EPA-600/R-96-108
September 1996

Site Specific Measurements of Residential Radon Protection Category

Final Report

by
Kirk K. Nielson, Rodger B. Holt, and Vern C. Rogers
Rogers & Associates Engineering Corporation
P.O. Box 330
Salt Lake City, UT 84110-0330

EPA Interagency Agreement RWFL 933783
DCA Agreement 95RD-30-13-00-22-001

EPA Project Officer: David C. Sanchez
National Risk Management Research Laboratory
Research Triangle Park, NC 27711

DCA Project Officer: Mohammad Madani
Florida Department of Community Affairs
2740 Centerview Drive
Tallahassee, FL 32399

University of Florida Project Directors: John F. Alexander and Paul D. Zwick
Department of Urban and Regional Planning
431 ARCH, University of Florida
Gainesville, FL 32611

Prepared for:
State of Florida
Florida Department of Community Affairs
2740 Centerview Drive
Tallahassee, FL 32399

and
U. S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before comp.

1. REPORT NO. EPA-600/R-96-108	2.	
4. TITLE AND SUBTITLE Site-specific Measurements of Residential Radon Protection Category		5. REPORT DATE September 1996 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Kirk K. Nielson, Rodger B. Holt, and Vern C. Rogers		8. PERFORMING ORGANIZATION REPORT NO. RAE-9226/7-1R2
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rogers and Associates Engineering Corporation P.O. Box 330 Salt Lake City, Utah 84110-0330		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. RWFL933783 (EPA IAG) 95RD-30-13-00-22-001 (DCA)
12. SPONSORING AGENCY NAME AND ADDRESS **EPA, Office of Research and Development** **Air Pollution Prevention and Control Division** **Research Triangle Park, NC 27711**		13. TYPE OF REPORT AND PERIOD COVERED Final; 7/94-6/95 14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES APPCD project officer is David C. Sanchez, Mail Drop 54, 919/541-2979.

16. ABSTRACT 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 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 (4,000 sq m), compared with the larger 4 million sq m 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 of the 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.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Radon	Stationary Sources	07B
Soils		08G, 08M
Emission		14G
Measurement		
Residential Buildings		13M

18. DISTRIBUTION STATEMENT **Release to Public**	19. SECURITY CLASS *(This Report)* **Unclassified**	21. NO. OF PAGES 58
	20. SECURITY CLASS *(This page)* **Unclassified**	22. PRICE

EPA Form 2220-1 (9-73)

FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

EPA REVIEW NOTICE

This report has been peer and administratively reviewed by the U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

ABSTRACT

The Florida Radon Research Program has developed standards for radon-resistant building construction, and has also developed state-wide maps and site testing protocols to identify the amount of radon resistance that is needed for particular regions or sites. This report examines the consistency of the site radon testing protocols with regional estimates from the Florida radon protection map. The protocols for site-specific tests were designed to represent areas of one acre ($4x10^3$ m^2) or less, compared with the 8,800-acre ($3.6x10^7$ m^2) regions typically shown on the radon protection map. The protocols were based on model calculations identical to those used to develop the map. However, there have been no previous comparisons of site-specific radon potential measurements with the categories shown on the radon protection map. This report documents a series of benchmark measurements of soil radon potential at sites located in areas that are designated by the map as having low, intermediate, and elevated radon potentials. This report also documents a simplified alternative approach for measuring soil radium distributions.

The protocol for the site specific measurements included collection of 20 soil samples from 5 boreholes, and measurement of their radium concentration by laboratory assay. The soil density, texture classification, radon concentration, and water table were also measured at each site. Seven sites were selected for the benchmark comparisons. Two were in areas mapped with a low radon potential category, three were in areas mapped with an intermediate radon potential category, and two were in areas mapped with an elevated radon potential category. The latitude and longitude of each site were measured with a global positioning system to positively associate the site with a polygon of the radon protection map.

The simplified alternative protocol for soil radium measurement involved gamma-ray logging of each of the five boreholes used for soil characterization. Although this simpler method gives faster results at lower cost, it is potentially less accurate because of the added uncertainty in calibrating gamma ray intensity to soil radium concentration. The potential errors are generally conservative, however, because radium variations are considered in interpreting the results and also because thorium-chain gamma rays increase the total radium estimate but not the radon source strength.

Soil radium concentrations ranged from 0.2 pCi g^{-1} to 20.8 pCi g^{-1}, and soil water contents ranged from 3.2% to 61.3% (dry mass basis). Soil textures were mostly sand, but about 30% were sandy loam, loamy sand, and finer-textured classifications. Soil densities ranged from 1.41 g cm^{-3} to 1.68 g cm^{-3}, and soil radon concentrations ranged from 91 to 4,130 pCi L^{-1}. Quality assurance analyses of 10% duplicates, blanks, and standards demonstrated adequate precision and accuracy control for the soil radium assays.

Analyses of the field measurements with the RAETRAD-F computer code and the laboratory radium assays demonstrated that both of the sites mapped in the elevated radon potential category had elevated radon potentials, and that both of the 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 third site mapped as intermediate had a low radon potential, but was near the interface of the low and intermediate categories. Although there was a significant probability of finding individual sites in any map region with differing radon potential categories, the sites selected for this study generally showed excellent correspondence between the mapped and measured categories.

Analyses of the field data with the RAETRAD-F computer code and the alternative borehole gamma-ray estimates of radium concentration gave similar results. Both of the sites mapped in the elevated radon potential category had elevated radon potentials, and both of the sites mapped in the low category 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 modeled to have elevated radon potential. The conservatism was attributed to use of total radium (including ^{232}Th-chain contributions) from the borehole measurements in the analyses, and possibly also to vertical mixing during soil boring.

A more generalized comparison between statewide RAETRAD-F calculations and the radon protection map also showed consistency. This comparison was complicated by an inherent difference in scale between regional variations (for areas averaging 8,800 acres) and localized variations (for sites of 1 acre or less). Nevertheless, the comparison suggested that even the complete state-wide distribution of radon potentials is consistent with the trends shown by the RAETRAD-F model.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 BACKGROUND

Radon (^{222}Rn) gas from the decay of naturally occurring radium (^{226}Ra) in soils can enter buildings through their foundations. If the radon entry rate is elevated and the building is not well ventilated, radon can accumulate to levels that can significantly increase the occupants' risks of lung cancer with chronic exposure. The degree of health risk is proportional to the long-term average level of radon exposure. The U.S. Environmental Protection Agency (EPA) attributes 7,000 to 30,000 lung cancer fatalities annually to radon, and recommends remedial action if indoor radon levels average 4 picocuries per liter (pCi L^{-1}) or higher (EPA92a; EPA92b).

The Florida Department of Community Affairs (DCA), under the Florida Radon Research Program (FRRP), has developed radon-protective building standards. For residences, these standards are given in the Florida Standard for Passive Radon-Resistant New Residential Building Construction (DCA95). This standard requires passive radon barriers in counties that adopt the standard. An earlier version of the standard (DCA94) contained more detailed requirements for both passive and active radon controls in areas identified by a radon protection map to have elevated radon potential. Although no longer 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 that is referenced frequently in this report (Nie94) 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 of the regions. The regions were then classified into low, intermediate, and elevated radon potoential 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 protocol was also developed under the FRRP (Nie94b) for measuring the soil radon potential category of specific sites in a way that corresponds to the radon protection map designations (Nie94).

However, the protocols for site-specific tests were designed to represent areas of one acre (4×10^{3} m^{2}) or less, compared with the 8,800-acre (3.6×10^{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 the inherent applicability of on-site measurements. For example, a prospective builder may suspect anomalous conditions at a site (from previous land use, soil or mineral observations, etc.) that could increase its radon potential above the mapped category. Alternatively, the builder may have reason to suspect that the land has lower radon potential than its conservatively mapped category, leading him to want to reduce or eliminate radon controls unless they are specifically needed. In either case, site-specific tests could lead to a more reliable decision.

The site-specific measurement protocol utilizes model analyses that are identical to those used to develop the radon protection map (Nie96). However, the site-specific protocol has not been previously evaluated by field measurements to determine its consistency with the radon protection map.

1.2 OBJECTIVE AND SCOPE

This report examines the consistency of the site-specific radon potential measurement protocol 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 measurements, including both field measurements and field sampling of soils for laboratory measurements, follow the site-specific protocols. The resulting data are analyzed by the RAETRAD-F computer code, which was developed for analyzing Florida measurements of site radon potential. The results of these analyses indicate the radon protection category of each benchmark measurement site, which is compared with the designation given for the site by the radon protection map.

Because of the limited time and budget for evaluating the site-specific protocol, only its primary aspects were tested. For example, the protocol requires testing after completion of any soil contouring or other activities that could affect the water table or soil distribution. The generic tests conducted in this study were performed primarily on undeveloped land, which was typical of land being used for construction in some of the areas but which may have required contouring before construction in others. The requirement for locations representative of planned or potential building locations also was satisfied by some of the sites, but not necessarily by others.

2. SITE-SPECIFIC MEASUREMENTS

The site-specific benchmark measurements in this study followed the draft protocol developed for use with the residential radon standard (DCA94). Additional measurements also followed a proposed alternative protocol for characterizing soil radium concentration profiles. The measurements were made at seven Florida sites. Two of the sites were identified by the radon protection map as having a green radon protection category, three were identified as having a yellow category, and two were identified as having a red category. The sites were selected considering the radon potential of the map polygon, its uniformity, the land use and accessibility of the site, and the permission granted by the site owner or occupant. The field procedures utilized portable equipment that could be hand-carried onto the site without requiring vehicle-mounted drilling or measuring equipment. The following sections describe the test protocol, site selection, and field procedures in more detail.

2.1 TEST PROTOCOL

This section presents the protocol for measuring the radon protection category of specific sites (Nie96). The 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.

2.1.1 Site Sampling and Measurements

Sampling of soils at the site shall utilize five boreholes spread over the entire site at locations corresponding to planned or potential building sites. For sites smaller than 1 acre, sampling shall utilize at least one borehole for every planned or potential residential building location. If the site consists of an individual lot for a single building, sampling boreholes may be reduced to as few as one, provided that if only one borehole is used, it is supplemented with two additional soil samples from locations at least 10 m away from the borehole location and from each other, and from soils representing the 0-61-cm depth interval.

Soils shall be collected from each borehole to represent four different depth intervals. The depth intervals are 0-61 cm, 61-122 cm, 122-183 cm, and 183-244 cm. The borehole samples and any supplementary samples shall be used for measurement of soil density and for textural classification. The remaining material from each depth interval may be composited for individual measurements of radium concentration. The concentration of radon in the soil gas shall be measured at or near each borehole site. Observations of water table depth may utilize any location(s) on the site or on vicinity property.

2.1.2 Soil ^{226}Ra Concentration

The concentrations of ^{226}Ra shall be measured for each depth interval by laboratory assays of the soil samples or by gamma-ray logging of the boreholes. Laboratory assays shall analyze gas-tight, 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 the same gas-tight and equilibrated container configuration as used for the samples. Suitable standard reference materials include soils, ores, or spiked earthen materials obtained from or prepared from liquid sources from the U.S. Department of Commerce (National Institute of Standards and Technology), EPA, or other sources approved by the DCA. The concentrations of ^{226}Ra shall be reported individually in pCi g^{-1} on a dry mass basis.

If ^{226}Ra concentrations are determined by borehole logging, a suitable gamma-ray detector shall be suspended in each borehole at depths corresponding to the centers of each of the four depth intervals for individual measurements. Additional measurements at the boundaries of each depth interval may also be made. A suitable gamma-ray detector is a calibrated gamma scintillation probe or diode-type gamma-ray spectrometer. Each measurement shall estimate ^{226}Ra or total radium (^{226}Ra + ^{228}Ra) with an uncertainty not exceeding ±0.3 pCi g^{-1}. The detector shall be calibrated in pCi g^{-1} on a dry mass basis by comparisons with laboratory assays as described in this section. Measurements at depth interval boundaries shall be weighted at 50% of the weights applied to measurements in the centers of depth intervals. Total radium measurements may be used as conservative estimators of ^{226}Ra, or they may be corrected for ^{228}Ra contributions only if the correction is based on explicit calibrated measurements of ^{232}Th-chain nuclides such as ^{228}Ra. Potential interferences by ^{40}K are generally smaller, and may be eliminated implicitly as part of the gamma radiation background or explicitly by separate ^{40}K radiation measurements.

