

THE FLORIDA RADON RESEARCH PROGRAM 1989-1995: A REVIEW OF SCIENTIFIC ACHIEVEMENT

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ABSTRACT

To reduce the exposure of Florida residents to radon, the Florida Legislature passed a 1988 bill requiring the development of standards for the construction of radon resistant new buildings and standards for the mitigation of radon in existing buildings. The Florida Department of Community Affairs (DCA) placed in charge of this development, launched a long-term, multi-million dollar state funded research program known as the Florida Radon Research Program (FRRP). From the beginning, DCA sought the cooperation of the United State Environmental Protection Agency (USEPA), the Florida Department of Health and Rehabilitative Services (HRS), the Florida State University System, and other participants nationwide for completion of the program. In late 1995 the FRRP completed its objectives and over the six-year period made a significant contribution to the knowledge and techniques in understanding and controlling indoor radon. By all measures, the FRRP was one of, if not the, largest radon research programs in the United States. The extensive scope of the FRRP covered the following related fields: soil-gas transport, soil and construction materials, radon entry and indoor radon modeling, mitigation techniques, building systems and environment, radon potential maps, and the development of radon-resistant construction standards for both residential and non-residential buildings. Most of the FRRP research results have been published in the USEPA report system and in national and international meetings and journals. Forty-five of the FRRP reports have been published by the USEPA as of April 1996. These published reports are tabulated and summarized in this paper. The tabulations are organized into the report title, author(s), the USEPA report number, and include a brief description of the content of the report. This paper represents a significant resource for radon and indoor air professionals and interested parties in related fields.

INTRODUCTION AND APPROACH

In 1989 the Florida Radon Research Program started under the administration of the Florida DCA, Division of Codes and Standards. Many researchers from Florida universities and research centers, government agencies, and private industry participated in the research program for approximately six years. The main objective of the FRRP was the development of new radon-resistant construction standards for residential and large buildings in Florida. To provide for a quick start, at the early stage, the FRRP was established with startup funding to the State University System (SUS) in Florida. The Board of Regents of the SUS was to provide a preliminary draft building code to the DCA, which would be used in the initial administrative rule process to set the standards. Florida DCA process was structured under the idea that FRRP is not only their project, therefore, participation from USEPA, HRS, and many other organizations was seriously sought from the beginning. During the span of the project, significant assistant, both technical and administrative, was received from the USEPA. The latter was delivered through the participation of the National Risk Management Research Laboratory (formerly Air and Energy Engineering Research Laboratory) of the Office of Research and Development (ORD) at Research Triangle Park in North Carolina.

In the process of achieving the main objective of the FRRP, research were administered, organized, and conducted virtually to cover all theoretical and experimental aspects of concern to the indoor radon problem and its interaction with building construction, systems, and the environment. For the purpose of this work, and to describe the nature of research covering, the subject of the main delivery of the research reports is generally classified into eight categories as the following: (A) soil/fill/construction materials characterization, evaluation, and modeling; (B) buildings and buildings support systems (BSS) characterization, evaluation, and modeling; (C) foundation and

building construction standards; (D) radon potential and protection mapping development; (E) radon measurement methodology and standards; (F) radon source-term and entry measurement, modeling, and computer codes; (G) indoor radon driving forces and concentration modeling and computer code; and (H) radon mitigation and control systems evaluation, development, and standards.

Research results and outcome from the FRRP have been published through the ORD system, and in national and international conferences and journals. However, the ORD publications provide for a systematic and uniform covering of the FRRP research results since final reports from all research contracts administered through the program are due to the Florida DCA and/or the USEPA under the contract requirement. As of April 1996, Forty-five FRRP-generated reports have been published by the USEPA. All publications were peer and administratively reviewed by the USEPA and other reviewers in accordance with the agency policy. Further all mentioned reports in this work are available to the public through the National Technical Information Services. There are over twenty other FRRP reports which are in various stages of the review process and completion but have not yet published. Those reports are not included in this work.

