United States Environmental Protection Agency
Research and Development

National Risk Management Research Laboratory
Research Triangle Park NC 27711

EPA/600/SR-96/108 November 1996

EPA

# Project Summary

# Site-Specific Measurements of Residential Radon Protection Category

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**The report describes a series of benchmark measurements of soil radon potential at seven Florida sites and compares the measurements with regional estimates of radon potential from the Florida radon protection map. The measurements and map were both developed under the Florida Radon Research Program to identify the amount of radon resistance that is needed for new buildings in different parts of Florida. While the measurement protocol and the radon map have a common theoretical basis, the tests were designed to represent small site areas (≤4 x $10^3$ $m^2$), compared with the larger 4 x $10^7$ $m^2$ regions typically shown on the radon protection map.**

**The comparisons included two sites mapped in the low-radon potential category, three in the intermediate category, and two in the elevated category. Twenty samples were collected at each site from five boreholes to depths of 2.4 m. Measurements included soil radium concentration, density, texture classification, radon concentration, and water table. A simplified alternative protocol for estimating soil radium distributions from gamma ray logs of the five boreholes was also examined.**

**The field measurements were analyzed with the RAETRAD-F computer code. The analyses showed that both sites mapped in the elevated radon potential category had elevated radon potentials, and that both sites mapped in the low category had low-radon potentials. Two of the three sites mapped in the intermediate category had intermediate radon potentials, while the radon potential of the third site was low, but near the boundary of the low and intermediate categories. Although there is a significant chance of finding individual sites with differing radon potential category in any map region, the sites selected for this study generally showed excellent correspondence between the mapped and measured categories.**

**Corresponding analyses using the borehole gamma ray estimates of radium gave similar results. Both sites mapped with elevated radon potential had elevated radon potentials, and both sites mapped with low potential had low-radon potentials. The intermediate-mapped site that measured low was again found to be low, but the other two intermediate-mapped sites were conservatively estimated to have elevated radon potential using the alternative radium estimates. The conservatism was attributed primarily to the influence of $^{232}$Th-chain contributions to the $^{226}$Ra estimates.**

**A more general comparison of statewide RAETRAD-F calculations and the radon protection map also showed general consistency. With adjustment for greater variations over regional areas compared to site areas, even the mapped statewide distribution of radon potentials was consistent with the trends shown by the RAETRAD-F model.**

***This Project Summary was developed by EPA's National Risk Management Research Laboratory's Air Pollution Pre-***

***vention 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, under the Florida Radon Research Program (FRRP), has developed radon-protective building standards for new residential construction. An earlier version of the standards contained more detailed requirements for passive and active radon controls in areas identified by a radon protection map to have elevated radon potential. Although not part of the adopted standard, the radon protection map and the related system for selecting different levels of radon control still provide useful guidance for residential radon control.

The radon protection map was developed by calculating the soil radon potentials for each of 3,919 regions of Florida from soil, geological, radiological, and hydrological properties. The regions were defined by the digital intersection of soil maps and surface geology maps. The radon potentials were expressed as the rate of radon entry into a reference slab-on-grade house that was numerically simulated to be located in each region. The regions were then classified into low, intermediate, and elevated radon potential categories, depending on whether indoor radon levels for the reference house could range as high as 4 pCi $L^{-1}$, as high as 8.3 pCi $L^{-1}$, or greater than 8.3 pCi $L^{-1}$.

A site-specific test protocol was developed under the FRRP for measuring the soil radon potential category of specific sites in a way that corresponds to the radon protection map designations. However, the protocols for site-specific tests were designed to represent small site areas of 1 acre ($4x10^3$ $m^2$) or less, compared with the larger 8,800-acre ($3.6x10^7$ $m^2$) regions typically shown on the radon protection map. The site-specific measurements were designed to supersede the regional map designations because of their better representation of specific sites. The site-specific measurement protocol uses the same theoretical basis as the radon protection map. However, the protocol has not been previously evaluated by field measurements to determine its consistency with the radon protection map.