2.1.3 Soil Density

In-situ soil density, if measured, shall be determined from the masses of samples of known volume (drive cylinder method, ASTM D2937) or by other methods approved by the DCA. Equipment used for the density measurements shall be suitably calibrated. The soil density measurements shall be reported in g cm^{-3} on a dry mass basis and may be reported individually (all 20 samples), as averaged by layer (four layer means), or as averaged for the entire site (one overall mean). Because of the relatively low sensitivity of indoor radon levels to soil density, the soil density need not be measured. If in-situ soil density is not measured, a default value of 1.5 g cm^{-3} shall be used in the analyses for computing the site radon protection category.

2.1.4 Soil Textural Classification

The textural classification of the site soils shall utilize laboratory or field methods (SCS75) to group the soils into one of the twelve textural classes defined by the U.S. Soil Conservation Service, listed in Table 2-1. The soil textural classes may be reported individually (all 20 samples), as aggregated by layer (four layer classes, determined from layer-composite samples), or as aggregated for the entire site (determined from one site-composite sample). If visually distinct classes are discernable among different samples, the site composite determination may not be used.

Because of the conservative results obtained with the sand classification and the prevalence of sandy soils throughout Florida, the soil textural classification need not be performed. If the soil textural classification is not performed, a default classification of "sand" shall be used in the analyses for computing the site radon protection category.

Table 2-1 SCS soil texture classes

1. Sand	5. Sandy clay	9. Clay
2. Loamy sand	6. Loam	10. Silty clay loam
3. Sandy loam	7. Clay loam	11. Silty clay
4. Sandy clay loam	8. Silty loam	12. Silt

2.1.5 Soil ^{222}Rn Concentration

The concentration of ^{222}Rn in soil gas shall be sampled by drawing soil gas from a driven tube or equivalent sampling system and measuring the ^{222}Rn concentration with a suitably calibrated radon measurement system. The soil radon measurements shall be conducted at each borehole location at a depth of 1.2 m or greater. To avoid soil disturbance, the soil gas samples shall be collected before drilling the boreholes, or afterward provided they are collected approximately 2-3 m away from the borehole locations. The soil radon measurement does not directly affect the calculation of radon potential unless the measurement exceeds the value calculated from the soil radium concentrations.

If ground water is encountered at depths shallower than 1.2 m at the time of field sampling, the requirement for a soil radon measurement may be waived if (a) there is no evidence that re-sampling during an alternative season would be successful and (b) soil surveys or similar studies show that seasonal water table depths come within 0.6 m from the surface. If either of these conditions is not satisfied, another soil radon measurement shall be attempted during a different season (3 to 9 months later). If ground water is again encountered at less than 1.2 m depth, the requirement for a soil radon measurement at the site shall be waived.

2.1.6 Water Table Depth

The depth of the water table at the site shall be specified in a manner that is consistent with the water table specifications used in developing the residential radon protection map (Nie95a). For the radon protection map, the minimum (most shallow seasonal) water table depth (in centimeters) and duration (in months) were specified from data in the STATSGO data base (SCS91). These data were in turn derived from county soil survey information, as is typically contained in local county soil survey reports (e.g., Tho85). If county soil survey reports are used as the data source, the water table data should be defined from the soil or combinations of soils that comprise the site. Average values shall be computed to represent the data in cases where ranges are reported (i.e., 70 cm would be computed to represent a reported water table depth range of 60 to 80 cm).

If local area information is unavailable, or if site-specific measurements are otherwise to be utilized, water table measurements shall be derived from at least four seasonal measurements of water table depth at 3-month intervals. The most shallow 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.

2.1.7 Analysis of Site-Specific Measurements

The site-specific measurement data shall be assembled and analyzed using the RAETRAD-F computer code (Rog95). The RAETRAD-F code simulates radon entry into the reference house in a way that corresponds to the calculations performed for the residential radon protection map. The user shall enter site identification information and the 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 required parameters for computing the annual average indoor radon distribution for the reference house. From this distribution, the code computes the 95% confidence limit for the annual average indoor radon concentration in the reference house (C_{95}). The code then compares C_{95} to the 4.0-pCi L^{-1} and

8.3-pCi L^{-1} cut points used in the radon protection map, and designates the site to have low, intermediate, or elevated radon potential. The RAETRAD-F code prints the user-specified input parameters, the calculated C_{95} value, and the site radon potential designation.

2.2 SITE SELECTION

The locations for the benchmark site-specific tests were selected to include different parts of Florida containing green, yellow, and red regions of the radon protection map. Other criteria for site selection included 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 panhandle part of Florida. Representativeness was based on qualitative field judgements that excluded areas that were obviously disturbed or otherwise atypical of the map polygon. For example, highway embankments that could contain materials hauled from other regions were excluded. Site accessibility was a critical factor in site selection. Since the protocol requires five borings to depths of 2.4 m (8 ft) on an acre, casual sampling along road-side fence lines was precluded, and permission for site access became more important. Related considerations included avoidance of buried utility lines, approximate 1-acre minimum areas, and convenient proximity to access roads.

Selection of red sites was dominated by accessibility. The FRRP research site near Bartow was chosen because of its red polygon location and its ownership by the Florida Institute of Phosphate Research, which has cooperated with past FRRP studies. An FRRP large-building study site on an adjacent parcel of land was similarly chosen after obtaining access permission through Southern Research Institute. Since no FRRP study sites were identified in yellow polygons, these sites were selected during the field trip, and permission was obtained at the time of sampling. An explanatory letter from DCA, shown in Figure 2-1, helped obtain owners' permission to sample their soil. The green sites were planned for FRRP study areas in Tallahassee, but were moved to nearby Wakulla and Jefferson Counties because of difficulty in penetrating their hard clayey strata with a light-duty soil auger.

STATE OF FLORIDA
DEPARTMENT OF COMMUNITY AFFAIRS

EMERGENCY MANAGEMENT • HOUSING AND COMMUNITY DEVELOPMENT • RESOURCE PLANNING AND MANAGEMENT

LAWTON CHILES
Governor

LINDA LOOMIS SHELLEY
Secretary

March 9, 1995

MEMORANDUM

TO: Land Owners and Occupants

FROM: Mo Madani, Planning Manager MM

SUBJECT: Land Access to Conduct Soil Tests

The Department of Community Affairs has contracted with the University of Florida and its subcontractor, Rogers & Associates Engineering Corporation, to perform a research study for evaluating procedures allowing testing of land for soil radon; the procedures will provide an alternate method to the proposed Radon Protection map(s). The maps are the basis for implementing the proposed Radon-Resistant Construction Standards, which show the regions of Florida that require special radon protection. Specifically, the DCA is evaluating a site-specific soil test protocol by comparing actual soil tests with the statewide soil radon potential map predictions.

An essential part of this research study is the collection of soil samples and measurements from selected locations in Florida for benchmark evaluations of the site-specific procedures. This letter is to inform you of our intent and to ask permission for our contractors to perform soil sampling for measurement procedures on your lands. The following conditions apply to testing:

1. Soil samples will be collected from up to 5 boreholes, not larger than 4-inches in diameter and not deeper than 8 feet. [This approach is very similar to current testing done at building sites for foundation soils tests.] Related measurements may be made at the borehole locations. Soil samples removed from the property will be disposed of after testing and will not be returned; the samples are non-hazardous. The boreholes will be re-filled after sample collection, and there will be minimal surface disturbance.

2740 CENTERVIEW DRIVE • TALLAHASSEE, FLORIDA 32399-2100

FLORIDA KEYS AREA OF CRITICAL STATE CONCERN
FIELD OFFICE
2796 Overseas Highway, Suite 212
Marathon, Florida 33050-2227

SOUTH FLORIDA RECOVERY OFFICE
P.O. Box 4022
8600 N.W. 36th Street
Miami, Florida 33159-4022

GREEN SWAMP AREA OF CRITICAL STATE CONCERN
FIELD OFFICE
155 East Summerlin
Bartow, Florida 33830-4641

Figure 2-1. DCA letter requesting permission for site access.

2. One-time site access is required for a period of approximately 2 to 4 hours. The DCA contractors are insured for liability from any injury or damage related to this work; you assume no liability in granting them access to your property.

3. The results of all measurements and sample analysis is used anonymously for the DCA's research program as a part of a geographic database. The name and/or address of the property, occupant, or land owner is not disclosed publicly and is not associated with the data maintained by the DCA or its contractors. If the property owner or occupant requests a copy of the tests results, the measurements made only at the subject property will be mailed by the DCA contractor to the address designated by the owner or occupant.

We appreciate your cooperation in providing them a site for this important study to allow safe growth and habitation throughout Florida. If there are any questions concerning these testing activities, please feel free to contact the Radon Program office at (904) 921-2313 or my office at (904) 487-1824.

MM/dfr

cc: Mr Stanley Latimer, University of Florida, Department of Urban and Regional Planning
Mr Kirk K. Nielson, Rogers & Associates Engineering Corp.

Figure 2-1. DCA letter requesting permission for site access (continued).

The sites where the field sampling and measurement protocols were conducted are illustrated in Figure 2-2. The two red-category sites (as designated by the radon protection map) were located at the FRRP research site (Polk-1) and an adjacent commercial building property in Bartow (Polk-2). The three yellow-category sites were located in Hernando and Sumter Counties. The Hernando County site was located in a highway median area 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. Accordingly, only three complete boreholes were drilled on this site. 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 two green-category sites were located in Wakulla and Jefferson Counties. The Wakulla County site was on undisturbed land of a power line corridor, and the Jefferson County site was on vegetation-cleared land in the margin between a pine tree farm and a U.S. highway right-of-way.

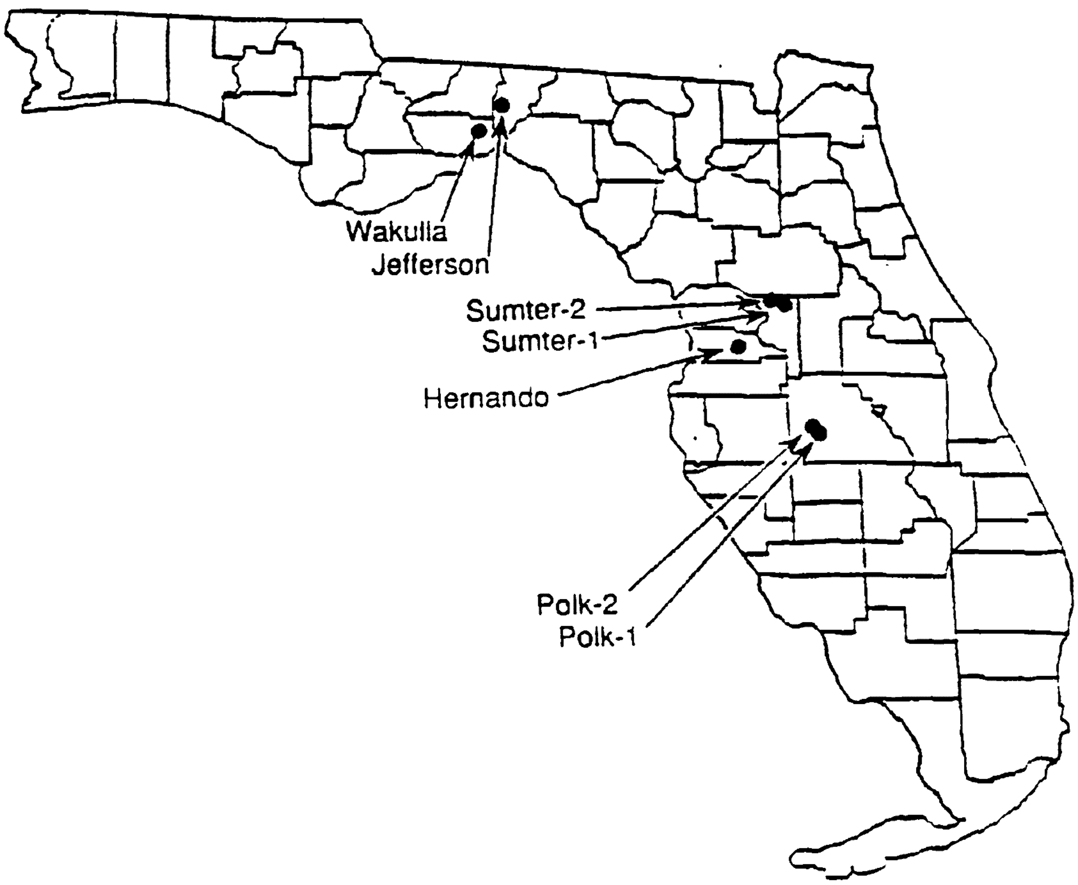

Figure 2-2. Field sampling locations.