RESULTS

A total of forty-nine volumes, from forty-five research reports, were published between 1991 and April of 1996 have been reviewed and tabulated. The last row of Table 1 shows the number of generated reports in each of the FRRP operating year based on the USEPA publications. Table 1 also shows the distribution of the general subject of main delivery of research reports (according to the classification categories A-H discussed in the previous section), for the USEPA-published research reports that were generated in the FRRP between 1991 and April 1996. It should be noted that classification of the research subject is based on the main component in the research work not the research application As seen in the table, the majority (20%) of current standing of published reports foul into category F; radon-source term and entry measurement, modeling, and computer codes. The minority covering is that of the subject of category H (6.7 %).. Research subject of category A; is the second in volume and forms 15.6% of the current standing of published reports. It followed by categories C and D subjects with 13.3% , category G subject with 11.1%, and category E subject with 8.89% covering. Table 2 shows the list of the current standing of USEPA-published FRRP research reports. The title and author (s) of the report are shown in the first column, followed by the USEPA report number in the second column. A condensed description about each report is shown in the third column. For the purpose of this work and due to the limitation of size, the description is designed to deliver brief statement describing the report with the objective of providing input to what is there rather than what have been found. Therefore, the description column shows a condensed statement about the content of the report rather than its major findings.

Table 1: Distribution of the general subject category of the FRRP USEPA-published research reports between 1991 and April 1996. The last row shows the number of report published for each year.

Category/Year	1991	1992	1993	1994	1995	1996
A	2	0	1	2	2	0
B	0	1	0	0	3	0
C	0	0	0	1	2	3
D	2	0	0	1	2	2
E	3	0	0	1	0	0
F	0	2	1	3	2	1
G	0	2	1	1	1	0
H	1	1	0	0	1	0
Number of Reports	8	6	3	9	13	6

Table 2: A description of the USEPA-published research reports generated by the Florida Radon Research Program between 1991 and April of 1996.

	Title/Author (s)	Document Number	Description
1.	Correlation of Florida Soil-Gas Permeabilities With Grain Size, Moisture, and Porosity. V.C. Rogers and K.K. Nielson	EPA-600/8-91-039	Presents a new correlation for predicting gas permeabilities of undisturbed or recompacted soils. This correlation is based on new in-situ Florida measurements and is a function of average grain diameter, moisture saturation fraction and porosity. Radon transport in soil is highly dependent on permeability.
2.	Proceedings of the Workshop on Radon Potential Mapping - Florida radon Research Program. K.K. Nielson and V.C. Rogers	EPA-600/9-91-044	Documents a workshop on radon potential mapping in Gainesville, FL, April 20, 1990. Presented the technical basis for defining an indoor radon potential maps and reviews existing radon maps and usage of aeroradiometric, geological, indoor radon, and other data.
3.	Feasibility and Approach for Mapping Radon Potentials in Florida. K.K. Nielson and V.C. Rogers	EPA-600/8-91-046	A review of previous radon potential mapping strategies and an evaluation of mapping strategies suitable for application to radon-resistant construction in Florida. Source, house and time variations influencing indoor radon are considered to quantify probable indoor radon concentrations.
4.	An Assessment Soil-Gas Measurement Technologies. H. E. Rector	EPA-600/8-91-050	A review and evaluation of technologies for measuring radon in soil gas. The measurement parameters, equipment needs, procedures and concepts to convert the data to estimates of radon potential are presented for the methods evaluated.
5.	Recommended Foundation Fill Materials Construction Standard of The Florida Radon Research Program. V.C. Rogers and K.K. Nielson	EPA-600/8-91-206	One of a series of five reports recommending building construction standards. Soil radon and radium limits are presented as a function of soil permeability. Information on radon entry rates into dwellings and Florida soils is included.
6.	Recommended Sub-Slab Depressurization Systems Design Standard of the Florida Radon Research Program. D.E. Hintenlang and C.E. Roessler	EPA-600/8-91-208	One of a series of five reports recommending building construction standards. The design elements of the recommended standard for sub-slab depressurization are presented along with information supporting the inclusion of each of these elements.
7.	Development of Alternate Performance Standard for Radon Resistant Construction Based On Short-Term/Long-Term Indoor	EPA-600/8-91-210a	A study of long and short term measurements in 80 Florida houses. It evaluates the coefficient of variation for the different

