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Project Summary

The RAETRAD Model of Radon Gas Generation, Transport, and Indoor Entry

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The report describes the theoretical basis, implementation, and validation of the RAdon Emanation and TRAnsport into Dwellings (RAETRAD) model, a conceptual and mathematical approach for simulating radon (^{222}Rn) gas generation and transport from soils and building foundations to the indoor environment. It has been implemented in a computer code of the same name to provide a relatively simple, inexpensive means of estimating indoor radon entry rates and concentrations. RAETRAD uses the complete, multiphase differential equations to calculate radon generation, decay, and transport by both diffusion and advection (with pressure-driven air flow). The equations are implemented in a steady-state, 2-dimensional finite-difference mode with elliptical-cylindrical geometry for maximum efficiency and modeling detail.

For validation, the air flow part of RAETRAD was compared with a 2-dimensional analytical calculation of air flow through a uniform field. Variations of less than 1% were observed between the analytical and numerical pressure fields. The radon generation, decay, and transport part of RAETRAD was validated by similar comparisons with 1-dimensional analytical calculations for open and concrete-covered soils. Most radon concentration profiles and surface radon fluxes for these comparisons were also within 1%.

RAETRAD calculations were also compared with empirical data from two 6 x 6 m research structures with floating-slab and slab-in-stem-wall construction. The comparisons included soil radon concentration profiles and indoor radon concentrations under different air pressure and ventilation conditions. The RAETRAD values were consistently within less than 1 standard deviation of the measured data. Indoor radon concentrations averaged within 11% of calculated values and had an average bias of only 3%. Comparisons with measurements from other houses showed greater variations due to assumptions about house floor slab integrity and diffusivity.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, 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

Elevated indoor radon concentrations usually result from elevated radon generation and mobility in soils combined with openings or pores in the building foundation. Although indoor radon levels are difficult to predict, long-term average levels can be estimated by mathematical models, which simulate the complex processes of radon generation, transport, and indoor entry using soil and house parameters. The RAETRAD model was developed to provide a new level of simplicity in detailed radon modeling. From user-specified house and soil properties, RAETRAD computes detailed air-pressure and radon-concentration profiles in the floor slab, foundation, and surrounding soils, and the resulting radon entry rate and indoor radon level.

RAETRAD is designed to address questions such as how strong and how close to the house can a radon source be for particular soil and ground water conditions without excessively elevating indoor radon levels? This information is important for planning and regulating soil excavation, for replacement at radium-contaminated sites, and also in regulating building construction in areas with high-radium strata or with fill soils of higher or lower radium concentration.

The RAETRAD model represents slab-on-grade houses of different sizes and shapes on soils with any distribution of radon source strengths, physical properties, water contents, and gas transport properties. It was developed in part under the Florida Radon Research Program (FRRP), which has been cosponsored by the Florida Department of Community Affairs and the U.S. Environmental Protection Agency. It has been used in the FRRP to characterize the effects of foundation soil and fill properties on indoor radon entry, to characterize the modes of radon entry, to characterize soil radon potentials for mapping of their geographic distributions, to develop simplified lumped-parameter models, and to support development of radon-protective building construction standards.

Theoretical Basis

RAETRAD computes radon production from radium decay in floor slabs, foundation structures, and surrounding soils. It also computes the detailed radon interactions in the solid, liquid, and gas phases of the soils and concretes, and radon gas transport and indoor entry by both diffusion (concentration-driven) and advection (with pressure-driven air flow). The theoretical equations used for defining radon generation and transport in the foundation and soil regions consider the effects of moisture and the simultaneous effects of diffusive and advective radon movement.

Steady-state radon entry rates and indoor radon concentrations are computed in a two-step process that involves first solving the air-pressure and airflow distributions in the soil and foundation regions, and then solving the corresponding radon concentration profiles, considering the localized radon generation rates, decay rates, and transport rates by diffusion and advection. The air pressure distributions under and near the house are solved with LaPlace's equation applied to discrete regions to represent specified floor, footing, and soil materials. The resulting localized airflow velocities are used in the corresponding radon calculations in computing simultaneous diffusive and advective radon transport. The equations are solved numerically in elliptical-cylindrical geometry to represent houses of different sizes and with varying rectangular aspect (length/width) ratios. Radon entry rates into a house are computed by integrating the total radon transport across the floor surface area. Indoor radon concentrations also are estimated from the computed entry rates by dividing by the house volume and its air ventilation rate.