2.3 FIELD PROCEDURES

The field sampling and measurement procedures conformed to the FRRP procedures given in "Standard Measurement Protocols, Florida Radon Research Program," (Wil91), or to American Society for Testing and Materials (ASTM) procedures where applicable procedures are given. For other tests or sampling needs, procedures were based on RAE field and laboratory practices. The field sampling and measurements were conducted during the period from March 12 to March 15, 1995. This section describes the procedures used for field measurements and for collection and analysis of the field samples.

2.3.1 Location

The latitude and longitude coordinates of each sampling and measurement site were measured using a global positioning system (NAV-5000D, Magellan Systems Corp., San Dimas, CA). These coordinates were subsequently analyzed by the Geographic Information System (GIS) at the University of Florida to positively determine the radon map polygon in which the tests were conducted. Individual sampling locations at each site were located at least 10 m apart, generally in an approximately square configuration.

2.3.2 Soil Sampling

At each site, five bore holes were sampled at each of the four prescribed depth increments, and two additional surface samples (0-61 cm depth) were collected for potential evaluation of the site from fewer borehole samples (as provided in Section 2.1.1 for small sites). The soil samples were collected from the drill cuttings of a 5-cm diameter soil auger (model 405.23, Arts Manufacturing & Supply, American Falls, ID) that was powered by a hand-held gasoline-powered drill (ED-2000, Echo, Inc., Lake Zurich, IL). The auger was threaded through a 5.5-cm hole in a surface platform that was used to collect and isolate soils from different depths (Figure 2-3). Upon attaining each incremental sampling depth (as measured on the augers), the drill was operated full speed without further depth advancement to bring all loose cuttings to the surface. The sample was then collected with a hand trowel from the surface pile of auger cuttings (Figure 2-3). After sample collection, the remaining material was cleaned from the surface platform before further advancing the auger to the next sampling depth. For clayey soils, the cuttings adhered to the auger, and were collected by removing the auger from the hole at regular depth intervals and manually removing the clayey soils from the auger.

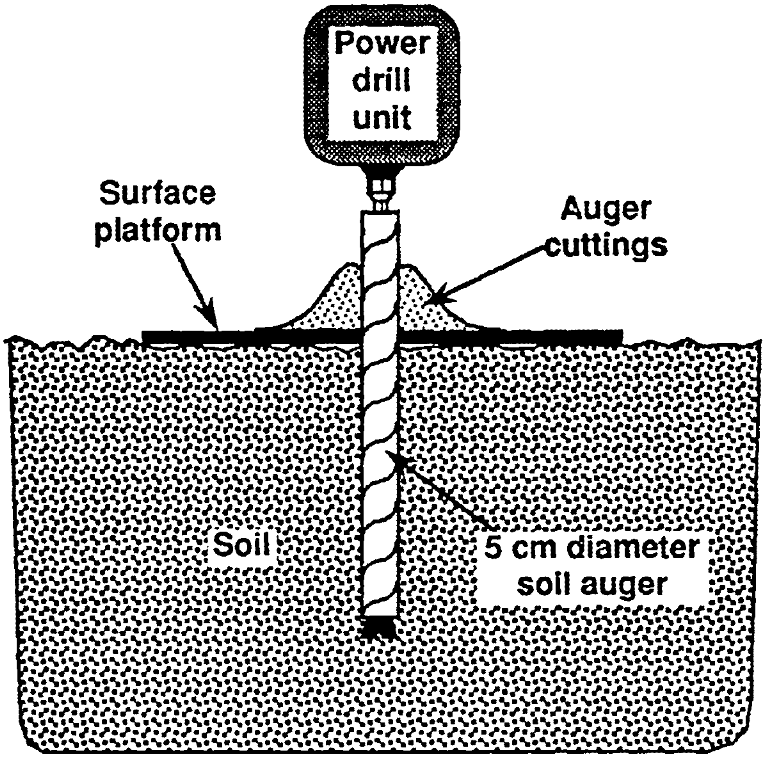

Figure 2-3. Soil sampling from auger cuttings.

Samples were immediately sealed into heavy gauge (0.1 mm) re-sealable polyethylene bags and labeled by site, location, and depth for transport to the RAE laboratory for radium assays. Approximately 350 g of soil was collected from each depth increment, and the remainder was discarded. The discarded cuttings were used to backfill each sampling hole after the samples were collected and sealed.

A density sample was collected at each site using a thin-walled steel drive cylinder, as prescribed by ASTM D2937 (Wil91). 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 completely transferred to a heavy gauge (0.1 mm) re-sealable polyethylene bag for weighing and moisture measurement in the laboratory.

Soil textural classifications were made from visual and tactile observations while bagging the auger cuttings for the radium samples. Water table depths similarly 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 state-wide radon maps (Nie95a).

Soil radon measurements were made from soil gas drawn from a depth of approximately 1 m using the internal pump in a portable radon monitor (AB-5, Pylon Electronics Inc., Ottawa, ON, Canada). The gas was drawn through a 6 mm I.D. steel pipe driven into the soil and connected by plastic tubing to the scintillation cell (110A, Pylon Electronics Inc., Ottawa, ON, Canada) and pump of the radon monitor. The monitor drew approximately 2 L min^{-1} of soil gas, and was operated for several minutes before connecting to the pipe to establish background. After connection to the soil gas pipe, the sampler was operated for approximately 10 to 35 minutes, after which the plastic tube was disconnected from the pipe to purge the cell with surface air. The alpha activity in the scintillation cell was counted over 2-minute intervals. Soil gas radon concentrations were computed from the continuously measured alpha counts using the calibration method and equations of Thomas and Countess (Tho79). The efficiency of the scintillation cell was determined previously from calibration analyses 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 utilized a 2.5-cm diameter sodium iodide gamma-ray scintillation probe connected to a digital scaler (Models 44-3 and 2220, Ludlum Measurements, Inc., Sweetwater, TX). 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 (Nie95b) 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.

2.4 LABORATORY PROCEDURES

The bore-hole soil samples were each weighed into tared steel cans and sealed for radium assay by the procedures described previously (Nie95a). The radium assays were performed after approximately 18 days equilibration. At least 10% duplicates, blanks, and standards were also analyzed for quality assurance purposes. Samples were dried as specified by ASTM D 2216-80 (Wil91), and the results were reported on a dry-mass basis. The soil density samples were completely transferred to laboratory beakers and dried as specified by ASTM D 2216-80 to determine dry sample density according to ASTM D 2937-83 (Wil91).

3. MEASUREMENT RESULTS

This chapter identifies the locations where site-specific measurements were performed and presents the results of the measurements and the supporting quality assurance data.

3.1 SITE LOCATIONS AND TEST RESULTS

The locations of each site and the results of the site-specific tests and laboratory analyses of field samples are presented in this section. The latitude and longitude coordinates of each test site are presented in Table 3-1, as they were measured by the global positioning system during the field sampling activities. The single coordinates correspond to an approximate centroid among the five site boreholes.

Table 3-1. Locations of the test sites.

Site	Latitude	Longitude
Polk-1	27° 53.676' N	81° 51.918' W
Polk-2	27° 53.765' N	81° 51.925' W
Sumter-1	28° 52.849' N	82° 05.238' W
Sumter-2	28° 56.095' N	82° 06.664' W
Hernando	28° 33.209' N	82° 18.129' W
Wakulla	30° 11.299' N	84° 11.484' W
Jefferson	30° 20.405' N	84° 00.935' W

Soil radium concentrations measured by laboratory assays of the borehole soil samples are presented in Table 3-2. The borehole gamma ray measurements at the centers of each sample depth interval are compared with the corresponding laboratory radium measurements in Figure 3-1. The scatter of the individual borehole measurements gives a correlation coefficient of $r^2 = 0.84$ for the least-squares regression of radium on gamma ray intensity. The least-squares fitted line is also compared with an independent calibration of the gamma ray probe, which is shown by the solid line in Figure 3-1. The independent calibration was used to estimate radium concentrations for each gamma ray measurement, and the resulting radium concentrations were averaged for each depth interval to obtain the comparison radium concentrations presented in Table 3-3. The averages and uncertainties in Table 3-3 weight the center measurement in each depth interval twice as much as measurements at the interval boundaries (neglecting the top surface boundary). Measured soil water contents and textural classifications for the depth intervals in each borehole are presented in Tables 3-4 and 3-5, respectively.

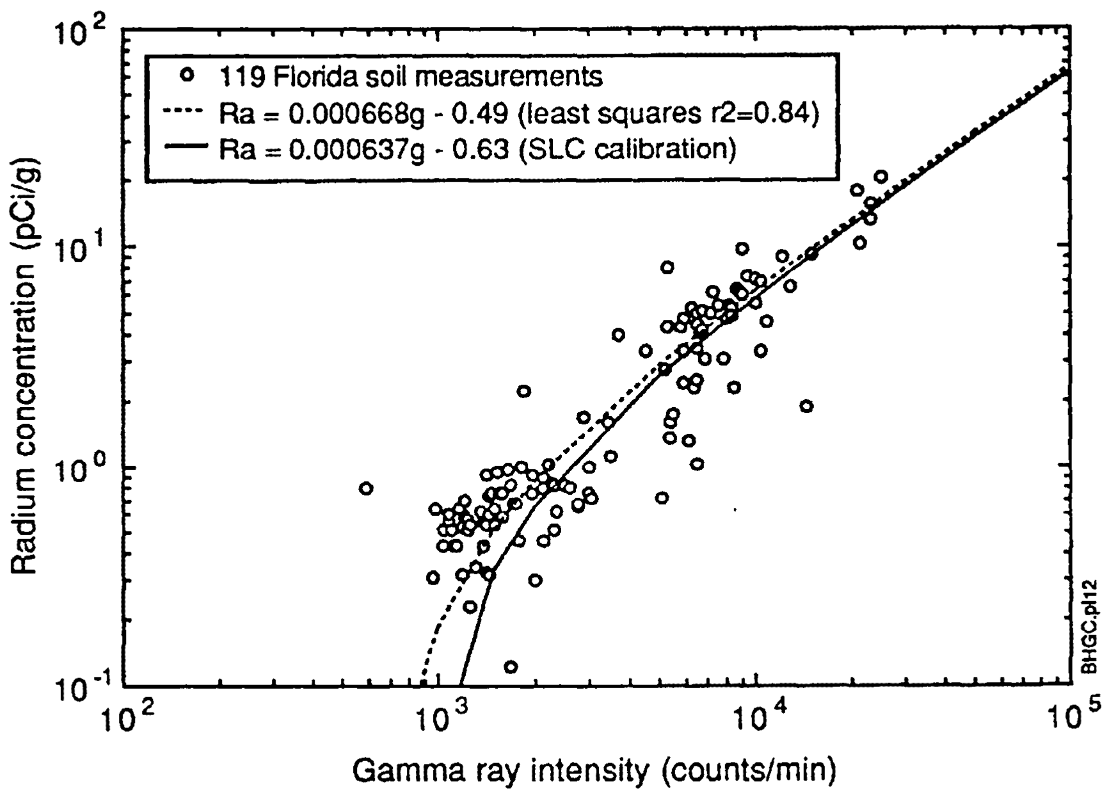

Figure 3-1. Comparison of laboratory assays with borehole measurements and gamma probe calibration.