	Title/Author (s)	Document Number	Description
	Radon Concentrations - Volume 1 - Technical Report. A.D. Williamson, S. E. McDonough , C.S. Fowler		measurement periods to establish confidence limits for short term measurements. This report indicates a seasonal effect on average radon.
8.	Development of Alternate Performance Standard for Radon Resistant Construction Based on Short-Term/Long-Term Indoor Radon Concentrations - Volume 2 - Appendices A.D. Williamson, S.E. McDonough, C.S. Fowler	EPA-600/80-91-210b	Appendices to a study of long and short term measurements in 80 Florida houses. These appendices include a summary and analysis of a Gainesville study, measurement data and quality control data.
9.	Standard Measurement Protocols - Florida Radon Research Program. A.D. Williamson and J.M. Finkel	EPA-600/8-91-212	A manual for FRRP soil and building measurement procedures. It contains field sampling protocols for soil gas permeability, Rn concentration, in-situ soil density, soil classification and penetrometer analysis; and diagnostic procedures for sub-slab Rn and communication, differential pressure and leakage measurements.
10.	Radon Pressure Differential Project, Phase I, Florida Radon Research Program. J. B. Cummings, J.J. Tooley, N. Moyer	EPA-600-R-92-008	Presents pressure differential results performed in 70 new (5 years or less) homes located in central Florida. Measurement were taken between the interior and outdoors, sub-slab area, and other locations. An average 7.23 ACH at 50 Pa. was found using blower door testing with 11.6% of the leaks in the duct system.
11.	Recommended Standard of the Florida Radon Research Program J. B. Cummings	EPA-600-R-92-010	One of a series of five report which recommended building construction standards developed by the Florida Radon Research Program. It presents recommendation for the heating, ventilating, and air conditioning (HVAC) standards of the FRRP.
12.	Modeling Radon Entry Into Florida Houses With Concrete Slabs and Concrete-Block Stem Walls. K.L. Revzan, W.J. Fisk, R.G. Sextro	EPA-600/R-92-119	A model for radon entry into a typical Florida house whose interior is slightly depressurized. Radon entry rates are calculated through the slab and for various slab/wall gaps. The effects of varying soil conditions are also examined.
13.	Guidance For Research House Studies of The Florida Radon Research Program - Volume 1: Research Plan. K. J. Gadsby and T. A. Reddy	EPA-600/R-92-191a	Preliminary methodology to develop a model-backed experimental protocol for a research house study. This experimental protocol is intended to identify and quantify the relative importance of radon entry pathways, radon movement

	Title/Author (s)	Document Number	Description
			within a house and to evaluate the effectiveness of radon resistant measures for house construction.
14.	Guidance For Research House Studies of The Florida Radon Research Program-Volume 2: Model-Backed Experimental Protocol For Determining Radon Resistance of Buildings. T.A. Reddy, K. Gadsby, A. Cavallo	EPA-600/R-92-191b	A description of a preliminary methodology to develop a model-backed experimental protocols for identifying and quantifying the relative importance of radon entry pathways, and evaluating the effectiveness of certain radon resistant measures for house construction.
15.	Recommended Performance Standard of The Florida Radon Research Program. S. E. McDonough and A.D. Williamson	EPA-600/R-92-198	One of a series of five reports recommending building construction standards. This report compares long and short term measurement results and recommends acceptable levels for various types of measurements. Additional indoor radon data from 80 Florida houses is included in this update to a previous report.
16.	Radon Mitigation Studies: South Central Florida Demonstration. C.S. Fowler, et al.	EPA-600/R-92-207	Evaluates sub-slab depressurization system (SSD) installations in 14 slab-on-grade house in Polk County, Florida; for optimal design criteria to recommend cost-effective mitigation in houses built over compacted soil fills.
17.	Reference Manual For RASSMIT Version 2.1 - Sub-Slab Depressurization System Design Performance Simulation Program. D. E. Hintenlang	EPA-600/R-93-027	A manual for a DOS-compatible computer program for sub-slab depressurization systems design and simulation, RASSMIT version 2.1. It uses finite difference numerical solutions to simulate pressure field extension associated with discrete pits and extended suction systems particularly on slab-on-grade residential structures (air permeability $< 10^{-6} \text{ cm}^2$).
18.	Proceedings of The Indoor Radon Modeling Workshop Florida Radon Research Program. D E. Hintenlang	EPA-600/R-93-052	Experts in various aspects of modeling evaluate models relating to radon in Florida buildings in this 1991 workshop. Guidance on the use of modeling as an aid to the development of building codes for radon resistant buildings is presented.
19.	Recommended Foundation Barrier Construction Standard of The Florida Radon Research Program. R. Eggink, E. Gazetas, D. Steuernagel, A. Scott	EPA-600/R-93-091	One of a series of five reports recommending building construction standards developed by the FRRP. This volume recommends foundation barrier construction standards of the FRRP. It includes: concrete mix, slab design, construction practices, opening and joint sealing, and sealant materials.

