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Project Summary

Development of a Radon Protection Map for Large Buildings in Florida

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A radon protection map was developed to show from soil and geologic features the areas of Florida that require different levels of radon protection for large building construction. The map was proposed as a basis for implementing radon-protective construction standards in areas of high radon risk and avoiding unnecessary regulations in areas of low radon risk.

The map utilized 3,919 geographic regions defined by digital intersection of soil maps with surface geology maps. Regional radon distributions were modeled from radon source and transport properties. Aeroradiometric measurements from the National Uranium Resource Evaluation (NURE) program were digitally overlaid on the map regions to estimate surface radium concentrations. Geologic classifications and radium and emanation measurements characterized deeper soils. Radon transport properties (moisture, diffusion coefficient, and air permeability) were calculated from data in soil survey data bases. Indoor radon was modeled as annual average concentrations in a reference large building. The reference building was modeled on the soil and moisture profiles of each region to determine regional radon potentials. Confidence limits for the regional radon distributions were calculated from variations in the regional radon source and transport properties.

Separate model analyses estimated the effectiveness of different building construction features in reducing radon entry. Radon resistance factors for each feature were ranked and ordered to select a group of passive features having a combined radon reduction of a factor of 3.3. A cost-benefit analysis used the feature effectiveness with regional radon variations to estimate a 95% confidence limit for optimum use of radon-protective features. The map was divided into green, yellow, and red tiers corresponding to regions with low (<4 pCi L^{-1}), intermediate (4 to 13 pCi L^{-1}), and elevated (>13 pCi L^{-1}) potential for annual average radon concentrations at the 95% confidence limit: the green tiers comprised 3,650 of the 3,919 regions, including 92.9% of the state area; yellow tiers comprised 223 regions, including 6.1% of the state area; and red tiers, 46 regions, including 1.0% of the state area.

The map was compared with over 275,000 measurements in 20,156 large buildings. A statewide bias of only -0.004 $\pm$ 1.067 standard deviations suggests excellent average agreement. Observations of 306 buildings with the greatest bias showed that, with crawl spaces, 89% measured low and only 11% measured high. For slab-on-grade buildings, 48% measured low and 52% measured high. The number of outlying comparisons was consistent with the number expected in the extremes of the bias distribution.

This Project Summary was developed by EPA's National Risk Management Research Laboratory's Pollution Prevention and Control Division, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report

***of the* same title (see Project Report ordering information at back).**

Introduction

Radon (^{222}Rn) gas from the decay of naturally occurring radium (^{226}Ra) in soils can enter indoors through building foundations. With elevated entry and inadequate ventilation, radon can accumulate to levels that pose significant risks of lung cancer with chronic exposure. The Florida Department of Community Affairs (DCA) is developing radon-protective building standards to reduce radon-related health risks. Statewide radon maps are also being developed to target the standards to regions of greatest need. This report describes a large building radon protection map that was developed to show where radon-protective building standards are needed and to avoid unnecessary standards where they are not needed.

Several institutional and scientific criteria led to the present technical approach. The maps had to identify as precisely as possible the regions needing radon-protective building features. The maps also had to avoid political and institutional boundaries (city, county, etc.) that are not radon-related. The maps were based on radon entry into a reference large building to accurately reflect regional soil and moisture effects. The approach used to achieve these objectives is similar to that used previously for the residential radon protection map. It therefore capitalizes on existing region, soil, geology, and radiological definitions, and involves:

a. Using the previously defined map polygons (defined from existing soil and geologic maps).

b. Using the previously defined soil profiles associated with each radon map polygon, and their associated radon generation and transport properties.

c. Calculating numeric indoor radon concentrations for individual soil profiles and a time- and area-weighted average to represent each radon map polygon.

d. Using cost-benefit analyses and feature effectiveness rankings to determine cut points for different levels of radon protection.

e. Plotting the large building radon protection map by color-coded radon protection tiers.

Indoor radon levels for large-buildings were calculated using new model analyses for a reference large building along with previous statewide calculations for houses. The new analyses were performed by the Florida Solar Energy Center (FSEC) using a representative subset of soil radon generation and transport properties. The analyses modeled the same reference large building on the soil and moisture profiles of each geographic region to reflect the regional differences in radon potential without interference from building differences. The radon calculations utilize data developed cooperatively by the University of Florida (UF), the Florida Geological Survey (FGS), the FSEC, the U.S. Geological Survey (USGS), and Rogers and Associates Engineering Corp. (RAE) working together in the Florida Radon Research Program (FRRP).

