United States
Environmental Protection
Agency

National Risk Management
Research Laboratory
Cincinnati, OH 45268

Research and Development

EPA/600/SR-96/005 March 1996

EPA

Project Summary

Residential Radon Resistant Construction Feature Selection System

Kirk K. Nielson, Rodger B. Holt, and Vern C. Rogers

The Florida Department of Community Affairs (DCA) has proposed standards for radon-resistant features in residential construction. The features consist of engineered barriers to reduce radon entry and accumulation indoors. The proposed standards require radon-resistant features in proportion to regional soil radon potentials, which are defined from a statewide radon potential map. The report describes the basis and development of the system for selecting radon control features for new house construction in different regions according to their mapped soil radon potentials.

The effectiveness of different radon control features was estimated from new laboratory measurements, analyses of new and previous house studies, and mathematical model simulations. The laboratory measurements characterized five brands of polyethylene sub-slab membranes to have equivalent radon diffusion coefficients of $3.4x10^{-7}$ cm^2 s^{-1} ± $6.3x10^{-8}$ cm^2 s^{-1}. The geometric mean air permeability of the membranes was $6.5x10^{-15}$ cm^2 with a geometric standard deviation of 8.4.

New house studies included 14 houses characterized by Southern Research Institute (SRI) and 10 houses characterized by University of Florida (UF). The analyses showed that both monolithic-slab (Mono) and slab-in-stem-wall (SSW) foundation designs can passively control indoor/sub-slab radon ratios to average levels of C_{net}/C_{sub} = $3.3x10^{-4}$ to $4.2x10^{-4}$. These ratios are slightly lower than measurements in other houses the previous year, and two to four times lower than ratios from earlier studies. The SRI ratios are 1.4 to 3.7 times lower than values from a lumped-parameter model, primarily due to improved sealing of slab penetrations. The UF ratios are within a factor of 1.74 of calculated ratios. The geometric mean of all measured C_{net}/C_{sub} ratios for Mono houses is $5.5x10^{-4}$ (GSD=3.14, n=43), and the geometric mean of ratios for SSW houses is $1.1x10^{-3}$ (GSD=3.02, n=52). The Mono design offers approximately twice as much passive radon resistance as SSW designs.

Radon Emanation and Transport into Dwellings (RAETRAD) model simulations estimated the numerical effectiveness of SSW, Mono, and floating-slab foundations in connection with other radon controls. The controls were ranked by decreasing effectiveness as: (1) active sub-slab ventilation system, (2) vapor membrane placement, (3) enhanced ventilation, (4) improved foundation design (SSW or Mono), (5) 10-cm slump concrete, (6) 15-cm slump concrete, (7) sealing of slab openings and cracks, (8) sealing of slab penetrations, (9) sealing of openings and only large cracks, (10) use of a passive sub-slab ventilation system, (11) compaction of fill soil, (12) elimination of slab reinforcement, and (13) reinforcement of re-entrant corners. From these

rankings, a passive group (items 4, 6, 8, and 9) was selected to reduce radon by a factor of 2.1. Active control by item (1) increased radon control to a factor of 9.3.

A Florida radon protection map was developed to show where the passive group was needed to keep radon below 4 pCi L^{-1} and where the active feature was also needed. The map shows three categories. The green category denotes regions where less than 5% of the area should exceed 4 pCi L^{-1} in a reference house. Other regions, where the top 5% of the computed radon levels fell between 4 and 8.3 pCi L^{-1}, were assigned to the yellow category, indicating a need for passive radon controls. Regions where the top 5% of the computed radon levels exceeded 8.3 pCi L^{-1} were assigned to the red category, indicating additional need for active radon controls.

This project summary was developed by National Risk Management and Research Laboratory's Air 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 generated from radium (^{226}Ra) decay in soils can enter houses through foundation openings. With elevated entry and inadequate ventilation, radon can accumulate to levels that pose significant risks of lung cancer with chronic exposure. The Florida DCA has proposed construction standards to protect public health by requiring radon-resistant building features in areas of elevated soil radon potential. The report describes a system for selecting different radon resistant features for new house construction in different regions according to their soil radon potentials.

The proposed DCA standards reduce radon entry into houses using different combinations of improved foundation designs, understructure sealing, altered air pressures, and other engineered features developed under their Florida Radon Research Program (FRRP). The proposed standards seek to minimize radon levels without undue cost by matching the radon resistance of required features to the soil radon potential of each geographic region. The radon potentials of different regions are estimated from a statewide map and data base developed by DCA specifically for this targeted use of radon-resistance features.