Table 3-2. Radium assays of the borehole soil samples

Site and Depth (cm)	Soil Radium Concentration (pCi g^{-1} ± 1 s.d.[a])				
	Borehole 1	Borehole 2	Borehole 3	Borehole 4	Borehole 5
Polk-1					
0 - 61	4.3 ± 0.3	4.2 ± 0.3	6.1 ± 0.3	6.2 ± 0.3	4.7 ± 0.3
61 - 122	7.1 ± 0.3	5.2 ± 0.3	4.2 ± 0.2	7.2 ± 0.3	5.4 ± 0.3
122 - 183	5.6 ± 0.3	6.5 ± 0.2	9.0 ± 0.2	6.2 ± 0.3	4.4 ± 0.2
183 - 244	5.0 ± 0.2	4.9 ± 0.2	5.4 ± 0.3	5.2 ± 0.3	5.3 ± 0.2
Polk-2					
0 - 61	9.7 ± 0.3	2.3 ± 0.2	15.8 ± 0.3	8.1 ± 0.3	20.8 ± 0.3
61 - 122	4.8 ± 0.2	3.1 ± 0.2	18.0 ± 0.3	5.0 ± 0.3	10.2 ± 0.3
122 - 183	4.4 ± 0.2	1.7 ± 0.2	9.3 ± 0.3	3.4 ± 0.3	13.4 ± 0.3
183 - 244	2.4 ± 0.2	7.3 ± 0.3	3.1 ± 0.2	4.6 ± 0.2	6.5 ± 0.3
Sumter-1					
0 - 61	0.8 ± 0.2	0.9 ± 0.2	1.0 ± 0.2	0.5 ± 0.2	0.8 ± 0.2
61 - 122	0.7 ± 0.2	0.8 ± 0.2	0.8 ± 0.2	0.6 ± 0.2	0.1 ± 0.2
122 - 183	0.3 ± 0.2	0.7 ± 0.2	1.7 ± 0.2	0.9 ± 0.2	0.5 ± 0.2
183 - 244	2.3 ± 0.3	1.9 ± 0.2	3.4 ± 0.3	1.0 ± 0.2	4.0 ± 0.3
Sumter-2					
0 - 61	0.6 ± 0.2	0.6 ± 0.2	0.5 ± 0.2	0.2 ± 0.2	0.4 ± 0.2
61 - 122	0.5 ± 0.2	0.6 ± 0.2	0.5 ± 0.2	0.4 ± 0.2	0.5 ± 0.2
122 - 183	0.6 ± 0.2	0.5 ± 0.2	0.6 ± 0.2	0.3 ± 0.2	0.3 ± 0.2
183 - 244	1.6 ± 0.2	1.6 ± 0.3	1.1 ± 0.2	3.4 ± 0.3	0.5 ± 0.2
Hernando					
0 - 61	0.8 ± 0.2	0.9 ± 0.2	0.7 ± 0.2	---[b]	---
61 - 122	0.5 ± 0.2	0.7 ± 0.2	0.5 ± 0.2	---	---
122 - 183	1.3 ± 0.2	1.0 ± 0.2	0.4 ± 0.2	---	---
183 - 244	3.5 ± 0.3	2.5 ± 0.3	1.0 ± 0.2	---	---
Wakulla					
0 - 61	0.8 ± 0.2	0.6 ± 0.2	0.9 ± 0.2	1.3 ± 0.2	0.8 ± 0.2
61 - 122	0.7 ± 0.2	0.6 ± 0.2	0.9 ± 0.2	1.7 ± 0.3	0.9 ± 0.2
122 - 183	2.0 ± 0.3	1.1 ± 0.3	0.5 ± 0.2	2.1 ± 0.3	2.4 ± 0.3
183 - 244	2.2 ± 0.3	1.3 ± 0.3	0.9 ± 0.2	0.8 ± 0.3	2.4 ± 0.3
Jefferson					
0 - 61	0.3 ± 0.3	0.6 ± 0.3	0.6 ± 0.3	0.4 ± 0.2	0.5 ± 0.2
61 - 122	0.7 ± 0.3	0.6 ± 0.2	0.4 ± 0.2	0.8 ± 0.2	0.6 ± 0.2
122 - 183	1.0 ± 0.2	0.6 ± 0.2	0.8 ± 0.2	0.7 ± 0.2	0.3 ± 0.2
183 - 244	0.9 ± 0.3	0.8 ± 0.3	0.8 ± 0.3	0.8 ± 0.3	0.6 ± 0.2

[a]1 standard deviation uncertainties, as computed from gamma-ray counting statistics.
[b]Only three complete boreholes were sampled at this site.

Table 3-3. Radium estimated from the borehole gamma ray measurements

Site and Depth (cm)	Soil Radium Concentration (pCi g^{-1} ± 1 s.d.[a])				
	Borehole 1	Borehole 2	Borehole 3	Borehole 4	Borehole 5
Polk-1					
0 - 61	3.2 ± 0.3	3.5 ± 0.3	4.4 ± 0.8	3.9 ± 0.3	5.1 ± 1.4
61 - 122	5.4 ± 1.3	4.5 ± 0.8	4.0 ± 0.9	5.1 ± 0.7	5.3 ± 1.1
122 - 183	5.7 ± 0.6	5.4 ± 0.9	5.7 ± 1.2	4.7 ± 0.8	4.1 ± 1.2
183 - 244	4.3 ± 0.7	5.0 ± 1.1	4.0 ± 0.3	3.5 ± 0.3	3.4 ± 0.3
Polk-2					
0 - 61	4.3 ± 1.0	4.4 ± 0.4	12.9 ± 0.3	4.5 ± 3.2	13.2 ± 1.3
61 - 122	3.1 ± 0.3	3.3 ± 0.7	11.6 ± 1.4	4.5 ± 2.5	13.2 ± 2.8
122 - 183	2.7 ± 0.4	3.1 ± 0.9	7.5 ± 2.6	3.3 ± 0.6	13.1 ± 3.3
183 - 244	3.5 ± 1.5	5.1 ± 0.5	4.6 ± 1.1	6.1 ± 1.7	8.3 ± 1.5
Sumter-1					
0 - 61	0.6 ± 0.3	0.8 ± 0.3	0.6 ± 0.3	0.4 ± 0.3	0.6 ± 0.3
61 - 122	0.7 ± 0.3	1.0 ± 0.3	0.8 ± 0.3	0.5 ± 0.3	0.6 ± 0.3
122 - 183	1.1 ± 0.7	1.5 ± 0.7	1.9 ± 1.4	0.5 ± 0.3	0.7 ± 0.3
183 - 244	3.0 ± 0.6	7.7 ± 4.1	5.3 ± 0.9	0.7 ± 0.3	2.1 ± 1.4
Sumter-2					
0 - 61	0.4 ± 0.3	0.4 ± 0.3	0.4 ± 0.3	0.4 ± 0.3	0.3 ± 0.3
61 - 122	0.4 ± 0.3	0.5 ± 0.3	0.5 ± 0.3	0.4 ± 0.3	0.4 ± 0.3
122 - 183	0.5 ± 0.3	1.1 ± 0.8	0.6 ± 0.3	0.5 ± 0.3	0.3 ± 0.3
183 - 244	1.7 ± 1.0	2.6 ± 0.3	1.5 ± 0.4	2.0 ± 0.9	0.3 ± 0.3
Hernando					
0 - 61	0.7 ± 0.3	1.0 ± 0.3	0.5 ± 0.3	---[b]	---
61 - 122	1.2 ± 0.5	2.4 ± 0.9	0.5 ± 0.3	---	---
122 - 183	2.7 ± 0.6	3.4 ± 0.3	0.5 ± 0.3	---	---
183 - 244	3.4 ± 0.3	3.4 ± 0.3	1.3 ± 0.4	---	---
Jefferson					
0 - 61	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.3
61 - 122	0.5 ± 0.3	0.4 ± 0.3	0.4 ± 0.3	0.6 ± 0.3	0.2 ± 0.3
122 - 183	0.9 ± 0.3	1.0 ± 0.3	0.9 ± 0.3	1.3 ± 0.3	0.4 ± 0.3
183 - 244	1.0 ± 0.3	1.2 ± 0.3	1.1 ± 0.3	1.4 ± 0.3	0.4 ± 0.3

[a]1 standard deviation uncertainties computed from measurement variations within depth intervals and gamma ray counting statistics.
[b]Only three complete boreholes were sampled at this site.

Table 3-4. Water contents of the borehole soil samples

Site and Depth (cm)	Water Content (% of dry mass)				
	Borehole 1	Borehole 2	Borehole 3	Borehole 4	Borehole 5
Polk-1					
0 - 61	5.4	4.7	4.3	6.0	4.2
61 - 122	6.2	5.8	4.5	5.0	4.9
122 - 183	6.2	6.6	5.5	5.9	5.2
183 - 244	5.2	4.4	5.3	5.6	5.1
Polk-2					
0 - 61	7.5	4.5	11.8	7.5	11.5
61 - 122	5.0	6.7	9.7	5.9	10.4
122 - 183	5.5	6.0	9.4	5.5	11.2
183 - 244	4.9	9.1	5.9	4.5	8.6
Sumter-1					
0 - 61	5.2	6.0	7.0	5.5	4.8
61 - 122	4.3	4.6	4.5	4.4	4.5
122 - 183	3.7	3.9	9.0	4.4	4.1
183 - 244	10.6	7.7	13.1	7.7	11.9
Sumter-2					
0 - 61	5.5	4.7	4.8	6.4	4.7
61 - 122	4.7	4.1	4.2	5.2	4.2
122 - 183	3.6	3.6	3.2	3.7	3.3
183 - 244	10.7	11.5	8.8	13.3	7.0
Hernando					
0 - 61	5.7	6.0	9.7	---[a]	---
61 - 122	4.5	5.3	5.9	---	---
122 - 183	9.5	5.6	5.0	---	---
183 - 244	14.6	13.0	10.0	---	---
Wakulla					
0 - 61	14.0	14.3	16.4	23.8	18.5
61 - 122	16.4	20.7	16.3	27.3	20.6
122 - 183	31.3	45.7	16.2	32.9	53.7
183 - 244	39.9	54.1	20.1	61.3	51.6
Jefferson					
0 - 61	6.1	5.8	6.5	6.1	6.2
61 - 122	5.7	6.1	9.8	7.0	6.4
122 - 183	11.5	12.0	14.5	13.8	12.9
183 - 244	16.3	18.8	16.5	25.3	16.6

[a]Only three complete boreholes were sampled at this site.