	Title/Author (s)	Document Number	Description
20.	Supplement to Standard Measurement Protocols - Florida Radon Research Program. A.D. Williamson and J.M. Finkel	EPA-600/R-94-001	Contains five additional standard measurement protocols: 1) small canister radon flux, 2) soil water potential, 3) indoor radon progeny, 4) radon entry rate and 5) duct system leakage.
21.	Characteristics of Florida Fill Materials And Soils - 1990. C.E. Roessler, R. Morato, D.L. Smith, J. Wherett	EPA-600/R-94-052	Presents laboratory analysis data for 23 sites across Florida representing 11 population centers. Data include in-situ and laboratory permeabilities; sieve and hydrometer analysis; soil-gas radon, Rn emanation percentage, and Ra-226 content.
22.	Laboratory Assessment of the Permeability and Diffusion Characteristics of Florida Concretes Phase 1: Methods Development and Testing. R. Snoddy	EPA-600/R-94-053	An analysis of ten Florida concrete samples to determine permeability and diffusivity. Correlations of permeability and diffusivity to various physical parameters were investigated but not established possibly due to unrepresentative samples.
23.	Soil and Fill Laboratory Support - 1991. C.E. Roessler, et al.	EPA-600/R-94-064	Results of the radiological analyses of soil and fill samples from sites in north and central Florida. Moisture content, radium-226 and radon emanation coefficient determinations were completed on 124 samples from 45 sites taken at different depths. Radium-226 concentrations ranged from less than 1 pCi/g to more than 10 pCi/g.
24.	Radon Generation and Transport Through Concrete Foundations. V.C. Rogers, K.K. Nielson, M.A. Lehto, R.B. Holt	EPA-600/R-94-175	Examines radon generation and transport through Florida residential concretes. The radium content and radon emanation coefficients of eleven concretes were measured.
25.	RAETRAD Version 3.1 User Manual. K.K. Nielson, V. Rogers, V.C. Rogers	EPA-600/R-94-195	A user manual for the RAETRAD computer program, version 3.1. It contains description for the program main menu options, defining paths, grating and processing input files, viewing and printing outputs, and sample problems.
26.	The RAETRAD Model of Radon Gas Generation, Transport, and Indoor Entry. K.K. Nielson, V.C. Rogers, V. Rogers, R.B. Holt	EPA-600/R-94-198	A description of the RAETRAD computer program which models radon gas entry into buildings. This model is adaptable to different slab shapes and radon source strengths. Due to efficient computational code it can be run on a desktop computer.
27.	Development of A Lumped-Parameter Model of Indoor Radon Concentrations.	EPA-600/R-94-201	A description of a lumped-parameter model to simplify evaluations of different construction options for attenuating

