ft), if the soil is uniform and has the limiting sandy texture. The sensitivity to non-uniform layers further shows that samples should be collected at intervals not exceeding about 0.6 m (2 ft). Therefore, if 2.4-m (8-ft) boreholes are sampled with compositing over 0.6-m (2-ft) intervals, four samples will be obtained from each borehole and a minimum of five boreholes will be required to represent the 4,000 m^2 unit area.

For site areas smaller than 4,000 m^2, fewer soil samples can be considered. However, fewer samples increases the uncertainty in the upper limit for the GSD, which also increases the calculated radon potential compared to the value that would be calculated if 20 samples were used. A mathematical accommodation is made to use fewer soil samples for sites smaller than 4,000 m^2. The approach transforms the GSD among the actual number of samples to an equivalent 20-sample GSD. The transformed GSD is larger to maintain an equivalent upper confidence limit. The transformation requires that the site have a slightly lower C_{gm} than if 20 samples were analyzed to compensate for the increased uncertainty in satisfying the prescribed C_{95} cut point limits.

The calculation of site-specific radon potentials from site measurements uses a specialized version of the RAETRAD computer code. The computer code, called RAETRAD-F, first calculates the geometric means and GSDs of the measured soil radium concentrations, and determines the seasonal water table distribution as it was defined for the radon protection maps. It then compares the measured soil radon concentration with concentrations calculated from the radium measurements and uses the larger of the two to extrapolate the deep-soil radium concentrations throughout the 2.4 - 5.0 m range.

The RAETRAD-F code next computes best estimates of indoor radon concentrations for the different seasonal water table conditions using the geometric means of the radium measurements. After determining the geometric mean annual radon concentration, C_{gm}, from the seasonal values, the variations among seasonal conditions and among the radium concentrations are used in Equation 3 to estimate C_{95}. If less than five boreholes were used, the code also modifies g_{Ra}. The resulting radon protection category is determined by comparing C_{95} to the 4.0- and 8.3-pCi L^{-1} cut points used in the radon protection map to determine whether the site is in the low, intermediate, or elevated radon protection category.

Site-Specific Radon Potential Measurement Protocol

A protocol has been developed for measuring the radon protection category of a building site. The protocol is an alternative to the radon protection map and must only be performed with standard methods after any site recontouring that could affect the water table or the distribution of soils. The protocol applies to land areas of 4,000 m^2 (1 acre) or smaller. Larger areas must be divided into ≤ 4,000 m^2 parcels for using this protocol.

Site Sampling and Measurements

Site soil sampling must use five boreholes spread over the site at potential building locations. Sites smaller than 4,000 m^2 require at least one borehole for every potential residential building location. If the site is an individual lot, as few as one sampling borehole may be used if it is supplemented with two additional soil samples at least 10 m away from the borehole and from each other, and from the 0 - 61 cm depth interval (representing horizontal and vertical variations). Soils shall be collected from each borehole to represent the 0 - 61, 61 - 122, 122 - 183, and 183 - 244 cm depth intervals. The borehole samples and any supplementary samples shall be used for measurement of density and for textural classification. The remaining material from each depth interval shall be composited for individual measurements of radium concentration. The concentration of radon in the soil gas shall be measured at or near one or more borehole sites. Water table depth must be determined on the site or on nearby property.

Concentrations of ^{226}Ra shall be measured from gastight sealed, equilibrated aliquots of individual samples using a calibrated gamma-ray spectrometer. The spectrometer shall be calibrated by analyses of standard reference materials and blanks in identical configurations. The concentrations of ^{226}Ra shall be reported individually in picocuries per gram on a dry mass basis.

The *in-situ* soil density shall be measured by the drive cylinder method, or by other methods approved by the DCA, using calibrated equipment. Soil density shall be reported in grams per cubic centimeter (dry mass basis) as 20 individual measurements, as four layer means, or as an overall site mean. If the *in-situ* soil density is not measured at the site, a default value of 1.5 g cm^{-3} shall be used in the analyses for computing the site radon protection category.