This report examines the consistency of analyses from the site-specific radon potential measurements with the Florida radon protection map. It also presents and evaluates a simplified alternative method for estimating soil radium profiles for use in the protocol. The consistency between the site-specific measurements and the map is examined from a series of benchmark measurements using the site-specific protocol in different Florida regions that lie within the red, yellow, and green areas of the radon protection map. The resulting data are analyzed by the RAETRAD-F computer code, which was developed for analyzing data from the site-specific measurements. The measurement results give the radon protection category of each site, which is compared with the category shown on the radon protection map.

## Site Selection

The locations for the benchmark site-specific tests included seven Florida sites: two in the green category on the radon protection map, three in the yellow category, and two in the red category. The sites were selected considering criteria for representativeness, accessibility, and convenience. The general color regions were selected from the elevated frequency of red regions in central Florida, the elevated frequency of yellow-regions in north-central Florida, and the nearly complete dominance of green regions in the Florida panhandle. Representativeness was based on qualitative field judgements that excluded areas that were obviously disturbed or otherwise atypical of the map region. For example, highway embankments were excluded. Related considerations included avoidance of buried utility lines, approximate 1-acre minimum areas, and convenient proximity to access roads.

The sites where the field sampling and measurement protocols were conducted are shown in Figure 1. The two red-category sites were selected for accessibility. The Polk-1 site was located at an FRRP research site already used for radon studies. An adjacent commercial building property in Bartow (Polk-2) was also available because of participation in another FRRP project. The three yellow-category sites were chosen in Hernando and Sumter Counties during the field trip. The Hernando County site was located in a highway median that contained old and apparently undisturbed native soil and vegetation. This site was selected to test the "smaller than 1 acre" option of the protocol (using only three boreholes). The Sumter County sites were on cleared but otherwise undisturbed land of a power line corridor (Sumter-1) and on cleared land of an interstate highway right-of-way (Sumter-2). The green-category site in Wakulla County was on undisturbed land of a power line corridor. The Jefferson County site was on vegetation-cleared land in the margin between private land and a U.S. highway right-of-way.

Latitude and longitude coordinates of each sampling and measurement site were measured using a global positioning system. The coordinates were subsequently analyzed by a Geographic Information System to positively determine the radon map polygon containing the site. Individual sampling locations at each site were located at least 10 m apart in an approximately square configuration.

## Field Procedures

Field sampling and measurement procedures used the FRRP procedures given in "Standard Measurement Protocols, Florida Radon Research Program," the American Society for Testing and Materials (ASTM) procedures where applicable, or Rogers and Associates Engineering Corporation procedures. The field sampling and measurements were conducted between March 12 and 15, 1995. The field procedures used portable equipment that could be hand-carried onto the site without requiring vehicle-mounted drilling or measuring equipment.

The site-specific protocol requires sampling of site soils and measurement of five parameters from the samples or from field measurements: (a) soil $^{226}Ra$ concentration, (b) soil density, (c) soil textural classification, (d) $^{222}Rn$ concentration in soil gas, and (e) water table minimum depth and duration.

Soil sampling used five boreholes spread over the site at locations corresponding to planned or potential building sites. For sites smaller than 1 acre, sampling used at least one borehole for every planned or potential residential building location. Soils were collected from each borehole to represent the 0-61, 61-122, 122-183, and 183-244 cm depth intervals. The samples were collected from the drill cuttings of a 5-cm diameter soil auger attached to a hand-held gasoline-powered drill. Samples were immediately sealed into heavy gauge (0.1 mm) polyethylene bags and labeled by site, location, and depth for transport to the Rogers and Associates laboratory for radium assays. Approximately 350 g of soil was collected from each depth increment.

