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Project Summary

Development of a Lumped-Parameter Model of Indoor Radon Concentrations

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The report describes a simplified, lumped-parameter model to characterize indoor radon concentrations from data that are more readily available than those required for existing mathematical models. The lumped-parameter model was developed from numerous sensitivity analyses with the more detailed RAETRAD model and from analyses of trends from empirical data sets. The model analyses established radon dependence on soil parameters, house size, floor cracks and openings, and indoor air pressures. The empirical analyses estimated house air infiltration properties, concrete slab diffusion properties, sub-slab ventilation effectiveness, and floor crack areas.

The lumped-parameter model was defined by simplifying these theoretical and empirical trends into a single equation. The equation expresses net soil-related indoor radon concentrations as a function of the sub-slab radon concentration, which defines the radon source strength, and a number of house parameters that characterize the radon entry and accumulation characteristics.

The model was validated by comparison to radon measurements at the Florida Radon Research Program radon test cells, by comparisons with soil radon potential mapping calculations, and by comparisons with indoor radon data at more than 60 houses. The test-cell comparisons exhibited an average agreement within 3% for the floating-slab cell and within 17% for the slab-in-stem-wall cell. The comparisons with soil radon potential mapping calculations showed a relative standard deviation of about 30%. The comparisons with house radon data depended on sub-slab ventilation system but averaged within a factor of 2 for both slab-in-stem-wall houses and monolithic slab houses.

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

A lumped-parameter model has been developed to provide a simple means of estimating indoor radon concentrations from data that are more commonly available than those required for existing, detailed mathematical models. It was developed under the Florida Radon Research Program (FRRP) to simplify evaluations of different construction options for attenuating indoor radon entry and accumulation. The FRRP technically supports the Florida Department of Community Affairs development of radon-resistant building construction standards. The lumped-parameter model consists of an empirical correlation of long-term average indoor radon concentrations with site parameters that include sub-slab radon levels and soil water contents, and house parameters that include house width and height, age, slab crack location, slab water/cement ratio, stem-wall type, indoor pressures driving air infiltration through the superstructure and the slab, and sub-slab ventilation effectiveness. The use of default

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values for some of these parameters further simplifies the model with little loss of accuracy.

Theoretical Basis and Development

The lumped-parameter model was developed from numerous sensitivity analyses with the more detailed RAETRAD model and from analyses of trends from empirical data sets that characterized building construction and performance. The theoretical RAETRAD analyses characterized radon entry by diffusion through the intact floor slab and by both diffusive and advective entry through cracks and openings in the building floor and foundation walls. The RAETRAD analyses suggested simplified approximations to express indoor radon as a function of radon source strength, house radon entry rates, and house ventilation parameters. Radon source strength was defined in terms of sub-slab radon concentration, and house radon entry rates were defined from floor openings, pressure driving forces, and slab diffusivity.

From RAETRAD sensitivity analyses, the interactive effects of soil type, house size, floor crack size and location, and indoor pressures were determined. House size had a relatively small, inverse effect when the slab radon entry rate was normalized by the house area and sub-slab radon concentration. Sub-slab radon depletion from leakage through cracks also caused a small, linear dependence of slab radon entry on crack location. Radon entry through cracks also was relatively uniform for a given soil when normalized by the crack area and sub-slab radon concentration. Entry through cracks varied linearly with indoor pressure and had an exponential dependence on soil type, which was represented by a surrogate of water saturation fraction. These effects were represented by simple, fitted parametric relationships that were combined into a single equation to express indoor radon as a function of sub-slab radon, soil water content (a surrogate that includes permeability effects), house width, floor crack location and area fraction, indoor pressure (driving soil gas entry), and house and soil ventilation rates.

Empirical Basis and Development

Empirical analyses of trends from prior data sets characterized house air infiltration properties, concrete slab diffusion properties, sub-slab ventilation effectiveness, and floor crack areas. The data on Florida house ventilation rates suggested a nominal 0.25 air change per hour (ach) passive infiltration rate with an age-dependent increase of 0.007 ach per year. The infiltration rates were expressed in terms of the passive, ventilating indoor air pressure, which was estimated from the FRRP house data to be -0.7 Pa. This value, combined with age-dependence, corresponds to a ventilation-pressure relationship of $\lambda_h = 0.31(\Delta P_v)^{0.6} + 0.007y$, where λ_h is the house air infiltration rate (ach), ΔP_v is the ventilating indoor pressure (Pa), and y is the age of the house (years).