This report presents the approach and data used for the large-building radon protection map; the radon calculations from multi-zone large-building modeling and existing residential modeling; the radon resistant construction features and their effectiveness and ranking; the cost-benefit analysis; the map technical definition; and the map validation.

Radon Distributions in the Reference Large Building

The FSEC 3.0 model was used for the multi-zone, large-building model calculations. For computational economy, the calculations were performed on only a representative subset of 11 soil series under different seasonal moisture conditions and different radon source combinations (a total of 124 model analyses). The complete soil and moisture details were then interpolated by fitting the large-building results to the previous Radon Emanation and Transport into Dwellings (RAETRAD) residential analyses. Regression coefficients for computing the statewide distributions from the large-building analyses averaged 0.99, and comparisons of individual and fitted calculations had a correlation coefficient of 0.998.

The FSEC 3.0 calculations utilized actual soil properties for the top 2.0 to 2.5 m and extrapolated soil properties for the remaining profile to a depth of 5.0 m. Different radon source strengths were allowed for the upper and lower zones. Soil moistures throughout the entire 5-m profile were defined for a high water table season, a low water table season (2 m lower), and 1-month intermediate-depth transition periods between seasonal levels. The soil moisture contents were calculated for each soil series from water drainage data.

The model analyses represented the reference large building as if it were located on each soil profile under each specified moisture and radon source condition. The reference large building was defined and analyzed to have the approximate characteristics of the Polk Life and Learning Center located in Bartow, Florida. The reference building consists of a single-story structure with a floor area of 1,808 m^2 (19,456 ft^2), and normalized dimensions of 1.6 x 1 x 0.12. The building has a floating-slab floor design with a 0.15 mm (6-mil) polyethylene vapor barrier between the slab and soil. Slab openings included a perimeter shrinkage crack (0.0007 m^2 crack area per m^2 floor area), and centrally located slab openings totaling 0.0004 m^2 open area per m^2 of floor area. A single air handler circulated internal and outdoor air through six zones. Two occupied zones were at -2 Pa and +2 Pa pressure, and a mechanical room was at -5 Pa and contained 67% of the floor leak area. The FSEC model calculations were compared previously with indoor radon measurements in the same building.

Soil radium concentrations were defined as the geometric means of NURE measurements for estimating median radon potentials in all map regions containing NURE data. Estimates for regions without NURE data were defined from the geometric mean for the geology unit containing the map region. In the few cases where NURE data missed an entire geology unit, the geometric mean for the regional soil unit was used. The geologic definitions for deep-soil radium classifications were developed by the USGS.

Radon Resistant Construction Features

The calculated statewide radon distributions readily show regional geographic differences, but their absolute values apply only to the reference large building. Actual radon levels in new buildings will differ because of design and operational differences, and they can be significantly reduced by incorporating radon-resistant features.

Construction features for reducing indoor radon levels are categorized as either passive or active. Passive features act as barriers to radon entry into the building. They generally have no mechanically operating parts that can be disabled, and they require no energy costs or user attention (except normal maintenance, such as re-caulking). An example of a passive radon control feature is the caulk seal around pipe penetrations in a floor slab. Active radon controls, on the other hand, generally require mechanical operation and incur energy costs for electric fans or supplemental heating and cooling. An example of an active radon control feature is a fan-driven sub-slab depressurization system.

Different passive and active radon control features reduce radon entry to different extents. Furthermore, certain features such as sealed floor cracks are unlikely to be implemented completely, but are still effective to the extent that they are utilized. For the large building analyses, five passive and three active radon control features were analyzed. The passive features include (a) sealed return ducts in the air handling system, (b) sealed slab penetrations, (c) sealing of most (80%) floor slab cracks, (d) monolithic design of the floor slab and foundation stem wall, and (e) use of low-slump (10-cm) concrete for the floor slab. The active features include (a) an active sub-slab depressurization system, (b) increased building ventilation by outdoor air, and (c) pressurization of the building interior.

The effectiveness of the radon control features was analyzed with the FSEC 3.0 model. In each simulation, the reference large building was placed on a soil profile with the desired water table depth, and indoor radon was averaged for the occupied building areas (zones 1 and 2). The effectiveness of each feature in reducing indoor radon was defined as a radon resistance factor, which was the ratio of radon concentrations in the reference large building without and with the feature:

$$RRF_i = C_o / C_i \qquad (1)$$

where:

RRF_i	=	radon resistance factor for feature *i* (dimension less),
C_o	=	radon concentration without feature *i* (pCi L^{-1}), and
C_i	=	radon concentration with feature *i* (pCi L^{-1}).