*In situ* soil density samples were collected at each site using a thin-walled steel drive cylinder, as prescribed by ASTM D 2937. The cylinder was inserted in the 0-30 cm depth range and was then excavated with a hand trowel. After removing excess material from the cylinder, the measured volume of soil was transferred to a heavy gauge (0.1 mm) re-sealable polyethylene bag for weighing and moisture

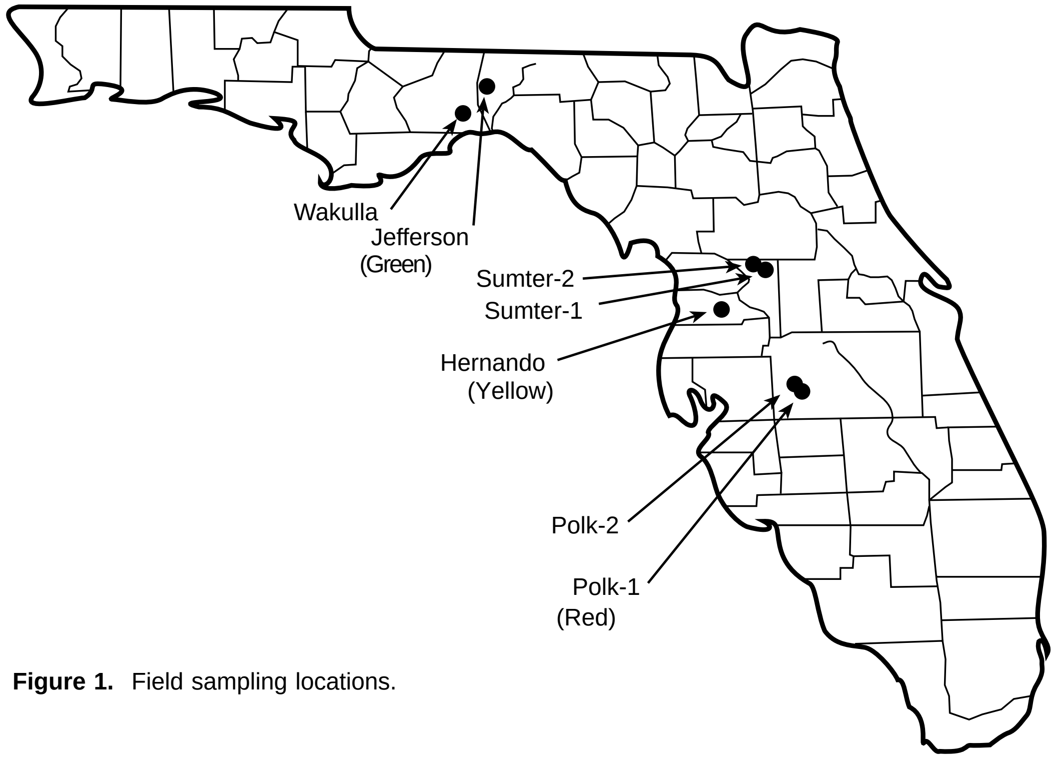


**Figure 1.** Field sampling locations.

measurement in the laboratory. Soil density was determined in grams per cubic centimeter on a dry mass basis.

Soil textural classifications were made from visual and tactile observations while bagging the auger cuttings for the radium samples. The textures were classified into one of the 12 classes defined by the U.S. Soil Conservation Service: sand, loamy sand, sandy loam, sandy clay loam, sandy clay, loam, clay loam, silty loam, clay, silty clay loam, silty clay, and silt.

Water table depths were observed, where possible, by measuring the distance from the soil surface to the surface of the water that occurred in the borehole prior to backfilling. Where water was not observed, estimates were obtained subsequently from the data used for the statewide radon maps.

The concentration of $^{222}Rn$ in soil gas was determined by drawing air from a driven tube into a calibrated radon measurement system. The tube (6 mm I.D. steel pipe) was driven to a depth of approximately 1 m and was connected by plastic tubing to the scintillation cell and pump of a radon monitor. The monitor drew approximately 2 L $min^{-1}$ of soil gas, and was operated for several minutes to establish background before connecting to the pipe. The sampler was operated for 10 to 35 minutes on the pipe, after which the plastic tube was disconnected to purge the cell with surface air. The alpha activity in the scintillation cell was recorded over 2-minute intervals. Soil gas radon concentrations were computed from the continuously measured alpha counts. The efficiency of the scintillation cell was determined previously from measurements at the U.S. Department of Energy's Technical Measurement Center radon chamber at Grand Junction, CO.