Table 3-5. Textural classifications of the borehole soil samples

Site and Depth (cm)	Textural Classification				
	Borehole 1	Borehole 2	Borehole 3	Borehole 4	Borehole 5
Polk-1					
0 - 61	Sand	Sand	Sand	Sand	Sand
61 - 122	Sand	Sand	Sand	Sand	Sand
122 - 183	Sand	Sand	Sand	Sand	Sand
183 - 244	Sand	Sand	Sand	Sand	Sand
Polk-2					
0 - 61	Sand	Sand	Sandy Loam	Sand	Sandy Loam
61 - 122	Sand	Sand	Loamy Sand	Sand	Sand
122 - 183	Sand	Sand	Sand	Sand	Sand
183 - 244	Sand	Sand	Sand	Sand	Sand
Sumter-1					
0 - 61	Sand	Sand	Sand	Sand	Sand
61 - 122	Sand	Sand	Sand	Sand	Sand
122 - 183	Sand	Sand	Sand	Sand	Sand
183 - 244	Loamy Sand	Sand	Sandy Loam	Sand	Loamy Sand
Sumter-2					
0 - 61	Sand	Sand	Sand	Sand	Sand
61 - 122	Sand	Sand	Sand	Sand	Sand
122 - 183	Sand	Sand	Sand	Sand	Sand
183 - 244	Sand	Loamy Sand	Sand	Sandy Loam	Sand
Hernando					
0 - 61	Sand	Sand	Sand	---[a]	---
61 - 122	Sand	Sand	Sand	---	---
122 - 183	Loamy Sand	Sand	Sand	---	---
183 - 244	Sandy Loam	Loamy Sand	Sand	---	---
Wakulla					
0 - 61	Sa Cl Loam	Sa Cl Loam	Sandy Clay	Clay	Clay Loam
61 - 122	Sandy Clay	Clay	Sandy Clay	Clay	Clay
122 - 183	Clay	Clay	Sandy Clay	Clay	Clay
183 - 244	Clay	Clay	Clay	Clay	Clay
Jefferson					
0 - 61	Sand	Sand	Sand	Sand	Sand
61 - 122	Sand	Sand	Sand	Sand	Sand
122 - 183	Loamy Sand	Loamy Sand	Sandy Loam	Loamy Sand	Loamy Sand
183 - 244	Sandy Loam	Sandy Clay	Sandy Loam	Clay Loam	Sandy Loam

[a]Only three complete boreholes were sampled at this site.

The radium profiles at undisturbed sites show a general trend of increasing concentration with depth, while radium at the reclaimed-land sites (Polk-1 and Polk-2) shows a more uniform or decreasing concentration with depth. The trends in water contents and textural classes show a tendency toward sandy cover soils over wetter, finer-grained soils at depth for the undisturbed sites. The radium concentrations, water contents, and textural classifications in the supplemental surface soil samples, as described in section 2.1.1, are presented in Table 3-6. These properties are generally consistent with the surface (0 to 61 cm depth) soil properties in Tables 3-2 through 3-5.

Table 3-6. Radium, water, and texture of surface soil samples

	Surface Location 1			Surface Location 2		
Site	Radium[a]	Water[b]	Texture[c]	Radium[a]	Water[b]	Texture[c]
Polk-1	4.7 ± 0.3	5.7	Sand	5.1 ± 0.3	3.0	Sand
Polk-2	11.7 ± 0.3	10.7	Sand	10.8 ± 0.3	5.6	Sand
Sumter-1	3.2 ± 0.3	8.3	Sand	0.9 ± 0.2	5.1	Sand
Sumter-2	0.6 ± 0.2	4.7	Sand	0.6 ± 0.2	5.3	Sand
Hernando	1.0 ± 0.2	4.6	Sand	1.0 ± 0.2	8.8	Sand
Wakulla	0.6 ± 0.2	20.5	Clay	0.8 ± 0.2	15.6	Clay
Jefferson	0.6 ± 0.2	6.7	Sand	0.4 ± 0.3	6.3	Sand

[a]pCi g^{-1} dry basis ± 1 standard deviation (uncertainty computed from counting statistics).
[b]Percent of dry soil mass.
[c]SCS soil texture class (SCS75).

The results of the soil density, soil radon, and water table measurements are presented in Table 3-7. The density measurements represent single samples at each site. The soil radon measurements similarly represent individual sampling locations. However, the concentrations represent averages of multiple counting intervals, from which the standard deviations were calculated. The water table was only observed at the Wakulla site; therefore the minimum depths and durations were primarily estimated from the Statsgo data (SCS91) used previously in developing the Florida radon maps (Nie95a).

Table 3-7. Soil density, radon, and water table measurements.

Site	Soil Density ($g\ cm^{-3}$)	Soil Radon ($pCi\ L^{-1}$)[a]	Water Table: Minimum Depth (cm)	Water Table: Duration[b] (months)	Basis[c]
Polk-1	1.60	1,600 ± 230 2,980 ± 60	152	3	Statsgo 110
Polk-2	1.62	1,360 ± 150 4,130 ± 150	152	3	Statsgo 110
Sumter-1	1.49	684 ± 75	183	6	Statsgo 120
Sumter-2	1.51	515 ± 54	183	6	Statsgo 120
Hernando	1.43	1,200 ± 60	183	6	Statsgo 121
Wakulla	1.68	15 ± 1[d]	61	12	Statsgo 45 & Field Meas.
Jefferson	1.41	91 ± 26	183	6	Statsgo 40

[a]From soil gas sample drawn from 1 m depth.
[b]Duration of high water table level.
[c]Water table data for the indicated Statsgo soil map units (Nie95a) or measurements.
[d]Incomplete sample owing to impermeable soil.

3.2 QUALITY ASSURANCE DATA

The 152 radium assays reported in Tables 3-2 and 3-6 were performed according to the protocols presented in Nie95a. These protocols have previously achieved prescribed standards of precision and accuracy (Nie95a). To demonstrate similar achievement of the same data quality objectives, additional analyses were performed to determine the precision and accuracy of the present radium assays. The extra analyses included approximately 10% duplicate assays, 10% blanks, and 10% replicate analyses of standards.

Two separate estimates of analytical precision were obtained from the radium assay data. The first is estimated from the average statistical precision of each assay. Expressing the precision as a relative standard deviation (standard deviation ÷ mean), the average of all assays for samples exceeding 2 pCi g^{-1} was 6.0%, compared to a data quality objective of 20% for this parameter. The second estimate of analytical precision was determined from the analyses of duplicate assays, which are reported in Table 3-8. The differences among duplicates, reported in the last column of Table 3-8, were averaged to obtain 0.0 pCi g^{-1}, which is an indication of no net bias. The average absolute difference, 0.2 pCi g^{-1}, indicates the average absolute agreement between the pairs of analyses. The relative standard deviation between the pairs of duplicate analyses was 4.3%, well within the 20% precision objective even though only 7 of the 16 pairs of duplicate assays exceeded 2 pCi g^{-1}. The relative standard deviation was computed as

$$RSD_{dup} = \sqrt{2n\sum(x_1-x_2)^2} \,/\, \sum(x_1+x_2) \tag{1}$$

where

RSD_{dup} = relative standard deviation among duplicates

x_1 = first observation

x_2 = second observation

n = number of pairs being compared.

Table 3-8. Comparison of duplicate radium assays to analytical precision.

Sample	Duplicate Assay Radium ± uncertainty ($pCi\ g^{-1}$)	Reference Radium Concentration ($pCi\ g^{-1}$)	Difference ($pCi\ g^{-1}$)
Polk-1, H-1, 4-6	5.8 ± 0.3	5.6	0.2
Polk-1, H-5, 4-6	4.6 ± 0.2	4.4	0.2
Polk-2, H-3, 2-4	18.0 ± 0.3	18.0	0.0
Polk-2, H-4, 6-8	4.7 ± 0.2	4.6	0.1
Polk-2, H-5, 0-2	20.5 ± 0.3	20.8	-0.3
Polk-2, H-5, 2-4	10.4 ± 0.2	10.2	0.1
Hernando, H-2, 2-4	0.8 ± 0.2	0.5	0.3
Hernando, H-5, 0-2	0.8 ± 0.2	0.7	0.1
Sumter-1, H-2, 0-2	0.8 ± 0.2	0.9	-0.1
Sumter-1, H-4, 4-6	0.3 ± 0.2	0.9	-0.6
Sumter-2, H-1, 0-2	0.4 ± 0.2	0.6	-0.2
Sumter-2, H-5, 0-2	0.4 ± 0.2	0.4	0.0
Wakulla, H-2, 2-4	0.5 ± 0.2	0.6	0.0
Wakulla, H-4, 4-6	1.6 ± 0.3	2.1	-0.5
Jefferson, H-3, 2-4	0.7 ± 0.2	0.4	0.3
Jefferson, H-5, 6-8	0.5 ± 0.2	0.6	-0.2
Average Difference ($pCi\ g^{-1}$)			0.0
Average Absolute Difference ($pCi\ g^{-1}$)			0.2
Relative Std. Dev. (all 16 pairs)			4.3%

Estimates of accuracy were made from analyses of blanks and from analyses of standards. The analyses of blanks utilized a 300 g aliquot of onyx rock that had been previously determined by extended counting to contain negligible quantities of radium or thorium (<0.1 $pCi\ g^{-1}$). The blank sample was sealed in a can identical to those used for the soil samples, and was counted repeatedly during the periods of sample analysis. The results of these counts are presented in Table 3-9. The average quantity of radium measured in the blank was 0.1 ± 0.2 $pCi\ g^{-1}$, well within the analytical standard deviation of ±0.2 $pCi\ g^{-1}$.

Table 3-9. Replicate radium assays of the blank sample.

$^{226}Ra \pm$ s.d. (pCi g^{-1})	$^{226}Ra \pm$ s.d. (pCi g^{-1})	$^{226}Ra \pm$ s.d. (pCi g^{-1})	$^{226}Ra \pm$ s.d. (pCi g^{-1})
0.0 ± 0.2	0.5 ± 0.2	0.0 ± 0.2	0.1 ± 0.2
0.4 ± 0.2	0.0 ± 0.2	0.1 ± 0.2	0.1 ± 0.2
0.3 ± 0.2	0.3 ± 0.2	0.3 ± 0.2	0.0 ± 0.2
0.3 ± 0.2	0.3 ± 0.2	0.1 ± 0.2	-0.2 ± 0.2
-0.3 ± 0.2			
		Average:	0.1 ± 0.2

The accuracy goal for the radium assays was to demonstrate agreement of better than ± 10% with standard reference materials. The reference material used with these analyses was prepared and distributed by the U.S. Department of Energy's Division of Remedial Action Projects through their Technical Measurements Center, which was operated by Bendix Field Engineering Corp. in Grand Junction, CO. The standard was certified to contain 15.12 ± 0.23 pCi g^{-1} of ^{226}Ra. It was sealed into a can identical to those used for the soil samples, and was counted at various times during the period when the soil samples were counted. The results of the assays on the standard are presented in Table 3-10. Their average bias of only 2% was well within the 10% accuracy goal, and demonstrates acceptable accuracy for this study.

Table 3-10. Replicate radium assays of the radium standard.

$^{226}Ra \pm$s.d. (pCi g^{-1})	Ra/Ref.	$^{226}Ra \pm$s.d. (pCi g^{-1})	Ra/Ref.	$^{226}Ra \pm$s.d. (pCi g^{-1})	Ra/Ref.	$^{226}Ra \pm$s.d. (pCi g^{-1})	Ra/Ref.
15.7 ± 0.4	1.036	15.8 ± 0.4	1.048	15.7 ± 0.4	1.036	15.4 ± 0.4	1.022
15.3 ± 0.4	1.010	15.1 ± 0.4	0.997	15.5 ± 0.4	1.022	15.6 ± 0.4	1.032
15.1 ± 0.4	0.999	15.5 ± 0.4	1.023	15.4 ± 0.4	1.021	15.4 ± 0.4	1.016
15.6 ± 0.4	1.034	15.6 ± 0.4	1.031	15.5 ± 0.4	1.023	14.9 ± 0.4	0.982
15.2 ± 0.4	1.005						
					Average:	15.4 ± 0.3	1.020 ± 0.017

4. MODEL ANALYSES AND MAP COMPARISONS

The measurements presented in Chapter 3 were analyzed with the RAETRAD-F model (Rog95) to determine the radon potential category of each site. These determinations were then compared with the categories assigned by the radon protection map. More general sensitivity analyses were also performed with the RAETRAD-F model to assess the general agreement between the site-specific modeling approach and the state-wide radon protection map classifications.