This report characterizes the radon resistance of different radon control features from new laboratory measurements on plastic membranes, analyses of new and previous house studies with lumped parameters, and simulations with the RAETRAD numerical model. The most cost-effective features are ranked and grouped into active and passive categories. From the combined effectiveness of each category and the mapped radon potentials of 3,919 Florida regions, each region is assigned to one of three radon protection categories to achieve a 4 pCi L^{-1} indoor radon average. The categories show where no supplementary radon controls are required, where passive controls are required, and where active controls are also required. A radon protection map is developed from the respective regional categories using green, yellow, and red to show the minimum regional radon-protective construction requirements.

Radon Resistance of Polyethylene Vapor Barrier Membranes

The radon transport properties of polyethylene vapor barrier membranes are required to correctly model radon entry through floor slabs. Although commonly used under Florida slabs, the membranes have generally been ignored in modeling because their radon transport properties were unknown. Radon diffusion and air permeability coefficients of polyethylene membranes were measured to fill the data gap and thereby provide for more accurate modeling of radon entry.

Five brands of 0.015-cm (6-mil) polyethylene membranes were purchased from different commercial suppliers in Central Florida. Actual membrane thicknesses averaged 0.012 ± 0.002 cm. Three 10-cm diameter circles were cut from each brand for radon diffusion measurements by the time-dependent method. Three 1.5 x 3.0 m sheets were cut from each brand for air permeability measurements. Each sheet was folded and sealed to form a 1.5-m square envelope, which was inflated, weighted by a 12-kg mass, and monitored for air pressure and volume changes.

The 15 radon diffusion measurements averaged $3.36 \times 10^{-7} \pm 6.3 \times 10^{-8}$ $cm^2\ s^{-1}$. Analysis of variance showed no significant differences ($p < 0.25$) among the five brands. The 15 air permeability measurements were log-normally distributed, with an overall geometric mean of 6.5×10^{-15} cm^2 and a geometric standard deviation of 8.4. Analysis of variance showed significant differences among the different brands ($p < 0.025$).

Lumped-Parameter Model Estimates of Feature Effectiveness

The effectiveness of different features in resisting radon entry was studied in several demonstration projects under the FRRP. These included two test cells and 20 houses studied by Geomet Technologies, Inc., 27 houses studied by Florida Solar Energy Center (FSEC), 30 houses studied by SRI, and 14 houses studied by UF. Fourteen additional houses have now been studied by SRI, and 12 additional houses by UF.

Previous Analyses

The effectiveness of different house construction features was compared using the net indoor/subslab radon concentration ratio (C_{net}/C_{sub}). Measured C_{net}/C_{sub} ratios for both SSW houses and Mono slab houses were highest for houses with no sub-slab ventilation (SSV) system, were slightly lower for houses with a passive SSV system, and were significantly lower for houses with active SSV systems. Measured C_{net}/C_{sub} ratios for SSW houses averaged 2.7×10^{-3} for houses without SSV systems, 4.9×10^{-3} for houses with capped SSV systems, 1.7×10^{-3} for houses with passive SSV systems, and 4.3×10^{-4} for houses with fan-activated SSV systems. Measured C_{net}/C_{sub} ratios for monolithic-slab houses averaged 2.3×10^{-3} for houses without SSV systems, 6.2×10^{-4} for houses with capped SSV systems, 2.2×10^{-3} for houses with passive SSV systems, and 4.4×10^{-4} for houses with fan-activated SSV systems.

The results of a second semi-empirical study suggested that SSW construction, when completed in accordance with the FRRP standard, reduces indoor radon to about 9×10^{-4} of the sub-slab concentration (with an uncertainty factor of 2.2). Mono slab construction may improve radon resistance by approximately 33%, reducing indoor radon levels by a factor of 0.67 compared to SSW construction. Activation of SSV systems with exhaust fans reduces the C_{net}/C_{sub} ratio by approximately 70%, reducing indoor radon levels to about 0.3 times the levels that occur when the SSV system is in the passive or capped mode. The measurements on active SSV systems are sparse and uncertain, however, due to the small number of houses where the SSV systems were activated.

New Data

Data from the 1993 FRRP New House Evaluation Program (NHEP) were compiled in terms of the lumped-parameter model parameters or their surrogates. The data were measured by SRI and UF. The SRI set contained 14 houses, eight of which were Mono slab-stem wall houses and six of which had slabs poured into SSW. The UF set contained 12 houses, 10 of which were Mono and two of which were SSW designs. The building shell and SSV systems constituted the major differences between the SRI and UF data sets. The SRI houses utilized hollow-block concrete walls for all but one house, while all 12 of the UF houses were built with frame walls. The SRI houses utilized ventilation mats for SSV systems, while the UF houses utilized suction pits in their SSV systems. Except for two UF houses, none of the SSV systems were activated in either group.