Borehole gamma ray logs were measured before backfilling each hole for comparison with the results of laboratory radium assays. The borehole logs used a 2.5-cm diameter sodium iodide gamma ray scintillation probe connected to a digital scaler. Individual 1-min counts were recorded at 30.5-cm intervals throughout the depth of each borehole. The same probe was calibrated in a separate study to yield 4,600 counts $min^{-1}$ in boreholes with 2.1 pCi $g^{-1}$ $^{226}Ra$ and 0.2 pCi $g^{-1}$ $^{228}Ra$ and a background rate of 590 counts $min^{-1}$ in low-radium boreholes.

## Laboratory Analyses

The borehole soil samples were weighed into tared steel cans and sealed for radium assay by the procedures described previously. Radium assays were performed after approximately 18 days equilibration in the sealed cans. Laboratory assays used a calibrated gamma ray spectrometer to determine concentrations of $^{226}Ra$ in picocuries per gram on a dry mass basis. At least 10% duplicates, blanks, and standards were also analyzed for quality assurance purposes. Samples were dried as specified by ASTM D 2216-80 for moisture determinations. The soil density samples were transferred to laboratory beakers and dried as specified by ASTM D 2216-80 to determine dry sample density according to ASTM D 2937-83.

## Test Results

Soil radium concentrations measured by laboratory assays of the borehole soils ranged from 0.1 to 20.8 pCi $g^{-1}$, compared to a range of 0.2 to 13.2 pCi $g^{-1}$ based on the borehole gamma ray measurements. The individual borehole measurements had a correlation coefficient of $r^2 = 0.84$ in a least-squares regression of radium on gamma ray intensity. An independent calibration of gamma activity was used to estimate radium concentrations from the gamma ray measurements, and the resulting radium concentrations were averaged by depth interval for comparison radium concentrations.

Extra laboratory radium analyses for quality assurance purposes included approximately 10% duplicate assays, 10% blanks, and 10% replicate analyses of standards. The precision as estimated from counting statistics for samples exceeding 2 pCi $g^{-1}$ was 6.0% (100 x standard deviation ÷ mean), compared to a data quality objective of 20% for this parameter. The corresponding analytical precision estimated from duplicate assays averaged 4.3%. The duplicate assays showed no net bias. The analyses of blanks averaged 0.1 ± 0.2 pCi $g^{-1}$, well within the analytical standard deviation of ±0.2 pCi $g^{-1}$. The analyses of a 15.12 ± 0.23 pCi $g^{-1}$ $^{226}Ra$ standard showed an average bias of only 2%, well within the 10% accuracy objective.

Soil moisture measurements on the laboratory radium samples ranged from 3.2 to 53.7% of dry mass. The soil textures were mostly (69%) sand, with the next most prevalent textures including clay (10%), loamy sand (8%), and sandy loam (7%).

Soil density measurements among the seven sites averaged 1.53 g $cm^{-3}$ with a standard deviation of 0.10 g $cm^{-3}$ and a range of 1.41 g $cm^{-3}$ (Jefferson site) to 1.68 g $cm^{-3}$ (Wakulla site). Soil radon concentrations ranged from 91 pCi $L^{-1}$ at the Jefferson site to 4,100 pCi $L^{-1}$ at the Polk-2 site. The water table was observed only at the Wakulla site; therefore the minimum depths and durations were primarily estimated from the Statsgo data used previously in developing the Florida radon maps.

## Model Analyses of Radon Protection Category

The measured data were analyzed with the RAETRAD-F computer code to determine the radon potential category of each site. The code simulated radon entry into the reference house in a way that corresponded to the radon protection map. The site-specific calculations were then compared with the mapped categories. More general sensitivity analyses were also performed with the RAETRAD-F model to assess the general, statewide agreement between the site-specific modeling approach and the statewide radon protection map.