Implementation

The differential equations describing air flow and radon generation and transport are solved numerically by finite-difference techniques. The house floor slab, footings, and soil layers are divided into numerous, user-defined mesh units for these analyses. Several analytical functions in RAETRAD enhance its computational efficiency and simplify its user interface. The numerical calculations of air flow and radon transport through floor cracks are accelerated by use of analytical functions to estimate the mesh-equivalent permeabilities and radon diffusion coefficients for the specified cracks, rather than using finely-graded numerical meshes to represent them. Analytical functions are also used to define soil radon diffusion coefficients and air permeabilities when measured values are unavailable. These use soil porosities, water contents, and textures to define the radon transport properties from empirical correlations with measured data. In addition to modeling symmetric cracks in the floor slab, RAETRAD also accommodates asymmetric openings such as utility penetrations that do not match the elliptical symmetry computed for the equivalent rectangular house shape. These are represented by multiple numerical calculations that determine transverse leakage terms for the discrete-point floor openings.

The numerical-analytical calculations are performed by computing all finite-difference coefficients for each model mesh unit and solving the equations simultaneously by a non-iterative matrix inversion technique. The resulting computer code is relatively small and efficient and operates in a Windows® environment on an IBM®-compatible personal computer. Typical execution times are on the order of 1-2 minutes or longer, depending on the complexity of the problem being solved and the speed of the computer. A user interface provides queries for definition of an input file and selection of appropriate input parameters. House parameters include area, volume, shape, ventilation rate, indoor air pressure, foundation depth, floor slab openings, and concrete properties. Soil parameters include layer thicknesses and localized values of soil density, moisture, radium concentration, and radon emanation coefficient. Certain properties, such as radon diffusion coefficient and air permeability, can be left unspecified for use of default values estimated within the computer code.

Comparisons with Analytical Data

The RAETRAD code was validated and benchmarked by several comparisons with analytical calculations and with empirical radon data. The analytical validations included comparison with a 2-dimensional air pressure field calculated for a simple uniform 15 x 31 ft (4.6 x 9.4 m) soil space with two different pressures applied at its top surface. Relative standard deviations of less than 1% were obtained between the RAETRAD calculations and the analytical pressure field at the 1-, 2-, 4-, 8-, and 15-ft (0.3-, 0.6-, 1.2-, 2.4-, and 4.6-m) depths below the pressure boundary.

Analytical validations with 1-dimensional radon generation and diffusion from an open soil and a concrete-covered soil suggested the utility of defining a small (0.1-ft or 0.3-m) mesh unit at the top of the soil profile to minimize the effects of mesh spacing. In these comparisons, both soil radon profiles and surface radon fluxes agreed consistently within less than 1%. Additional 1-dimensional validations included a uniform soil with radon generation, diffusion, and advective transport. In this case, the air flow velocities were forced by an external definition of a uniform pressure gradient, since RAETRAD is designed to compute only realistic, 2-dimensional pressure profiles. Again, agreement was within less than 1% for all cases of air flowing into the soil profile. When air was drawn from the profile, a depletion of the profile was observed that caused a maximum error of 4% for the case that was analyzed. This error was reduced by considering a thicker soil profile and was exaggerated if a thin soil layer was considered.

Comparisons with Empirical Data

Comparisons of RAETRAD calculations with empirical radon measurements utilized two test-cell structures (6 x 6 m) constructed in South-Central Florida and monitored primarily by Southern Research

Institute (SRI). One of these structures (test cell 1) utilized floating-slab floor construction with concrete-block stem walls over a concrete footing. The other structure had similar footings and stem walls, but its floor slab was poured to extend into a course of chair blocks at the top of the stem wall. Both cells had identical wood-frame superstructures, without windows, that were sealed with 2-3 cm of polyurethane foam to minimize air infiltration. Soil densities, radium concentrations, radon emanation coefficients, and moistures were measured in this project from numerous cores collected around and under the test cells. SRI provided measured soil radon and air permeabilities, and indoor pressures, air ventilation, and radon concentrations.