Radon diffusion measurements in Florida concrete floor slabs suggested a correlation with their water/cement ratio as a surrogate for their radon diffusion coefficient. The resulting trend had an exponential-dependence on the water/cement ratio of the concrete. Sub-slab ventilation (SSV) effectiveness was approximated from reviews of prior performance by an 80% effectiveness estimate for active SSV systems and approximately 6% effectiveness for passive SSV systems. Floor crack areas were recognized as being difficult to characterize by visual inspection, and to consist of an approximate 0.2% leakage area plus an additional 0.29% that could result from a hollow stem wall.

Lumped-Parameter Model

The lumped-parameter model used the combined fitting constants from the theoretical and empirical analyses to express the net, soil-related indoor radon as a function of 11 variables and 14 constants. The resulting expression for the lumped parameter model is

$$C_{net} = C_{in} - C_{out} = \frac{3.6 C_{sub} f_{ssv}}{h[0.31(\Delta P_v)^{0.6} + 0.007y]}$$

$$[(2x10^{-3} + 2.9x10^{-3}\delta)\,(\frac{1}{70} + \Delta P e^{-3-0.045c^{6S}})$$

$$+2.9x10^{-7} e^{11.4W} + 3.5x10^{-5}(\frac{x_{crk}}{x_h}) + \frac{4.6x10^{-5}}{x_h}]$$

where

- C_{net} = net indoor radon concentration from sub-slab sources (pCi L^{-1})
- C_{in} = total indoor radon concentration (pCi L^{-1})
- C_{out} = outdoor (background) radon concentration (pCi L^{-1})
- C_{sub} = sub-slab radon concentration (pCi L^{-1})
- f_{ssv} = radon reduction factor from sub-slab ventilation (f_{ssv}=0.2 for active system, 0.936 for passive system, and 1 for capped or no system)
- h = height of indoor volume (m)
- ΔP_v = ventilation-driving indoor-outdoor pressure difference (Pa)
- y = house age (years)
- δ = 1 for hollow-block stem walls and 0 for poured monolithic stem walls
- ΔP = indoor-outdoor pressure difference (Pa)
- S = sub-slab soil water content (fraction of saturation)
- W = concrete slab water/cement ratio
- x_{crk} = location of dominant crack from perimeter of house (m)
- x_h = house minor dimension (width) (m) = $r_h\sqrt{\pi}$.

The factor C_{sub}, f_{ssv}, and h directly multiply the net indoor radon concentration predicted by the lumped-parameter model. The ventilation-driving indoor pressure, ΔP_v, also directly affects the indoor radon level with the nominal age dependence. The remaining terms account for particular mechanisms or variations in indoor radon entry. The first term in the brackets is a product of crack area fraction ($2x10^{-3}$ + $2.9 \times 10^{-3}\delta$) and radon entry velocity. The 1/70 term approximates diffusive entry through the crack and the $\Delta P exp(-3-0.045e^{6S})$ term approximates advective entry through the crack. The second major term in the brackets accounts for radon diffusion through the slab and depends on the water/cement ratio of the concrete. The third term in the brackets slightly increases the effect of radon diffusion through the slab due to slab crack location, and the last term in brackets slightly increases the diffusive entry through the slab for small structures.

For the reference house conditions used previously (ΔP = -2.4Pa), the lumped-parameter model estimates that slightly over half of the radon entry occurs by advection through floor cracks and openings for a monolithic slab house, and about two-thirds occurs by advection through the openings for a slab-in-stem wall (SSW) house. To estimate absolute indoor radon concentrations, the sub-slab radon concentration can be represented by measured values or calculated from surrogates such as radon flux or soil-gas radon concentrations.

Model Validation

Calculated indoor/sub-slab radon ratios (C_{net}/C_{sub}) from the lumped-parameter model were compared with measured data from the FRRP test cells, with reference data used to generate soil radon potential maps, and with measured data from FRRP demonstration and evaluation houses. The test-cell data were compared for each of eight sets of conditions, involving both floating-slab and SSW construction, and indoor pressures from passive to -50 Pa. The ratios of calculated/measured C_{net}/C_{sub} ratios varied by about 40-50%, but averaged 0.97 for the floating-slab cell and 0.83 for the SSW cell.