House air leakage was compared under passive pressure conditions. The SRI houses had an average natural ventilation rate of only 0.19 air changes per hour (ach), while the UF houses averaged 0.29 ach (possibly due to frame versus masonry construction, or occupancy and protocol differences). The average of the observed floor crack areas for the SRI houses was more than twice as high as the average for the UF houses. However these averages come from variable data, and additional cracks may be concealed. The SRI mean is dominated by the SSW houses, which averaged three to five times higher than the other groups.

The geometric means of the C_{net}/C_{sub} ratios for the passive-control SRI measurements averaged $1.6x10^{-4}$ for the Mono houses and $4.2x10^{-4}$ for the SSW houses. The geometric means of the C_{net}/C_{sub} ratios for the passive-control UF measurements averaged $1.0x10^{-3}$ for the Mono houses and $4.1x10^{-4}$ for the SSW houses. The single active-system Mono house had a C_{net}/C_{sub} ratio of $6.2x10^{-4}$, and the active-system SSV house had a C_{net}/C_{sub} ratio of $1.7x10^{-4}$.

Lumped-Parameter Model Comparisons

The measured C_{net}/C_{sub} ratios for the SRI and UF houses were compared with corresponding C_{net}/C_{sub} ratios that were calculated using the lumped parameter model as reported previously. The lumped parameters used in the comparisons were defined primarily from site-specific measurements or surrogates.

The measured ratios for the SRI houses are lower than the calculated values by factors of 3.7 for the eight Mono houses and 1.4 for the six SSW houses. The lower measured ratios are attributed to improved sealing of slab penetrations by SRI in the present study. Since the Mono houses have virtually no advective radon entry routes other than slab penetrations, the greatest difference was noted for the SRI Mono houses. The SSW houses, despite improved sealing, still have permeable channels at the stem walls where advective radon entry can occur.

The 10 UF Mono houses show closer agreement between measured and calculated radon ratios, differing by an average factor of 1.74. The closer agreement suggests better consistency with the previous radon resistance effectiveness on which the lumped-parameter model is based. The two UF SSW houses have significantly lower measured radon ratios than the calculated values (by an average factor of nearly 2.7). This lower ratio may reflect better construction technique; however it is more uncertain because only two houses are being compared.

Comparisons with Prior Measurements

The present NHEP measurements of C_{net}/C_{sub} ratios can be interpreted better with the perspective of the two prior sets of NHEP house studies by the present contractors and others. The prior studies, primarily covered the FY-91 and FY-92 budget periods. Two prior FSEC sets of Mono houses are intermediate between the Geomet '91 and SRI '91 sets and the UF '92 set and the present SRI data set. The geometric mean of all of the passive Mono houses is $5.5x10^{-4}$ (GSD = 3.14).

The present C_{net}/C_{sub} ratios for passive SSW houses are only slightly lower than the FSEC '92 and UF '92 data. However, the present data are well below the range of the FSEC '91, the Geomet '91, and the SRI '91 studies. The geometric mean of all of the passive SSW houses is $1.1x10^{-3}$ (GSD = 3.02). The 52 SSW houses comprising this estimate therefore are approximately half as resistant to radon entry as the 43 Mono houses. The chronological trend in C_{net}/C_{sub} ratios is shown by time averages in the full report. The improvement in radon control may potentially be attributed to increased experience in building the passive radon control features. At least some of the 1991 studies included houses built before the radon standard or allowed builders to select their own passive features from earlier alternatives. Subsequently, closer surveillance and training by FRRP researchers ensured that most or all of the desired radon-resistant features were actually incorporated.

Data for estimating the effectiveness of active SSV systems are limited. The geometric mean of seven Mono houses with active SSV systems is $3.3x10^{-4}$ (GSD = 1.51). The geometric mean of the 17 SSW houses with active SSV systems is nearly identical at $3.4x10^{-4}$ (GSD = 2.58).

RAETRAD Model Estimates of Feature Effectiveness

The radon resistance effectiveness of different construction features was also evaluated by numerical simulations with the RAETRAD model. The RAETRAD model uses multiphase calculations of radon generation and transport, including moisture effects on the radon entry simulations. The simulations utilized reference houses and soil profiles to compare indoor radon levels with and without the different building features. The effectiveness of each feature was defined as the ratio of the reference indoor radon concentration (without the feature) to the indoor radon concentration with the feature. For interactive features, several reference houses are defined so that the feature effectiveness can be evaluated with the different interactions. The features evaluated include the effects of fill soil compaction, sub-slab vapor barriers, slab reinforcement, reinforcement of re-entrant slab corners, sealing of slab penetrations, closure and sealing of large slab openings, reduction of water/cement ratio (as estimated by reduced concrete slump), and use of different slab edge details.