The RAETRAD-F code computed statistical parameters from the site measurements to characterize the site radium distributions, the annual water table distribution, the soil moisture profiles, and other parameters. It then computed the annual average indoor radon distribution for the reference house. From this distribution, the code computed the 95% confidence limit for the annual average indoor radon concentration in the reference house ($C_{95}$) to correspond with the radon protection map. The code finally compared $C_{95}$ to the 4.0- and 8.3-pCi $L^{-1}$ cut points used in the radon protection map, and designated the site to have low, intermediate, or elevated radon potential.

The potential radon concentrations and site classifications from these analyses are given in the third and fourth columns of Table 1 for comparison with the classifications of the radon protection maps. Both sites located in a red (elevated) radon potential category on the radon protection map were determined to have a corresponding elevated radon potential classification by the site-specific tests using the laboratory radium assays. Two of the three sites that were mapped in the intermediate radon potential category (Sumter-1 and Hernando) were determined to have a corresponding intermediate (yellow) radon potential classification by the site-specific tests using the laboratory radium assays. The other site mapped in the intermediate radon potential category (Sumter-2) was determined to have a low (green) classification by the site-specific tests but was within 8% of the boundary between the green and yellow categories. The two sites mapped in the low-radon potential category were both determined to have a corresponding low-radon (green) potential classification by the site-specific tests.

Corresponding separate model analyses used the alternative radium distributions estimated from the borehole gamma ray measurements instead of the laboratory radium assays. The potential radon concentrations and site classifications from these analyses are given in the fifth and sixth columns of Table 1. Both sites mapped in an elevated (red) radon potential category were again determined to have a corresponding elevated radon potential classification by the tests using borehole gamma ray logs. Two of the three sites mapped in the intermediate radon potential category (Sumter-1 and Hernando) were also found to have an elevated (red) radon potential classification using the alternative radium distributions from the borehole logs. The other site mapped in the intermediate radon potential category (Sumter-2) was again determined to have a low (green) classification by the alternative radium distributions. The two sites mapped in the low-radon potential category were determined to have a corresponding low-radon (green) potential classification by the alternative analyses.

The comparisons in Table 1 show agreement or conservative differences between the map and site-specific analyses. The differences for the Sumter-2 site result from the conservative land classification by the radon potential map. Although locally elevated conditions were found for the other six sites, this site reflects the general conservatism (95% confidence limit) of the radon potential map. The only other sites showing differences, Sumter-1 and Hernando, were correctly modeled from the laboratory radium assays but were

***Table 1.*** *Potential Radon Concentrations and Site Radon Potential Categories from RAETRAD-F Analyses*

| | | *Using Lab Radium Assays* | | *Using Borehole Gamma Logs* | |
|---|---|---|---|---|---|
| *Site* | *Radon Protection Map Category* | *Potential Radon Conc. (pCi $L^{-1}$)* | *Site Radon Potential Category* | *Potential Radon Conc. (pCi $L^{-1}$)* | *Site Radon Potential Category* |
| *Polk-1* | *Red* | *35.2* | *Elevated (Red)* | *27.7* | *Elevated (Red)* |
| *Polk-2* | *Red* | *104.5* | *Elevated (Red)* | *70.4* | *Elevated (Red)* |
| *Sumter-1* | *Yellow* | *8.1* | *Intermediate (Yel.)* | *9.0* | *Elevated (Red)* |
| *Sumter-2* | *Yellow* | *3.7* | *Low (Green)* | *3.5* | *Low (Green)* |
| *Hernando* | *Yellow* | *6.8* | *Intermediate (Yel.)* | *13.3* | *Elevated (Red)* |
| *Wakulla* | *Green* | *2.1* | *Low (Green)* | *1.8*[a] | *Low (Green)* |
| *Jefferson* | *Green* | *2.1* | *Low (Green)* | *2.4* | *Low (Green)* |

[a]*Assumes 1 pCi $g^{-1}$ radium concentrations in holes where water precluded gamma ray measurements.*

conservatively modeled by the borehole gamma ray logs. In general, the comparisons show good correspondence between the detailed field tests and the map predictions and comprise an acceptable benchmark between measured and mapped radon potentials.