4.1 MODEL ANALYSES OF RADON PROTECTION CATEGORY

The measurements from each of the seven sites were analyzed by the RAETRAD-F model as described in Section 2.1.7 to determine their site radon potential category. Radium distributions were entered for all five boreholes from six of the sites to represent a 1-acre parcel of land. For the Hernando County site, the three completed boreholes were used to represent a half-acre area (Nie96). Corresponding soil texture classes were used as listed in Table 3-5, and soil density, soil radon, and water table data were used as listed in Table 3-7. The resulting printouts from the RAETRAD-F code for each analysis are presented in Figures 4-1 through 4-7 for the respective Polk-1, Polk-2, Hernando, Sumter-1, Sumter-2, Wakulla, and Jefferson County sites.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 27.8946 Deg N, 81.8653 Deg W
County: Polk
State: Florida
Zipcode:

Run Date: 4-14-1995
Run Time: 8:31
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.605
Average Site Soil Texture: Sand

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	4.30	4.20	6.10	6.20	4.70
2 - 4 ft	7.10	5.20	4.20	7.20	5.40
4 - 6 ft	5.60	6.50	9.00	6.20	4.40
6 - 8 ft	5.00	4.90	5.40	5.20	5.30

Soil Radon Concentrations (pCi/L)

Sample 1	Sample 2
1600.0	2978.0

Water Table Depth (ft)

Months	Depth
3.00	5.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 35.2 pCi/L

This site is in a
RED
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt

Agent for: RAE

Figure 4-1. RAETRAD-F printout for the Polk-1 site.

```
                    Analysis of Site Test Data for
          RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
                         using RAETRAD-F  v.1.1
                              written by
              Rogers & Associates Engineering Corporation

SITE Location: 27.8961 Deg N, 81.8654 Deg W
       County: Polk                                  Run Date:  4-14-1995
        State: Florida                               Run Time:  8:25
      Zipcode:                                           User: Rodger Holt

INPUT DATA Measured by: RAE
                       Average Site Dry Density (g/cc):   1.616

          Radium Concentrations (pCi/g)
            Depth    Hole  1  Hole  2  Hole  3  Hole  4  Hole  5
          --------  -------  -------  -------  -------  -------
          0 - 2 ft     9.70     2.30    15.80     8.10    20.80
          2 - 4 ft     4.80     3.10    18.00     5.00    10.20
          4 - 6 ft     4.40     1.70     9.30     3.40    13.40
          6 - 8 ft     2.40     7.30     3.10     4.60     6.50

          Soil Textures
            Depth    Hole  1  Hole  2  Hole  3  Hole  4  Hole  5
          --------  -------  -------  -------  -------  -------
          0 - 2 ft  Sand     Sand     SaLom    Sand     SaLom
          2 - 4 ft  Sand     Sand     LSand    Sand     Sand
          4 - 6 ft  Sand     Sand     Sand     Sand     Sand
          6 - 8 ft  Sand     Sand     Sand     Sand     Sand

          Soil Radon Concentrations (pCi/L)
          Sample 1  Sample 2
          --------  --------
           1363.0    4128.0

          Water Table Depth (ft)
           Months     Depth
          --------  --------
            3.00      5.00

RESULTS   +-----------------------------------------------------+
          |                                                     |
          |   RESIDENTIAL SITE INDOOR RADON POTENTIAL: 104.5 pCi/L   |
          |                                                     |
          |                  This site is in a                  |
          |                         RED                         |
          |    radon protection category as referenced by the   |
          |              Florida Radon Protection Map           |
          |                                                     |
          +-----------------------------------------------------+

I certify that the site and input data are correct to the best of my knowledge.


___________________________________      ___________________________________
Rodger Holt                              Agent for: RAE
```

Figure 4-2. RAETRAD-F printout for the Polk-2 site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 28.8808 Deg N, 82.0873 Deg W
County: Sumter
State: Florida
Zipcode:

Run Date: 4-14-1995
Run Time: 8:19
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.490

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	.80	.90	1.00	.50	.80
2 - 4 ft	.70	.80	.80	.60	.10
4 - 6 ft	.30	.70	1.70	.90	.50
6 - 8 ft	2.30	1.90	3.40	1.00	4.00

Soil Textures

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	Sand	Sand	Sand	Sand	Sand
2 - 4 ft	Sand	Sand	Sand	Sand	Sand
4 - 6 ft	Sand	Sand	Sand	Sand	Sand
6 - 8 ft	LSand	Sand	SaLom	Sand	LSand

Soil Radon Concentrations (pCi/L)

Sample 1
684.0

Water Table Depth (ft)

Months	Depth
6.00	6.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 8.1 pCi/L

This site is in a
YELLOW
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt

Agent for: RAE

Figure 4-3. RAETRAD-F printout for the Sumter-1 site.

```
                    Analysis of Site Test Data for
          RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
                       using RAETRAD-F  v.1.1
                             written by
              Rogers & Associates Engineering Corporation

SITE Location: 28.9349 Deg N, 82.1111 Deg W
       County: Sumter                          Run Date:  4-14-1995
        State: Florida                         Run Time:  8:16
      Zipcode:                                     User: Rodger Holt

INPUT DATA Measured by: RAE
                        Average Site Dry Density (g/cc):    1.509

          Radium Concentrations (pCi/g)
            Depth    Hole  1  Hole  2  Hole  3  Hole  4  Hole  5
          --------   -------  -------  -------  -------  -------
          0 - 2 ft       .60      .60      .50      .20      .40
          2 - 4 ft       .50      .60      .50      .40      .50
          4 - 6 ft       .60      .50      .60      .30      .30
          6 - 8 ft      1.60     1.60     1.10     3.40      .50

          Soil Textures
            Depth    Hole  1  Hole  2  Hole  3  Hole  4  Hole  5
          --------   -------  -------  -------  -------  -------
          0 - 2 ft   Sand     Sand     Sand     Sand     Sand
          2 - 4 ft   Sand     Sand     Sand     Sand     Sand
          4 - 6 ft   Sand     Sand     Sand     Sand     Sand
          6 - 8 ft   Sand     LSand    Sand     SaLom    Sand

          Soil Radon Concentrations (pCi/L)
          Sample 1
          --------
            515.0

          Water Table Depth (ft)
           Months     Depth
           --------  --------
            6.00       6.00

RESULTS   +-----------------------------------------------------------+
          |                                                           |
          |   RESIDENTIAL SITE INDOOR RADON POTENTIAL:    3.7 pCi/L   |
          |                                                           |
          |                    This site is in a                      |
          |                          GREEN                            |
          |     radon protection category as referenced by the        |
          |              Florida Radon Protection Map                 |
          |                                                           |
          +-----------------------------------------------------------+

I certify that the site and input data are correct to the best of my knowledge.


____________________________________     ____________________________________
Rodger Holt                              Agent for: RAE
```

Figure 4-4. RAETRAD-F printout for the Sumter-2 site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 28.5535 Deg N, 82.3022 Deg W
County: Hernando — Run Date: 4-14-1995
State: Florida — Run Time: 8:22
Zipcode: — User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.433

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3
0 - 2 ft	.80	.90	.70
2 - 4 ft	.50	.70	.50
4 - 6 ft	1.30	1.00	.40
6 - 8 ft	3.50	2.50	1.00

Soil Textures

Depth	Hole 1	Hole 2	Hole 3
0 - 2 ft	Sand	Sand	Sand
2 - 4 ft	Sand	Sand	Sand
4 - 6 ft	LSand	Sand	Sand
6 - 8 ft	SaLom	LSand	Sand

Soil Radon Concentrations (pCi/L)

Sample 1
1197.0

Water Table Depth (ft)

Months	Depth
6.00	6.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 6.8 pCi/L

This site is in a
YELLOW
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt — Agent for: RAE

Figure 4-5. RAETRAD-F printout for the Hernando site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 30.1883 Deg N, 84.1914 Deg W
County: Wakulla
State: Florida
Zipcode:

Run Date: 4-14-1995
Run Time: 8:12
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.676

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	.80	.60	.90	1.30	.80
2 - 4 ft	.70	.60	.90	1.70	.90
4 - 6 ft	2.00	1.10	.50	2.10	2.40
6 - 8 ft	2.20	1.30	.90	.80	2.40

Soil Textures

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	SaCLm	SaCLm	SaCly	Clay	CLoam
2 - 4 ft	SaCly	Clay	SaCly	Clay	Clay
4 - 6 ft	Clay	Clay	SaCly	Clay	Clay
6 - 8 ft	Clay	Clay	Clay	Clay	Clay

Soil Radon Concentrations (pCi/L)

Sample 1
15.0

Water Table Depth (ft)

Months	Depth
3.00	2.00
3.00	2.00
3.00	2.00
3.00	2.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 2.1 pCi/L

This site is in a
GREEN
radon protection category as referenced by the
Florida Radon Potential Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt

Agent for: RAE

Figure 4-6. RAETRAD-F printout for the Wakulla site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 30.3401 Deg N, 84.0156 Deg W
County: Jefferson
State: Florida
Zipcode:

Run Date: 4-14-1995
Run Time: 8:08
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.407

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	.30	.60	.60	.40	.50
2 - 4 ft	.70	.60	.40	.80	.60
4 - 6 ft	1.00	.60	.80	.70	.30
6 - 8 ft	.90	.80	.80	.80	.60

Soil Textures

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	Sand	Sand	Sand	Sand	Sand
2 - 4 ft	Sand	Sand	Sand	Sand	Sand
4 - 6 ft	LSand	LSand	SaLom	LSand	LSand
6 - 8 ft	SaLom	SaCly	SaLom	CLoam	SaLom

Soil Radon Concentrations (pCi/L)

Sample 1
91.0

Water Table Depth (ft)

Months	Depth
6.00	6.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 2.1 pCi/L

This site is in a
GREEN
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt

Agent for: RAE

Figure 4-7. RAETRAD-F printout for the Jefferson site.

The potential radon concentrations and site classifications from these analyses are presented in columns 3 and 4 of Table 4-1 for comparison with the classifications of the radon protection maps. Both of the sites that were located in an elevated radon potential category (as designated by the radon protection map) were determined to have a corresponding elevated (Red) 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 (Green) radon potential classification by the site-specific tests.

Table 4-1. 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.

Corresponding separate model analyses used alternative radium distributions that were estimated from the borehole gamma ray measurements (Table 3-3) instead of the laboratory radium assays. The individual RAETRAD-F printouts from these analyses are presented in the Appendix. The potential radon concentrations and site classifications from these analyses are summarized in columns 5 and 6 of Table 4-1 for comparison with the previous analyses and the map classifications. Both of the sites that were located in an elevated radon potential category (as designated by the radon protection map) were again determined to have a corresponding elevated (Red) radon potential classification by the site-specific tests that used borehole gamma ray logs. Two of the three sites that were mapped in the intermediate radon potential category (Sumter-1 and Hernando) were also found to have an elevated (Red) radon potential classification when the model analyses utilized the alternative radium distributions from the borehole gamma ray 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 site-specific tests. The two sites mapped in the low radon potential category were both determined to have a corresponding low (Green) radon potential classification by the alternative model analyses.

The comparisons summarized in Table 4-1 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 (Nie94; Nie95a). The only other sites showing differences, Sumter-1 and Hernando, were correctly modeled from the laboratory radium assays but were conservatively modeled by the borehole gamma ray logs. 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 Sumter-2 sites could also be attributed to random variation, since they are within approximately 8-12% of the respective 8.3 pCi L^{-1} and 4.0 pCi L^{-1} map category cut points.

The sites selected for this study showed good correspondence between the detailed field tests and the map predictions. The measurements and analyses comprise an acceptable benchmark between measured and mapped radon potentials. It should be noted that the potential radon concentrations printed in Figures 4-1 through 4-7, in the Appendix, and in Table 4-1 are 95% confidence limit values, as described in section 2.1.7, and should not be confused with median or most likely site radon levels.