The houses were modeled on a 4.3-m soil profile with a water table at 2.5 m depth and its resulting moisture profile. Three reference houses were defined for the floating slab, SSW, and Mono cases. The reference houses had a 8.6 x 16.5 m footprint, and an interior height of 2.4 m. The indoor air pressure and outdoor air exchange rate were -2.4 Pa and 0.25 h^{-1}, respectively, consistent with previous analyses.

Ranking and Groupings of Construction Features

The various features were ranked in descending order of effectiveness. The reference case was defined as the common floating slab house with no SSV system. The reference house had a sub-slab vapor barrier, since this is commonly used or required by building codes. The rank-ordered list of radon resistance factors is shown in Table 1. Several factors were grouped with an average effectiveness because of their dependence on slab edge details. Where the most radon-resistant approach was already standard building practice, the factors are less than unity. In these cases, the feature ranking is listed as the reciprocal of the factor, but the factor is not included in the composite because it is already being utilized. Fea-

Table 1. *Ranking of Residential Construction Features by Average Radon Resistance Effectiveness*

Construction Feature	Effectiveness $C_{ref}/C_{feature}$	Relative to	Summary Rank Effectiveness
1. Active SSV system	4.45	No SSV	4.45
2a. No vapor barrier - floating slab	0.57	6 mill v. barrier*	0.48 (2.1)
2b. No vapor barrier - SSW	0.47	6 mil v. barrier	"
2c. No vapor barrier - monolithic	0.40	6 mil v. barrier	"
3. Enhanced ventilation	2	0.25 ach	2
4a. Monolithic slab & stem wall	1.76	Floating Slab	1.62
4b. Slab poured into stem wall	1.47	Floating Slab	"
5a. 10-cm concr. slump - floating slab	1.17	20-cm slump	1.33
5b. 10-cm concr. slump - SSW	1.26	20-cm slump	"
5c. 10-cm concr. slump - monolithic	1.40	20-cm slump	"
6a. 15-cm concr. slump - floating slab	1.08	20-cm slump	1.15
6b. 15-cm concr. slump - SSW	1.12	20-cm slump	"
6c. 15-cm concr. slump - monolithic	1.17	20-cm slump	"
7. Seal slab openings & cracks	1.15	Unsealed	1.15
8. Seal slab penetrations	1.13	Unsealed	1.13
9. Seal openings & large cracks	1.10	Unsealed	1.10
10. Passive SSV system	1.07	No SSV	1.07
11. Compacted fill soil	0.98	Uncompacted	0.98 (1.02)
12. Non-reinforced slab	1.01	Reinforced	1.01
13. Reinforced re-entrant corners	1.001	Non-reinforced	1.001
Passive Group 4, 6, 8, 9 Average (Minimum)			2.3 (2.1)
Active plus Passive Group Average (Minimum)			10.3 (9.3)

* 1 mil = 25.4 μm.

tures were also distinguished between active and passive categories, based on use of mechanical control and association of operational costs. Thus, all of the features in Table 1 are considered passive except for the SSV system and the enhanced ventilation option.

Building features were selected on the basis of effectiveness and cost for the composite passive or active groups after excluding those already required by existing building codes. Features with less than 10% effectiveness also were eliminated. For the passive group, slab-edge detail dominated, and is recommended as the prime radon control feature for new construction. Other effective features included low-slump concrete and sealing of slab penetrations, large floor openings, and cracks. These features, grouped at the bottom of Table 1, give an average passive radon resistance of a factor of 2.3. However, since SSW houses may have significantly lower radon resistance effectiveness, a more conservative (passive-group) value of 2.1 was chosen for use in feature selection based on the 1.47 factor for SSW construction (item 4b in Table 1). The other passive features are optional. SSV systems (suction pit or ventilation mat type) are recommended as the only cost-effective active features. They may be even more effective than indicated in Table 1. While also effective, enhanced ventilation incurs unacceptable operating costs for sustained use. The active SSV radon control system is estimated to reduce indoor radon by at least a factor of 4.45. When used with the average passive features, the house radon resistance is increased to a factor of 10.3. From cost/benefit considerations, the set of passive features should be incorporated with the active SSV system wherever active radon control is needed.