Soil texture classification shall use laboratory or field methods to select one of the 12 SCS classes: sand, loamy sand, sandy loam, sandy clay loam, sandy clay, loam, clay loam, silty loam, clay, silty clay loam, silty clay, or silt. The classifications should be reported for all 20 samples, or for homogeneous sites, for the four layer classes, or for the entire site. Because of the conservative results obtained with the sand classification and the prevalence of sandy soils throughout Florida, soil texture classifications need not be performed if a default classification of “sand” is used in the analyses.

Soil gas ^{222}Rn concentrations shall be sampled by drawing soil gas from a driven tube and measuring the ^{222}Rn concentration with a calibrated device. The soil radon measurements must be made near one or more borehole locations at 1.2 m or deeper. To avoid radon perturbation, the gas samples shall be collected before soil boring, or afterward if they are about 2 - 3 m away from the bore holes. If the water table is shallower than 1.2 m at the time of soil gas sampling, soil radon measurements may not be required, if (a) the minimum water table depth is less than 0.6 m and (b) there is no evidence that the water table would be below 1.2 m during an alternative season.

The water table depth shall be specified, as for the radon protection map, as the minimum water table depth (in centimeters) and duration (in months). These data may be obtained from the STATSGO data base, from county soil survey data, or from measurements during at least four seasons at 3-month intervals. The shallowest of these shall be defined as the minimum water table depth, and a minimum duration of 3 months shall be defined unless a longer time is indicated by the measurements.

Data Analysis

The site-specific measurements shall be assembled and analyzed using the RAETRAD-F computer code. The RAETRAD-F code automatically implements the equations in this report with the reference house specifications in a way that corresponds to the calculations performed for the residential radon protection map. The user is prompted to enter the site identification information and individual site measurement data. The code then computes the appropriate statistical parameters for the radium measurements, the annual water table distribution from the water table data, the soil moistures from the texture and density data, and all other parameters required for the annual average indoor radon distribution for the reference house. From this distribution, a C_{95} value is computed and compared to the 4.0- and 8.3-pCi L^{-1} cut points, and the site is designated to have either low, intermediate, or elevated radon potential. The printed output from the RAETRAD-F code includes the user-specified input parameters, the calculated C_{95} value, and the site radon potential designation.

Summary and Conclusions

The site-specific protocol and basis described in the full report can be used to measure and interpret features at a site to give supplementary guidance on the possible need for radon-protective construction features. Although site-specific tests can help in making more informed decisions, the user should also consider the relative costs of using conservative radon controls and the EPA guidance on further reducing radon levels even below 4 pCi L^{-1}.

The site-specific protocol is defined from sensitivity analyses of radon entry into a reference house as determined by the RAETRAD model. By using the same model, reference house, and other parameters used for the residential radon protection maps, the present protocol has the same basis as the maps. The sensitivity analyses identified radium concentration, soil layer depth, soil density, soil texture, and water table depth as the independent parameters dominating indoor radon. Of these, radium and water table depth were most important. Soils up to 2.4 m deep contributed to indoor radon in uniform-soil scenarios, and soil layers exceeding approximately 0.6 m thickness significantly affected radon levels in cases of non-uniform radium.

A conservative upper limit for radon potential, defined as the 95% confidence limit for radon in the reference house, was defined mathematically to correspond to the radon protection map. The number of samples needed to represent a site was determined from the equivalent regional precision attained by the radon protection map. Based on the sensitivity of the contributing soil depth and layer thickness, the site-specific measurements were shown to require 20 samples for every 4,000 m^2 (1 acre). These samples are distributed throughout four depth increments that extend to a depth of 2.4 m. An equivalent precision is computed for a smaller parcel of land using fewer samples.

The site-specific protocol involves drilling five boreholes in each 4,000 m^2 parcel of land. Twenty soil samples obtained from the borings are used for radium measurements. The soil borings are also used for density and textural estimates unless default values are chosen. A soil radon measurement detects the potential presence of anomalous elevated-radium materials at depth. The site water table depths are defined from soil survey data or site observations. The site measurements are analyzed by a special-purpose computer code called RAETRAD-F to determine the upper limit for indoor radon concentrations in the reference house. Using the same category definitions as for the residential radon protection map, the RAETRAD-F code determines whether the site is in the low, intermediate, or elevated map category for radon protection purposes.

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The complete report, entitled "Site-Specific Protocol for Measuring Soil Radon Potentials for Florida Houses," (Order No. PB96-175260; Cost: $21.50, subject to change) will be available only from:

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