Significant synergism between features involved interactions with the foundation design. Analyses for only floating slab designs gave conservatively lower effectiveness factors than if other slab designs were considered. Therefore, analyses relative to floating slab floors were used in estimating and ranking the effectiveness of each radon resistance factor. The RRF factors averaged 1.98 for sealed return ducts, 1.75 for sealed slab penetrations, 1.64 for mostly sealed perimeter floor cracks, 1.64 for monolithic slab and stem wall, and 1.16 for reduced-slump concrete. RRF factors for active features were 4.5 for active sub-slab depressurization, 2.33 for increased ventilation by outdoor air, and 2.31 for building pressurization.

The return duct sealing feature was removed from the passive feature group for the radon standard because duct sealing is already required by the Florida Energy Code. The RRF for perimeter crack sealing was combined with that for monolithic slab design because of their identical magnitude and their interaction when combined. The overall RRF for the passive feature group was therefore defined as 3.3 from the product of 1.75x1.64x1.16. This factor is used in the cost-benefit analysis to estimate benefits from passive radon controls. The passive features can therefore reduce radon levels in large buildings from as much as 13 to less than 4 pCi L^{-1}. Similar grouping and selection of active radon control features is not required for the large-building radon protection map.

Cost-Benefit Analysis

The radon distributions calculated for each geographic region are compared with the 4-pCi L^{-1} radon standard to determine the potential need for radon control features. Although the distribution medians could be used for this comparison, medians just below the 4-pCi L^{-1} level would permit up to half of the polygon's land area to exceed the standard without requiring radon controls. A more conservative approach is desirable; however, the costs of requiring radon controls in more buildings are less effective because they would include increasing proportions of buildings in low-radon-potential areas. Therefore, a cost-benefit analysis was performed to determine the appropriate confidence limit to apply to the regional radon distributions for comparing them to the standard. The confidence limit constitutes a safety factor that is based on the geographic variation in regional radon potential.

The cost-benefit analysis optimizes the trade-off between added costs for radon controls and health benefits from reduced radon levels. It assumes complete compliance in regions where radon controls are required. A cost-benefit analysis previously helped determine the indoor radon remedial action limit of 4 pCi L^{-1}. Given this limit, an upper confidence limit was defined for regional radon levels that balanced the benefits from reduced radon exposure with the costs of the radon controls in an entire region. The confidence limit was determined as for the residential map using the following iterative approach:

Step 1. Choose an initial confidence limit.

Step 2. Eliminate those regions (map polygons) of the state identified by the statewide radon distribution calculations to have indoor radon concentrations of less than 4 pCi L^{-1} at the selected confidence limit.

Step 3. Determine the confidence limit for the remaining areas for which the health benefit from implementing radon controls equals the cost for implementing the controls.

Step 4. Replace the initial confidence limit chosen in step 1 with the final confidence limit calculated in step 3.

Step 5. Repeat steps 2 through 4 until the assumed initial confidence limit equals the calculated final confidence limit.

A cost of \$90 per 93 m^2 (1,000 ft^2) of building footprint was estimated from UF data for sealing cracks and penetrations. An additional cost of \$35 per 93 m^2 of building footprint for improved concrete brings the passive-group total to \$125 per 93 m^2. The cost of installing an active sub-slab depressurization system is approximately \$50 per 93 m^2 of building footprint.

A statewide distribution of soil-related radon concentrations in buildings was determined by combining individual distributions from each region. The resulting statewide distribution was integrated to show cumulative totals. For example almost 90% of the state would cause radon levels of less than 1.75 pCi L^{-1} in the reference building. Based on the EPA action level, potential radon levels exceeding 4 pCi L^{-1} require at least passive radon controls. Multiplying by the passive effectiveness of 3.3 indicates that radon levels exceeding 13 pCi L^{-1} require the additional control of active radon controls. Other parameters used in the cost-benefit analysis include an average occupancy factor (3.33 persons per 93 m^2), an effective annual benefit from radon reduction (4.32×10^{-5} lives saved per person pCi L^{-1} year of exposure reduction), and an average cost for each life saved (\$700,000 per life).

The cost-benefit analysis gave a confidence limit of 94.3%, indicating that if at least 5.7% of a region would exceed 4 pCi L^{-1}, it is cost-effective to institute passive radon control features throughout the region. For convenience in preparing the radon protection map, a conservative confidence limit of 95% is recommended and used. The EPA's traditional recommendations of a 95% upper confidence limit for data used in risk assessment calculations are consistent with this value.

Large Building Radon Protection Map

The large-building radon protection map divided the 3,919 map regions defined previously into three radon protection categories, based on their numerical radon concentrations at the 95% confidence limit. Regions with limiting radon levels below the 4 pCi L^{-1} limit were colored green to designate low radon potential. Limiting radon levels in the remaining polygons were then colored yellow to designate intermediate radon potential if they were below the 13 pCi L^{-1} threshold, or red to designate elevated radon potential.