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.

4.2 GENERALIZED MODEL-MAP COMPARISONS

A second, more generalized comparison was also made between RAETRAD-F calculations and the data plotted on the state-wide radon protection map. This comparison addressed each of the 3,919 polygons except those controlled by lakes or other surface water, but it relied on generic data rather than site-specific measurements for input to the RAETRAD-F code.

The basis of the generalized model-map comparisons was the state-wide polygon definitions of soil radium concentrations. The radium distributions computed for each map polygon from National Uranium Resource Evaluation (NURE) aeroradiometric data were first plotted in terms of the geometric mean versus the geometric standard deviation for each polygon. Polygons mapped in the red (elevated radon potential) category were plotted with circles; polygons mapped in the yellow (intermdediate 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, shown in Figure 4-8, shows 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 scatter plot. For the RAETRAD-F calculations, all soils were represented conservatively by sand. This coarse texture provided maximum permeability and diffusivity and minimal water retention, thus permitting as much surface radon release as possible. Soil radon concentrations were defined to be small (10 pCi L^{-1}) to avoid RAETRAD-F adjustments for deeply-buried elevated-radium layers. Water tables were defined to have a minimum depth of 3 m (10 ft) for a duration of 3 months. Soil radium distributions were defined to be log-normal with geometric means and geometric standard deviations (GSD) that were varied to fall into different map categories. For each of fifteen RAETRAD-F calculations, 20 log-normal radium concentrations with the desired geometric mean and GSD were computed. GSDs of 1.05, 2, 3, 4, and 5 were used with geometric means of 0.4, 1, and 3 pCi g^{-1}. From the computed values of C_{95} for each GSD, corresponding C_{95} values were interpolated at the 4 pCi L^{-1} (green-yellow) and 8.3 pCi L^{-1} (yellow-red) map cut points.

The resulting cut point lines separating the color categories of the radon protection map were plotted on Figure 4-8 for comparison with the individual points representing each map polygon. As expected, the map data points are generally clustered by color category, with occasional outliers caused by high water tables (positive outliers) or elevated geologic radium sources (negative outliers). The lines calculated generically by RAETRAD-F have approximately correct shapes and spacing, but are shifted to the left of where they would provide an ideal fit. This difference in GSD is expected, since the maps utilize large-area regional GSDs that are dominated by aeroradiometric and soil variations, while the RAETRAD-F analyses utilize GSDs controlled by radium and moisture variations over a 1-acre site.

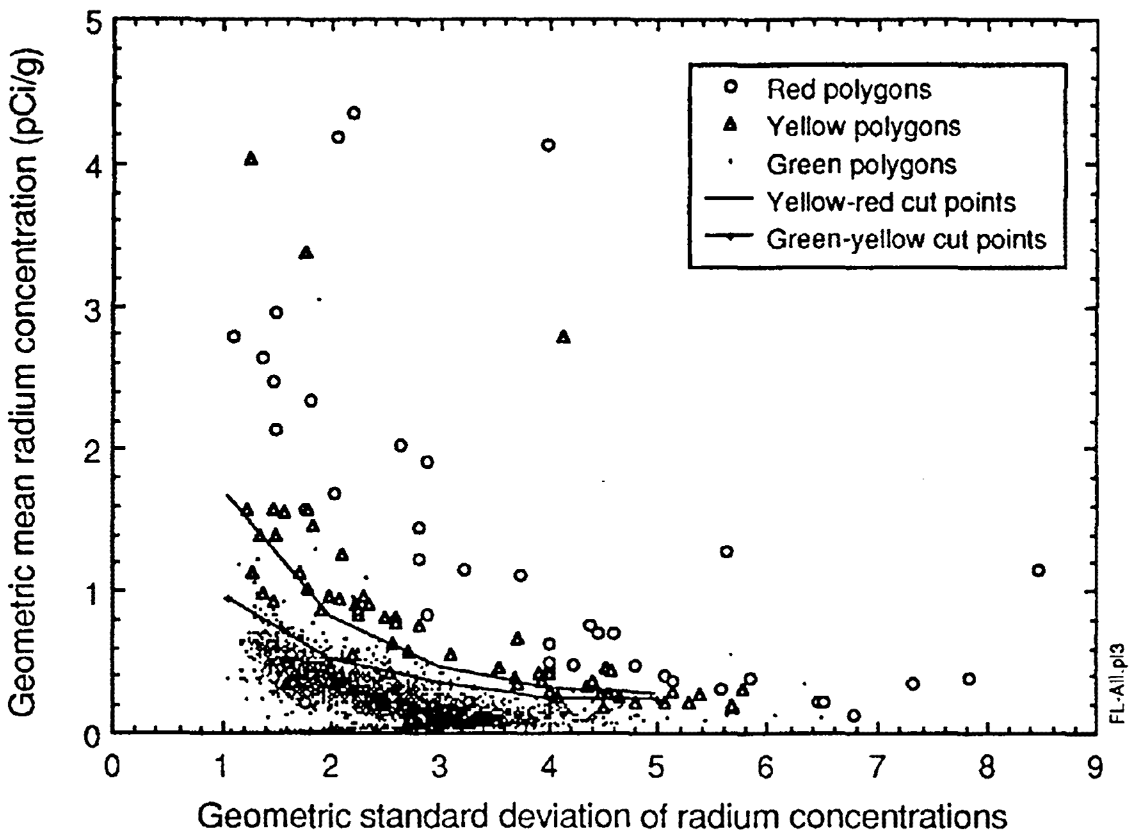

Figure 4-8. Comparison of radon protection map and RAETRAD-F data domains.

As suggested by Figure 4-8, the generic map data have GSDs about 0.5 greater than the site-specific data. Thus, an increase of 0.5 in the site-specific GSDs would improve their correspondence with the regional GSDs plotted on the radon protection map. Although it is reasonable to expect that a site-specific GSD is smaller than the regional GSDs, there is presently no theoretical basis to estimate how much larger the regional variations may be. An example plot, shown in Figure 4-9, shows that the increase of only 0.5 in the site-specific GSD gives good agreement with the primary clusters of yellow-polygon data that separate the green and red data domains.

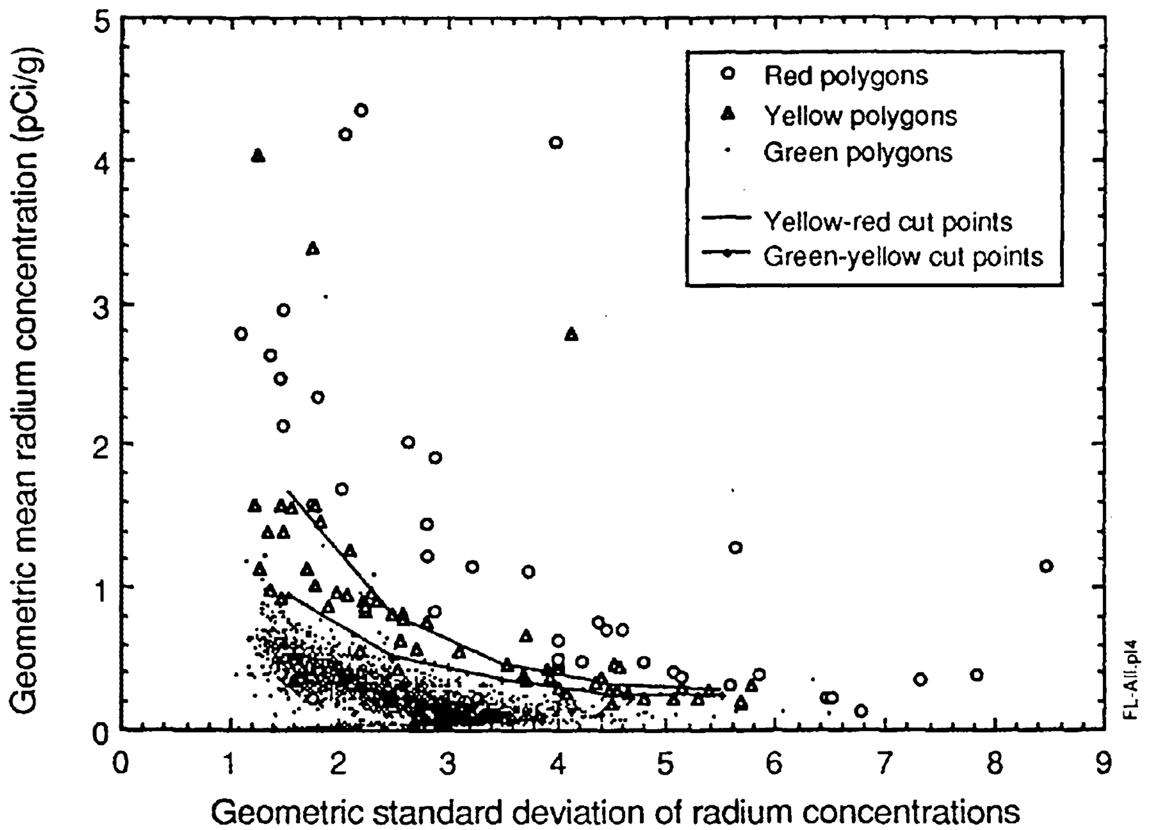

Figure 4-9. Comparison of radon map and shifted RAETRAD-F data domains.

4.3 SUMMARY OF MODEL-MAP COMPARISONS

Site-specific measurements using the measurement and analysis methods prescribed by the original site characterization protocol (Nie96) 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 of the sites mapped with low or elevated classifications retained the same category under the alternative protocol, two of the 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 regional variations (for areas averaging 8,800 acres) and localized variations (for sites of 1 acre or less). Nevertheless, this comparison suggests that even the complete state-wide distribution of radon potentials is consistent with the trends shown by the RAETRAD-F model, which is prescribed for analyzing site-specific measurement data.

5. LITERATURE REFERENCES

DCA94 Florida Department of Community Affairs, Florida Standard for Radon-Resistant Residential Building Construction, Tallahassee FL: Florida Department of Community Affairs, proposed Rule 9B-52, amended December 1994.

DCA95 Florida Department of Community Affairs, Florida Standard for Passive Radon-Resistant New Residential Building Construction, Tallahassee, FL: Florida Department of Community Affairs, Radon Program, July 1, 1995.

EPA92a U.S. Environmental Protection Agency, A Citizen's Guide to Radon, second edition, Washington, DC: U.S. Environmental Protection Agency report *ANR-464*, May 1992.

EPA92b U.S. Environmental Protection Agency, Technical Support Document for the 1992 Citizen's Guide to Radon, Washington D.C.: U.S. Environmental Protection Agency report *EPA-400-R-92-011* (NTIS PB92-218395), May 1992.

Nie94 Nielson, K.K., Holt, R.B., and Rogers, V.C., Residential Radon Resistant Construction Feature Selection System, Research Triangle Park, NC: U.S. Environmental Protection Agency report *EPA-600/R-96-005* (NTIS PB96-153473), February 1996.

Nie95a Nielson, K.K., Holt, R.B., and Rogers, V.C., Statewide Mapping of Florida Soil Radon Potentials, Volumes 1 and 2, Research Triangle Park, NC: U.S. Environmental Protection Agency report *EPA-600/R-95-142(a,b) (NTIS PB96-104351 and 104369)*, September 1995.

Nie95b Nielson, K.K., Lund, D.M., Rogers, V.C., Rogers, B.C., and Holt, R.B., Preferential Radon Transport through Permeable Channels in Soils, Salt Lake City, UT: Rogers & Associates Engineering Corporation report *RAE-9418/1-6*, June 1995.

Nie96 Nielson, K.K., Rogers, V.C., and Holt, R.B., Site-Specific Protocol for Measuring Soil Radon Potentials For Florida Houses, Research Triangle Park, NC: U. S. Environmental Protection Agency report EPA-600/R-96-045 (NTIS PB96-175260), April 1996.