	Title/Author (s)	Document Number	Description
	K.K. Nielson, V.C. Rogers, R.B. Holt		indoor radon entry and accumulation from data that is more commonly available. The model is developed from empirical analysis of building construction and performance measurements and a theoretical sensitivity analysis from the RAETRAD model.
28.	Soil Radon Potential Mapping of Twelve Counties In North-Central Florida. K.K. Nielson, R.B. Holt, V.C. Rogers	EPA-600/R-94-218	Provides separate radon potential maps plotted for the median 75%, 90%, and 95% confidence limits for twelve counties in North-Central Florida. The maps are designed to show areas that have different levels of radon potential based on soil and geographical features.
29.	Air Infiltration Measurements Using Tracer Gases: A Literature Review. M. M. Samfield	EPA-600/R-95-013	Provides review and comparison of tracer gases that have been used for the measurement of air infiltration into structures and interzonal flows within a structure. Tracer gases included but are not limited to sulfur hexafluoride, carbon dioxide, and argon.
30.	Feasibility of Characterizing Concealed Openings in the House-Soil Interface for Modeling Radon Gas Entry. K.K. Nielson and V.C. Rogers	EPA-600/R-95-020	An examination of the feasibility of characterizing the total effective size of openings in the house-soil interface using a lumped-parameter model, based on the RAETRAD model for radon entry.
31.	Radon Generation and Transport In Aged Concrete. V. C. Rogers, K.K. Nielson, R.B. Holt.	EPA-600/R-95-032	Results of a characterization study of radon generation and transport in concrete samples collected from 12 to 45 years old residential slabs in Florida. Compares measurement results of the old samples with newly poured concrete in Florida residential..
32.	Lumped- Parameter Model Analyses of Data from the 1992 New House Evaluation Project - Florida Radon Research Program. K.K. Nielson, R. B. Holt, V.C. Rogers	EPA-600/R-95-090	A further analysis of radon-resistant construction features and data from the New House Evaluation Project. This analysis was aimed at characterizing the radon resistance of the house-soil interface for different foundation designs and comparing the effectiveness of active and passive protection features.
33.	Laboratory Assessment of the Permeability and Diffusion Characteristics of Florida Concretes: Phase II. Field Samples and Analysis.	EPA-600/R-95-103	An analysis of Florida concrete samples to determine permeability and diffusivity. Correlations of permeability and diffusivity to site added water, sand and stone mix, and fly ash content were evaluated.

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	R. Snoddy		
34.	Evaluation of Building Design, Construction, and Performance for the Control of Radon In Florida Houses - Evaluation of Radon Resistant Construction Techniques in Eight New Houses. D.E. Hintenlang, A. Shankar, F.T. Najafi, C.E. Roessler	EPA-600/R-95-114	Eight houses in north central Florida were built using proposed passive radon resistant construction standards. Post-construction monitoring was performed under different heating, ventilation and air conditioning system configurations. Indoor radon, house ventilation rates slab differential pressure and interzone pressures were monitored.
35.	Statewide Mapping of Florida Soil Radon Potentials Volume 1. Technical Report. K.K. Nielson, R.B. Holt, V.C. Rogers	EPA-600/R-95-142a	Defines discrete areas (polygons) in Florida according to the University of Florida GeoPlan Center. Documents and utilizes soil profiles and characteristics (Ra content, Rn emanation/diffusion, water content, etc...). Estimates radon potential for each polygon using a model reference house and the RAETRAD program, so only soil effects were considered.
36.	Statewide Mapping of Florida Soil Radon Potentials Volume 2. Appendices A-P. K.K. Nielson, R.B. Holt, V.C. Rogers	EPA-600/R-95-142b	A second volume of the study that tabulated soil profile data (source characteristics), geology maps, and quality assurance data used in developing the Florida radon potential maps. Provides maps of the calculated radon potential distribution per polygon.
37.	Soil And Fill Laboratory Support - 1992 Radiological Analyses. C.E. Roessler, H. Mohammed, R. Richards, H. Nguyen	EPA-600/R-95-145	Results of the radiological analyses of soil and fill samples from sites in north and central Florida. Moisture content, radium-226 and radon emanation coefficient determinations were completed on 288 samples from 75 sites taken at different depths. Radium-226 concentrations ranged from less than 1 pCi/g to more than 10 pCi/g.
38.	Design and Testing of Sub-Slab Depressurization For Radon Mitigation In North Florida Houses Part I--Performance and Durability - Volume 1. Technical Report C.E. Roessler, et al.	EPA-600/R-95-149a	An evaluation of sub-slab depressurization (SSD) techniques in nine slab-on-grade houses built on native soil in North-Central Florida, six in Gainesville and three in Ocala. Seven of the evaluated houses have simple, rectangular floor plans and two have L-Shaped designed.
39.	Design and Testing of Sub-Slab Depressurization For Radon Mitigation In North Florida Houses Part I-Performance and Durability - Volume 2. Data Appendices	EPA-600/R-95-149b	A documentation of data for Volume 1 of an evaluation of SSD techniques in North-Central Florida. It includes characterization measurements for 12 candidate homes in