The green category, which requires no radon controls beyond adherence to existing building codes, consists of 3,650 regions (92.9% of the state area). The yellow category, which requires passive radon controls, consists of 223 polygons (6.1% of the state area). The red category, which requires both passive and active radon controls, consists of 46 polygons (1.0% of the state area).

The large-building radon protection map includes slightly less area in the red category, but more than twice as much area in the yellow category as the previous residential radon protection map, because of two competing differences. The larger yellow category resulted from consistently higher average radon levels in the large-building simulations than in the previous residential radon simulations. The slightly smaller red category resulted from a greater effectiveness of passive radon controls in large buildings than in residences (3.3 versus 2.1), thereby making passive controls adequate in a few regions where active controls were needed for residences.

Statewide Validation of the Large-Building Radon Protection Map

The large-building radon protection map was validated by comparing radon measurements with the mapped radon distributions. Despite construction and occupancy differences between the reference and measurement buildings, indoor radon data from the Florida Health and Rehabilitative Services (HRS) large-building data base provided the most direct comparisons. The data base contained over 300,000 individual measurements in nearly 22,000 buildings throughout Florida in the November 1994 comparison set. Although dominated by population centers (49% of the buildings in 6 of the 67 counties), data were sufficient to represent parts of most counties.

The radon comparisons utilized a bias statistic to normalize each comparison to a common basis. The normalization was required because radon distributions in some polygons had much greater variance than in others. The bias statistic used for the comparisons had the form:

$$Z = [\ln(\text{Meas}) - \ln(\text{Map})] / \sqrt{(\ln G_{Meas})^2 + (\ln G_{Map})^2} \qquad (2)$$

where:

Z	=	measurement-map bias statistic (standard deviations),
Meas	=	value of the measured parameter (point in time),
Map	=	median value of the mapped distribution (annual average basis),
G_{meas}	=	uncertainty [geometric standard deviation (GSD)] in representing the annual average by a measured value, and
G_{map}	=	GSD of the mapped distribution.

The estimate of G_{Meas} was calculated from previous comparisons of short-term and annual-average indoor radon estimates in houses, and was adjusted for the difference between house and large-building occupancy using data for schools. The resulting estimate of $G_{Meas} = 2.2$ was used statewide for estimating the uncertainty in annual average radon concentrations from a single measurement in a large building. The statewide distribution of bias statistics averaged -0.004, showing that, on average, the measurements and calculated values were equivalent. The standard deviation of the Z distribution was 1.067, indicating that the variations between the measured and calculated values were essentially equivalent to the variations predicted from the map and measurement uncertainties.

A search for *potential* radon anomalies used the distribution of comparison statistics. Buildings with very large positive or negative Z statistics were identified, and their locations and attributes were compiled from HRS data to identify possible trends or regional clusters. Nine counties in three parts of the state contained 313 of the 422 identified buildings. Of these, 168 were potential negative anomalies (measurements lower than calculated values) and 145 were potential positive anomalies (measurements higher than calculated values).

Non-intrusive field observations were made at 306 of the buildings. The construction type, adjacent pavement coverage, type of entry doors, building purpose (for occupancy estimates), and the elevation difference between grade and the first floor were recorded. Gamma radiation and latitude/longitude coordinates were also measured. Several significant trends were observed. Buildings constructed with crawl spaces accounted for only 15% of the observed buildings (47 total), but of these buildings, 89% were potential negative anomalies. Slab-on-grade buildings accounted for 257 buildings, or 84% of the observed buildings, with almost equal numbers of potential positive and negative anomalies. A total of 10 observed buildings were frame construction, and all 10 were potential negative anomalies. Similarly, nine buildings were observed that were of poured-concrete construction, and eight of these were potential negative anomalies. With exposed (no veneer) concrete block construction, 85% of the buildings were potential positive anomalies, and only 15% were potential negative anomalies.

The overall comparison of the measured and mapped radon levels is excellent. Approximately 69% of the 20,156 points surveyed lie within 1 standard deviation of their mapped value, compared to 68% expected from map and measurement uncertainties. Similarly, 93% were within 2 standard deviations of mapped values, compared to approximately 95% expected from map and measurement uncertainties. Partitioning the field observation cases into potential negative or positive anomalies gives further insight.

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The complete report, entitled "Development of a Radon Protection Map for Large Buildings in Florida," (Order No. PB96-168 216; Cost: $31.00, subject to change) will be available only from:
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