Field soil sampling at the test cell site extended only to 4-7 ft (1.2-2.1 m) depths for most cores; hence deeper soil regions were extrapolated from existing moisture and radium data. Calculated radon concentration profiles were within 4.4% of the means of measured values under test cell 1, compared to a 34% root-mean-square uncertainty among the measured values. Calculated radon profiles were within 18% of the means of measured values under test cell 2, compared to a 42% root-mean-square uncertainty among the measured values. Measured soil air permeabilities differed from values calculated from soil density, moisture, and texture by 42% based on composite averages at four depths. Excluding a heterogeneous, low-permeability layer under part of the site, the agreement was improved to 24% relative standard deviation.

Indoor radon in the test cells was analyzed by RAETRAD to compare with measurements before and after drilling a center hole in each of their slabs. For the initial slab conditions, RAETRAD computed 97 pCi L^{-1} in test cell 1, only 2% above the mean of the measured values, 95 ± 44 pCi L^{-1}. The radon computed by RAETRAD for test cell 2 was 20 pCi L^{-1}, which was 10% below the mean of the measured values, 22 ± 7 pCi L^{-1}. With a 10-cm center hole in each slab, test cell 1 was computed to have an indoor radon concentration of 212 pCi L^{-1}, which was 17% below the mean of the measured values, 255 ± 78 pCi L^{-1}. Test cell 2 with a center hole had a computed radon concentration of 87 pCi L^{-1}, which was 18% above the mean of the measured values, 74 ± 33 pCi L^{-1}. Computed air pressure and radon concentration profiles under test cell 1 had relative standard deviations from measured values of 11 and 12%, respectively, which were smaller than the standard deviations among the replicate measurements. Computed air pressure and radon concentration profiles under test cell 2 had relative standard deviations from measured values of 25 and 20%, respectively, which also were smaller than the standard deviations among the replicate measurements.

Additional comparisons of RAETRAD calculations with radon measurements in the test cells were performed with test cell 2 at indoor pressures of -10 and -20 Pa instead of its passive-condition pressure of -0.6 Pa. For the -10 Pa condition, test cell 2 was computed to have an indoor radon concentration of 51.5 pCi L^{-1}, which was 3% higher than the measured 50 pCi L^{-1} value. For the -20 Pa condition, an indoor radon concentration of 42.9 pCi L^{-1} was computed by RAETRAD, 14% lower than the measured value of 50 pCi L^{-1}. Collectively, the six model comparisons with indoor radon measurements in the test cells had an average difference of 11%, with an average bias of -3%.

Comparisons of RAETRAD calculations with indoor radon measurements in 50 FRRP demonstration houses exhibited much larger variations (geometric standard deviations of 2.8) and a bias of a factor of 0.56 below the measured values. This was attributed to the much less detailed characterization of the houses, primarily with respect to the concrete slab integrity and diffusivity. Significant unobserved holes or cracks (>50 cm^2) near utility penetrations or by walls, bathtubs, or other features could cause this much bias, as could a 3-fold higher radon diffusion coefficient than was used for the floor (0.001 $cm^2\ s^{-1}$). Observations and measurements support either of these possibilities.

Conclusions

RAETRAD provides a relatively simple, 2-dimensional numerical-analytical simulation of steady-state radon generation and movement into rectangular-equivalent slab-on-grade houses. It combines detailed airflow and radon source, transport, and decay calculations to accurately assess the effects of soil moisture, radon source distribution, and other soil and house variables of interest. Validations with special-case analytical calculations demonstrated accuracy to within approximately 1%. Comparisons with empirical data from FRRP test-cell structures demonstrated accuracy that was well within the uncertainty of the empirical measurements. Application to other houses was limited by assumptions about their floor slab integrity and diffusivity.

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The complete report, entitled "The RAETRAD Model of Radon Gas Generation, Transport, and Indoor Entry," (Order No. PB95-142030; Cost: $27.00, subject to change) will be available only from

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