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	C.E. Roessler et al.		Gainesville/Ocala, post-mitigation procedures and data collection forms, data for nine selected homes, and weather data.
40.	Demonstration of Radon Resistant Construction Techniques - Phase II. Final Report J.L. Tyson and C.R. Withers	EPA-600/R-95-159	A study of homes built to demonstrate active and passive radon resistant construction techniques in Florida Homes. Houses were monitored during construction, and numerous parameters were measured for the soil, slab and house ventilation along with indoor radon.
41.	Site-Specific Characterization of Soil Radon Potentials. K.K. Nielson, R.B. Holt, V.C. Rogers,	EPA-600/R-95-161	This report develops a mathematical basis for using simple site measurements to estimate soil radon potential. Field tests of 26 sites were conducted to evaluate the utility of these measurements. The marginal precision of the simple measurements increases the uncertainty of the site-specific estimates.
42.	New House Evaluation of Potential Building Design and Construction For The Control of Radon In Marion and Alachua Counties, Florida. F.T. Najafi, et al.	EPA-600/R-95-170	A study of 14 homes built in accordance with the Draft Florida Standard for Radon Resistant Building Construction. Some of the homes included sub-slab ventilation systems. The results of numerous measurements to characterize the houses are included as well as recommendations for the draft standard.
43.	HVAC Systems as a Tool in Controlling Indoor Air Quality: A Literature Review. M. M. Samfield	EPA-600/R-95-174	A review of how HVAC system design and maintenance may contribute to soil gas entry, indoor air pollution, Sick Building Syndrome and Building Related Illness. This report is based on a literature survey covering 1988 through 1993.
44.	Residential Radon Resistant Construction Feature Selection System. K.K. Nielson, R.B. Holt, V.C. Rogers	EPA-600/R-96-005	An analysis of residential radon resistant building features using the RAE/TRA computer model. The construction features are ranked according to their effectiveness in reducing radon entry. Includes information on the development of the Florida Radon protection map.
45.	Test Cell Studies of Radon Entry. A.D. Williamson, C.S. Fowler, S.E. McDonough	EPA-600/R-96-010	An evaluation of the effectiveness of slab-in-stem wall with floating slab construction practices on radon entry into structures. Includes measurements of radon transport and entry for model validation and determination of the effect of high radium fill soil placed on low radium native soil on indoor

	Title/Author (s)	Document Number	Description
			radon concentration.
46.	Technical Basis For A Candidate Building Materials Radium Standard. V.C. Rogers and K.K. Nielson	EPA-600/R-96-022	Provides a candidate building materials radium standard and a summary of the technical basis for the standard. The standard limits the total radium concentration 10 pCi/l for any materials used in concrete and to 5 pCi/l for concrete used in the construction of habitable structures.
47.	Development of A Radon Protection Map For Large Buildings In Florida. K.K. Nielson, R.B. Holt, V.C. Rogers	EPA-600/R-96-028	Presents a radon protection map for Florida large buildings. The map shows the areas that require different levels of radon protection from soil and geographical features. The map was proposed as a basis for implementing radon-resistant building construction standards in areas of high radon risk and avoiding unnecessary regulation in areas of low radon risk.
48.	Effectiveness of Radon Control Features In New House Construction - South Central Florida. C.S. Fowler, S.E. McDonough, A.D. Williamson	EPA-600/R-96-044	Evaluates the effectiveness of monolithic and slab-in-wall slab types in 14 houses built in accordance with the Florida proposed radon-resistant construction standards in south central Florida. Sites were selected with a minimum soil gas concentration of 1,000 pCi/l. Slab integrity was monitored over time, and post-construction measurements were made in all houses.
49.	Site-Specific Protocol For Measuring Soil Radon Potentials For Florida Houses. K.K. Nielson, V.C. Rogers, R.B. Holt	EPA-600/R-96-045	Presents a protocol to provide a basis to guide measurement and interpretation of radon-related features in a particular site of existing residential radon protection maps. Site conditions that differ from the general ones used in developing the map may be used to correct for radon potential above the mapped category.