Development and Use of the Florida Radon Protection Map

A Florida Radon Protection Map was developed for use with the 1994 proposed Florida Standard for Radon Resistant Residential Building Construction. This map was designed to show where radon controls are required, and which regions require active controls to supplement passive controls to achieve a 4 pCi L^{-1} limit. The radon protection map was based on a statewide data base and map of soil radon potential, the effectiveness of radon control features, and a cost-benefit analysis that determined the appropriate margin of safety for the radon protection map. The radon protection map was developed as illustrated in the full report. Soil and geology maps defined the 3,919 polygons for the radon protection map. Nearly 0.3 million National Uranium Resource Evaluation (NURE) aeroradiometric measurements, geologic radium values, radon emanation measurements, soil physical and hydrological properties, and water table data were used in model simulations of radon entry. These determined the distribution of soil radon potentials for each map polygon. From the statewide distribution of soil radon potentials, indoor radon distributions were computed for the reference house for use in a cost-benefit analysis to determine the appropriate margin of safety for the radon protection map.

Indoor radon levels for the reference house used its ventilation rate (0.25 ach) and volume (350 m^3), with the existing calculated soil radon potentials. The numerical relation between indoor radon and radon potential for the reference house is:

$$C_{indoor} = C_{outdoor} + 1.3\ Q \quad (1)$$

where:

C_{indoor} = annual average radon in the reference house (pCi L^{-1}),

$C_{outdoor}$ = annual average outdoor radon (pCi L^{-1}),

1.3 = reference house unit conversion (pCi L^{-1} per mCi y^{-1}), and

Q = median soil radon potential (mCi y^{-1}).

The safety margin for the radon protection map stems from the goal of keeping indoor radon as low as reasonably achievable, not to exceed 4 pCi L^{-1}. Based on the cost-benefit analysis, a 95% confidence limit was found to be cost-effective for the radon protection map. This means that, if more than 5% of a polygon area is predicted to have indoor radon concentrations above 4 pCi L^{-1} (in the reference house), then radon controls are required for the entire polygon. The soil radon potentials at the 95% confidence limit, tabulated in the radon potential map report, replaced Q in Eq. (1) to define the indoor radon levels that exceeded 95% of the reference-house values in a polygon, but that were below the top 5% of the reference-house radon levels in the polygon.

Polygons with less than 5% of their area exceeding 4 pCi L^{-1} were colored green on the protection map to show where the Standard requires no special radon controls beyond those provided by present building codes and practices. Polygons where the upper 5% of the computed indoor radon levels exceed 4 pCi L^{-1} but are less than 8.3 pCi L^{-1} were colored yellow to show where the Standard requires passive radon controls in new houses. Polygons where the upper 5% of the computed indoor radon levels exceed 8.3 pCi L^{-1} were colored red to show where the proposed Standard requires active radon controls in addition to passive controls. The Florida radon protection map is intended solely for supporting the proposed radon standard.

The radon protection map was compared numerically with 9,038 indoor radon measurements from three data sets. The middle 95% of the map range included 95.4% of the 2,952 Geomet land-based data points, which best represent Florida, with 1.9% below and 2.7% above the mid-range, compared to 2.5% expected for each. The 2,095 measurements in the Geomet population-based data set averaged slightly lower, with 4.0% below and 1.5% above the 95% mid-range, compared to 2.5% expected for each. The 3,938 measurements in the Florida Health and Rehabilitative Services residential data set were slightly high, with 0.7% below and 4.7% above the 95% mid-range, compared to 2.5% expected for each.

Over 250 houses with the greatest differences between measured and predicted indoor radon concentrations showed trends that offer further explanations. Houses above the 95% mid-range were about 25 times more likely to use slab-on-grade construction than to have crawl spaces, while the opposite trend was seen for houses below the mid-range. Similarly, houses above the 95% mid-range were about 50% more likely to use hollow-block construction than frame construction, and the opposite trend was also seen for houses below the mid-range. These trends are consistent with model predictions. Considering the variations in both measurements and map calculations, the measurements give excellent overall statewide validation of the radon protection map.

K. Nielson, R. Holt, and V. Rogers are with Rogers and Associates Engineering Corp., Salt Lake City, UT 84110.
***David C. Sanchez** is the EPA Project Officer (see below).*
The complete report, entitled "Residential Radon Resistant Construction Feature Selection System," (Order No. PB96-153473; Cost: $19.50, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
Air Pollution Prevention and Control Division
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

United States
Environmental Protection Agency
National Risk Management Research Laboratory (G-72)
Cincinnati, OH 45268

Official Business
Penalty for Private Use $300

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No. G-35

EPA/600/SR-96/005