Comparisons of calculated C_{net}/C_{sub} ratios with soil radon potentials calculated for maps for Alachua County, Florida, had an overall relative standard deviation of 30%, with most of the differences occurring with the dry, sandy-soil profiles. In general, the comparison showed a positive bias for the lumped-parameter model that was associated with inherent differences between the lumped-parameter model and the radon mapping algorithm. Since neither explicitly defines fill soil layers or detailed crack properties, these are represented implicitly, as required for the different purposes of characterizing soil radon potentials for mapping and house radon resistance for the lumped-parameter model.

For comparisons of calculated C_{net}/C_{sub} ratios with FRRP house data, information was compiled from 20 houses studied by Geomet Technologies, Inc., 13 houses studied by Florida Solar Energy Center, and 30 houses studied by Southern Research Institute. The houses varied from new to 36 years old, were almost entirely slab-on-grade, and included a nearly equal mix of SSW and monolithic slab-wall construction. Many had SSV systems installed, including both suction-pit and ventilation-mat designs.

Net indoor radon data were obtained by subtracting outdoor radon concentrations from measured indoor values. The outdoor concentrations were estimated from a set of theoretical, 1-dimensional diffusion-dispersion calculations to develop a correlation based on sub-slab radon levels and soil properties. The theoretical calculations used a reference set of atmospheric dispersion data and boundary conditions for normal turbulence conditions, and led to the correlations $C_{out} = C_{sub}(9x10^{-5}-8.7x10^{-5}S)$. This relationship corresponds to about 0.1 pCi L^{-1} outdoors for a sub-slab radon concentration of 2,000 pCi L^{-1} in sandy soil.

Measured C_{net}/C_{sub} ratios for both SSW and monolithic slab houses were highest for houses with no SSV system, were slightly lower for houses with a passive SSV system, and were significantly lower for houses with active SSV systems. Houses with capped SSV systems were erratic, being higher than those without SSV systems for SSW houses and lower than those without SSV systems for monolithic slab houses. Calculated C_{net}/C_{sub} ratios, using best-estimate input parameters, were lower than measured ratios for all of the SSW and monolithic slab houses by a factor that averaged 0.5±0.3 among the SSV categories. The only exception was the capped-SSV case for monolithic-slab houses, where a 3-fold higher calculated value raised the average ratio to 1.1±1.2 for the SSV categories if it is included.

Alternative estimates of floor crack and opening areas were explored as a possible explanation of the higher observed indoor radon concentrations. Estimates of the areas required to give agreement between the lumped-parameter model and the measured data were excessive. Alternative estimates of concrete water/cement ratios to explain the differences may be plausible, however. Average water/cement ratios of 0.64 to 0.70 were estimated to explain the respective passive-SSV and active-SSV data for both SSW and monolithic houses. For no-SSV houses, however, higher water/cement ratios of 0.77 were required. Another explanation of the discrepancy may be the void volume of the SSV systems, in which the sub-slab radon concentrations typically were measured. These sub-slab volumes may have lower concentrations than the soil pore volumes in contact with most of the slab, therefore giving a high estimate for the measured C_{net}/C_{sub} ratio.

Conclusions and Recommendations

The lumped-parameter model combines theoretical and empirical trends to form a simple expression to estimate indoor radon concentrations for Florida slab-on-grade houses. The expression retains the fundamental, parametric dependencies of the more detailed models and data sets. It agrees with FRRP radon test cell data within averages of 3-17%, and with indoor radon data from over 60 houses within about a factor of two (houses being higher). Its agreement with radon mapping calculations is within about 30%, owing to fundamental differences in the purposes of the two algorithms being compared.

The present analyses suggest several parameters to be included in future new house evaluation projects. These include outdoor radon concentrations (for obtaining *net* indoor levels), concrete slab diffusion properties (water/cement ratio, diffusion coefficient, or density), and surface soil radon fluxes (as possible surrogates for sub-slab radon on undeveloped land). The analyses also suggest potential improvements in the lumped-parameter model. These include improved, alternative definitions of floor crack and opening areas and their associated permeability, an improved correlation for predicting concrete diffusivity, and representation of sub-slab void volumes associated with SSV systems for their effects on sub-slab radon measurements. Even without these changes, however, the lumped-parameter model is useful for predicting indoor radon concentrations from a minimum of readily obtainable parameters. It also is useful for interpreting and coordinating data from the FRRP New House Evaluation Project and for providing additional focus for that project.

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***David C. Sanchez** is the EPA Project Officer (see below).*
The complete report, entitled "Development of a Lumped-Parameter Model of Indoor Radon Concentrations," (Order No. PB95-142048; Cost: $27.00, subject to change) will be available only from
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