The conservatism in the gamma ray measurements could have resulted from any of several recognized systematic sources, including contributions from natural thorium-chain radionuclides to the radium estimates and to a lesser extent, auger smearing of elevated-radium soils from the deepest strata into upper, low-radium soil regions around the borehole. The differences for the Sumter-1 and -2 sites could also be attributed to random variation, since they are within approximately 8-12% of the respective 8.3- and 4.0-pCi $L^{-1}$ map category cut points.

The simplified alternative protocol for site radium estimates proved to give generally equivalent or conservative results. Although the simpler method gave faster results at lower cost, it was potentially less accurate because of the added uncertainty in calibrating gamma ray intensity to soil radium concentration. The potential errors were conservative, however, because the potentially increased radium variations served to raise the 95% confidence limits of potential radon concentration calculated by RAETRAD-F. The alternative protocol was also conservative because thorium-chain gamma rays increased the total radium estimate from gamma radiation, even though the thorium-chain radionuclides do not produce $^{222}Rn$.

## Generalized Model-Map Comparisons

A second, more generalized comparison was also made between RAETRAD-F calculations and the data used for the statewide radon protection map. This comparison addressed most of the 3,919 map polygons, but it relied on generic data rather than site-specific measurements for input to the RAETRAD-F code.

The generalized comparisons used the statewide polygon definitions of soil radium distributions. The geometric mean radium concentrations were plotted against their geometric standard deviations for each polygon. Polygons mapped in the red (elevated radon potential) category were plotted with circles; polygons mapped in the yellow (intermediate radon potential) category were plotted with triangles; and polygons mapped in the green (low-radon potential) category were plotted with small dots. The resulting scatter plot showed distinct grouping that corresponds to map categories.

For comparison with RAETRAD-F, calculations were performed to estimate where the green-yellow and yellow-red cut points would fall on the above scatter plot. For the RAETRAD-F calculations, all soils were represented conservatively by sand. This conservative texture provided maximum permeability and diffusivity and minimal water retention, permitting as much surface radon release as possible. Water tables were also defined conservatively low. Soil radium distributions were defined to be log-normal with geometric means and geometric standard deviations (GSDs) that were varied to obtain different radon potentials corresponding to the green-yellow and yellow-red cut points.

The generic cut point lines calculated by RAETRAD-F had similar shape and spacing trends to those of the three categories of polygon points but were biased lower than the GSDs of the polygon points. The difference in GSD was expected, since the maps use large-area regional GSDs dominated by aeroradiometric and soil variations, while the RAETRAD-F analyses use local GSDs controlled by radium and moisture variations over a 1-acre site. An increase of only 0.5 in the site-specific GSDs gave good agreement between the calculated generic site radon potentials and the statewide clusters of red, yellow, and green polygon data.

## Summary

Site-specific measurements using the measurement and analysis methods prescribed by the original site characterization protocol gave identical radon protection categories to those shown on the radon protection map at six of the seven sites that were tested. At the remaining site, the potential radon concentration ($C_{95}$=3.7 pCi $L^{-1}$) was slightly below the map cut point of 4 pCi $L^{-1}$ that would have placed it into an equivalent category. The conservative display by the map is expected, since the map categories are defined to contain significant areas with lower radon potentials.

Slightly more conservative site categories were obtained using the alternative protocol that replaces laboratory radium assays with field borehole gamma ray logs. Although all sites mapped with low or elevated classifications retained the same category under the alternative protocol, two intermediate-class sites were indicated as elevated. This conservatism could potentially be eliminated by alternative calibrations or field instruments that reduce $^{232}Th$-chain radionuclide interference.

On a broader scale, less-specific comparisons of the radon protection map with the site-specific data analysis model (RAETRAD-F) also show consistency. This comparison is complicated by an inherent difference in scale between large regional variations and local site variations. Nevertheless, the comparison suggests that even the complete statewide distribution of radon potentials is consistent with the trends shown by the RAETRAD-F model, which is prescribed for analyzing site-specific measurement data.

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***David C. Sanchez** is the EPA Project Officer (see below).*
*The complete report, entitled "Site-Specific Measurements of Residential Radon Protection Category," (Order No. PB97-104707; Cost: $21.50, subject to change) will be available only from*

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