Rog95 Rogers, V., Rogers, V.C., and Nielson, K.K., RAETRAD-F: User's Guide for Analyzing Site-Specific Measurements of Soil Radon Potential Category for Florida Houses, Salt Lake City, UT: Rogers & Associates Engineering Corp. report *RAE-9226/7-2R1*, May 1996.

SCS75 Soil Conservation Service, Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys, Washington D.C.: U.S. Department of Agriculture, Soil Conservation Service. *Agriculture Handbook No. 436*, 1975.

SCS91 Soil Conservation Service, State Soil Geographic Data Base (STATSGO) Data Users Guide, Lincoln, Nebraska: National Soil Survey Center, Soil Conservation Service, U. S. Department of Agriculture, draft report, 84pp, 1991.

Tho79 Thomas, J.W. and Countess, R.J., Continuous Radon Monitor, *Health Physics* **36**, 734-738, 1979.

Tho85 Thomas, B.P., Cummings, E., and Wittstruck, W.H., Soil Survey of Alachua County Florida, Gainesville, FL: U.S. Department of Agriculture, Soil Conservation Service. 1985.

Wil91 Williamson, A.D. and Finkel, J.M., Standard Measurement Protocols, Florida Radon Research Program, Research Triangle Park, NC: U.S. Environmental Protection Agency report *EPA-600/8-91-212 (NTIS PB92-115294)*, November 1991.

Appendix

RAETRAD-F Analyses
Using Borehole Gamma Ray Estimates of Radium Concentrations

```
                    Analysis of Site Test Data for
        RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
                    using RAETRAD-F   v.1.1
                           written by
            Rogers & Associates Engineering Corporation

SITE Location: 27.8946 Deg N, 81.8653 Deg W
       County: Polk                                Run Date: 10- 6-1995
        State: Florida                             Run Time:  9:47
      Zipcode:                                         User: Rodger Holt

INPUT DATA Measured by: RAE
                        Average Site Dry Density (g/cc):    1.605
                             Average Site Soil Texture:     Sand

          Radium Concentrations (pCi/g)
            Depth    Hole  1  Hole  2  Hole  3  Hole  4  Hole  5
          --------   -------  -------  -------  -------  -------
          0 - 2 ft     3.20     3.50     4.40     3.90     5.10
          2 - 4 ft     5.40     4.50     4.00     5.10     5.30
          4 - 6 ft     5.70     5.40     5.70     4.70     4.10
          6 - 8 ft     4.30     5.00     4.00     3.50     3.40

          Soil Radon Concentrations (pCi/L)
          Sample 1  Sample 2
          --------  --------
           1600.0    2978.0

          Water Table Depth (ft)
           Months    Depth
          --------  --------
            3.00      5.00

RESULTS   +----------------------------------------------------------+
          |                                                          |
          |    RESIDENTIAL SITE INDOOR RADON POTENTIAL:  27.7 pCi/L  |
          |                                                          |
          |                     This site is in a                   |
          |                           RED                            |
          |      radon protection category as referenced by the     |
          |               Florida Radon Protection Map              |
          |                                                          |
          +----------------------------------------------------------+

I certify that the site and input data are correct to the best of my knowledge.

____________________________            ____________________________
Rodger Holt                             Agent for: RAE
```

Figure A-1. RAETRAD-F printout for the Polk-1 site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 27.8961 Deg N, 81.8654 Deg W
County: Polk
State: Florida
Zipcode:

Run Date: 10- 6-1995
Run Time: 9:51
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.616

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	4.30	4.40	12.90	4.50	13.20
2 - 4 ft	3.10	3.30	11.60	4.50	13.20
4 - 6 ft	2.70	3.10	7.50	3.30	13.10
6 - 8 ft	3.50	5.10	4.60	6.10	8.30

Soil Textures

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	Sand	Sand	SaLom	Sand	SaLom
2 - 4 ft	Sand	Sand	LSand	Sand	Sand
4 - 6 ft	Sand	Sand	Sand	Sand	Sand
6 - 8 ft	Sand	Sand	Sand	Sand	Sand

Soil Radon Concentrations (pCi/L)

Sample 1	Sample 2
1363.0	4128.0

Water Table Depth (ft)

Months	Depth
3.00	5.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 70.4 pCi/L

This site is in a
RED
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt

Agent for: RAE

Figure A-2. RAETRAD-F printout for the Polk-2 site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 28.8808 Deg N, 82.0873 Deg W
County: Sumter
State: Florida
Zipcode:

Run Date: 10- 6-1995
Run Time: 9:54
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.490

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	.60	.80	.60	.40	.60
2 - 4 ft	.70	1.00	.80	.50	.60
4 - 6 ft	1.10	1.50	1.90	.50	.70
6 - 8 ft	3.00	7.70	5.30	.70	2.10

Soil Textures

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	Sand	Sand	Sand	Sand	Sand
2 - 4 ft	Sand	Sand	Sand	Sand	Sand
4 - 6 ft	Sand	Sand	Sand	Sand	Sand
6 - 8 ft	LSand	Sand	SaLom	Sand	LSand

Soil Radon Concentrations (pCi/L)

Sample 1
684.0

Water Table Depth (ft)

Months	Depth
6.00	6.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 9.0 pCi/L

This site is in a
RED
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt

Agent for: RAE

Figure A-3. RAETRAD-F printout for the Sumter-1 site.

```
                    Analysis of Site Test Data for
          RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
                     using RAETRAD-F  v.1.1
                           written by
             Rogers & Associates Engineering Corporation

SITE Location: 28.9349 Deg N, 82.1111 Deg W
       County: Sumter                           Run Date: 10- 6-1995
        State: Florida                          Run Time:  9:57
      Zipcode:                                      User: Rodger Holt

INPUT DATA Measured by: RAE
                     Average Site Dry Density (g/cc):    1.509

          Radium Concentrations (pCi/g)
            Depth    Hole  1  Hole  2  Hole  3  Hole  4  Hole  5
          --------  -------  -------  -------  -------  -------
          0 - 2 ft      .40      .40      .40      .40      .30
          2 - 4 ft      .40      .50      .50      .40      .40
          4 - 6 ft      .50     1.10      .60      .50      .30
          6 - 8 ft     1.70     2.60     1.50     2.00      .30

          Soil Textures
            Depth    Hole  1  Hole  2  Hole  3  Hole  4  Hole  5
          --------  -------  -------  -------  -------  -------
          0 - 2 ft  Sand     Sand     Sand     Sand     Sand
          2 - 4 ft  Sand     Sand     Sand     Sand     Sand
          4 - 6 ft  Sand     Sand     Sand     Sand     Sand
          6 - 8 ft  Sand     LSand    Sand     SaLom    Sand

          Soil Radon Concentrations (pCi/L)
          Sample 1
          --------
            515.0

          Water Table Depth (ft)
           Months    Depth
          --------  --------
            6.00      6.00

RESULTS   +------------------------------------------------------+
          |                                                      |
          |   RESIDENTIAL SITE INDOOR RADON POTENTIAL:  3.5 pCi/L |
          |                                                      |
          |                  This site is in a                   |
          |                        GREEN                         |
          |     radon protection category as referenced by the   |
          |             Florida Radon Protection Map             |
          |                                                      |
          +------------------------------------------------------+

I certify that the site and input data are correct to the best of my knowledge.

_____________________________         _____________________________
Rodger Holt                           Agent for: RAE
```

Figure A-4. RAETRAD-F printout for the Sumter-2 site.

```
                    Analysis of Site Test Data for
             RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
                        using RAETRAD-F  v.1.1
                              written by
               Rogers & Associates Engineering Corporation

SITE Location: 28.5535 Deg N, 82.3022 Deg W
       County: Hernando                            Run Date: 10- 6-1995
        State: Florida                             Run Time: 10:00
      Zipcode:                                         User: Rodger Holt

INPUT DATA Measured by: RAE
                        Average Site Dry Density (g/cc):   1.433

          Radium Concentrations (pCi/g)
            Depth    Hole  1  Hole  2  Hole  3
          --------  -------  -------  -------
          0 - 2 ft      .70     1.00      .50
          2 - 4 ft     1.20     2.40      .50
          4 - 6 ft     2.70     3.40      .50
          6 - 8 ft     3.40     3.40     1.30

          Soil Textures
            Depth    Hole  1  Hole  2  Hole  3
          --------  -------  -------  -------
          0 - 2 ft  Sand     Sand     Sand
          2 - 4 ft  Sand     Sand     Sand
          4 - 6 ft  LSand    Sand     Sand
          6 - 8 ft  SaLom    LSand    Sand

          Soil Radon Concentrations (pCi/L)
          Sample 1
          --------
           1197.0

          Water Table Depth (ft)
           Months    Depth
          --------  --------
            6.00      6.00

RESULTS   +-----------------------------------------------------------+
          |                                                           |
          |   RESIDENTIAL SITE INDOOR RADON POTENTIAL:  13.3 pCi/L    |
          |                                                           |
          |                    This site is in a                      |
          |                           RED                             |
          |      radon protection category as referenced by the       |
          |               Florida Radon Protection Map                |
          |                                                           |
          +-----------------------------------------------------------+

I certify that the site and input data are correct to the best of my knowledge.


____________________________________      ____________________________________
Rodger Holt                               Agent for: RAE
```

Figure A-5. RAETRAD-F printout for the Hernando site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 30.1883 Deg N, 84.1914 Deg W
County: Wakulla
State: Florida
Zipcode:

Run Date: 10- 6-1995
Run Time: 10:05
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.676

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	1.00	1.00	1.00	1.00	1.00
2 - 4 ft	1.00	1.00	1.00	1.00	1.00
4 - 6 ft	1.00	1.00	1.00	1.00	1.00
6 - 8 ft	1.00	1.00	1.00	1.00	1.00

Soil Textures

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	SaCLm	SaCLm	SaCly	Clay	CLoam
2 - 4 ft	SaCly	Clay	SaCly	Clay	Clay
4 - 6 ft	Clay	Clay	SaCly	Clay	Clay
6 - 8 ft	Clay	Clay	Clay	Clay	Clay

Soil Radon Concentrations (pCi/L)

Sample 1
15.0

Water Table Depth (ft)

Months	Depth
3.00	2.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 1.8 pCi/L

This site is in a
GREEN
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt ______________________ Agent for: RAE ______________________

Figure A-6. RAETRAD-F printout for the Wakulla site.

Analysis of Site Test Data for
RESIDENTIAL RADON CONTROL CATEGORY CLASSIFICATION
using RAETRAD-F v.1.1
written by
Rogers & Associates Engineering Corporation

SITE Location: 30.3401 Deg N, 84.0156 Deg W
County: Jefferson
State: Florida
Zipcode:

Run Date: 10- 6-1995
Run Time: 10:08
User: Rodger Holt

INPUT DATA Measured by: RAE
Average Site Dry Density (g/cc): 1.407

Radium Concentrations (pCi/g)

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	.30	.30	.30	.30	.30
2 - 4 ft	.50	.40	.40	.60	.20
4 - 6 ft	.90	1.00	.90	1.30	.40
6 - 8 ft	1.00	1.20	1.10	1.40	.40

Soil Textures

Depth	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5
0 - 2 ft	Sand	Sand	Sand	Sand	Sand
2 - 4 ft	Sand	Sand	Sand	Sand	Sand
4 - 6 ft	LSand	LSand	SaLom	LSand	LSand
6 - 8 ft	SaLom	SaCly	SaLom	CLoam	SaLom

Soil Radon Concentrations (pCi/L)

Sample 1
91.0

Water Table Depth (ft)

Months	Depth
6.00	6.00

RESULTS

RESIDENTIAL SITE INDOOR RADON POTENTIAL: 2.4 pCi/L

This site is in a
GREEN
radon protection category as referenced by the
Florida Radon Protection Map

I certify that the site and input data are correct to the best of my knowledge.

Rodger Holt

Agent for: RAE

Figure A-7. RAETRAD-F printout for the Jefferson site.