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PASSIVE RADON CONTROL FEATURE EFFECTIVENESS IN NEW HOUSE CONSTRUCTION IN SOUTH CENTRAL FLORIDA

Charles S. Fowler, Susan E. McDonough, and Ashley D. Williamson
Southern Research Institute
Birmingham, AL

David C. Sanchez
U.S. Environmental Protection Agency
Research Triangle Park, NC

ABSTRACT

The State of Florida has a draft radon standard for new construction. This study was conducted to evaluate the effectiveness of two slab types (monolithic and slab-in-stem wall) in retarding radon entry in new houses built in accordance with the proposed standard over high radon potential soils. Fourteen houses were monitored during their construction on sites whose soil gas radon concentrations ranged from 1000 to 12,000 pCi/L. The slab integrity was monitored over time, and post-construction ventilation and radon entry measurements were made in all the houses. The slabs-in-stem wall exhibited significantly more slab cracking than did the monolithic slabs. Those houses also had higher average radon entry rates, radon entry velocities, and concentration ratios than the monolithic slab houses. Both slab types proved to be effective in retarding radon entry, especially when penetrations were properly sealed.

INTRODUCTION

Background

The Florida Radon Research Program (FRRP) was implemented to provide radon research related to the detection, control, and abatement of radon in new house construction and in existing buildings. The purpose for this research effort was the development of construction standards for radon resistant buildings and corresponding standards for mitigation of radon in existing buildings. From the fundamental studies in the first years of the program came a draft standard for radon-resistant building construction. The FRRP then shifted emphases to field evaluation or validation of specific areas of the proposed standards (Sanchez et al 1990). The majority of these demonstration studies have been evaluations of new houses conducted either in Alachua and Marion Counties (GEOMET 1992, Najafi et al 1993, Hintenlang et al 1993) or in Polk and Hillsborough Counties (Tyson and Withers 1992, 1993). In these studies it was found that implementing the standard recommendations resulted in low indoor radon concentrations in most cases. However, many of the houses were built on sites that had soil gas radon concentrations of less than 1000 pCi/L. In many of the houses built on more elevated radon potential soils, the passive construction features alone did not seem to control radon entry sufficiently to keep indoor radon concentrations below 4 pCi/L. One possible contributing factor to some of the failures was the fact that the builders did not always communicate schedule changes reliably to the investigators, who then were not able to inspect all of the slab sealing features as they were supposed to be accomplished. Finally, in the course of these studies, it was determined that some measurement or experimental protocols were not as effective as others in determining certain critical parameters, and that the frequency or timing of collecting other useful data could be improved.

Project Objectives

Part of the Florida's approach in the mapping endeavors has been to map different levels of radon potential within the state. The results of some of the previous studies have indicated that in the lower and medium potential areas of the state, application of requirements of the standards seems to be effective at controlling indoor radon concentrations. However, results from the few houses from previous studies that were built in the higher radon potential areas have been inconclusive. The overall purpose of this proposed work was to evaluate the performance and effectiveness of the radon resistant features of the "passive" barrier floor system in 14 new houses built over relatively high radon potential (> 1000 pCi/L) soils in South Central Florida. Areas where houses were being constructed on reclaimed phosphate mining lands and mineralized former groves where the soil gas radon was closer to 10,000 pCi/L or higher were actively sought in order to test the radon resistant features in close to "worst case scenarios."

Within the context of this overall purpose, there were two specific objectives that influenced the approach to the research.

1. Evaluate the relative effectiveness of two slab edge details, monolithic slab (MS) and slab-in-stem wall (SSW), in providing resistance to radon entry.
2. Evaluate the effect of sealing slab penetrations on radon entry into houses.

Technical Approach

Sites were sought in areas of the region that were known or projected from past experience to have high probability of having elevated soil gas radon concentrations. A package of information on the project, the standards, and the requirements for participation in the study was prepared and presented to builders or to prospective home owners in these areas, and their involvement was solicited. The construction of the selected houses was monitored with the aid of a construction check list developed for that purpose, and diagnostic measurements were made of the site, the slab, and the completed house according to pre-determined protocols. All of the houses used in this research were of slab-on-grade construction, and efforts were made to have a balanced number of MS and SSW houses. An active sub-slab depressurization (ASD) system using ventilation matting was installed in each house selected and constructed as part of the study. Data were collected of the site, the fill soil (if used), the concrete placement, curing, and cracking, the installation of the air handling (AH) system, and the completed house radon and infiltration characteristics. Throughout the data collection and analysis, pre-determined checks were made and analyzed of data quality indicators. These included calibrations of the measurement devices, replication of certain measurements, and the ongoing adherence to good measurement practices.

MATERIALS AND METHODS

Site Selection

Once a candidate site was identified and permission was obtained from either the builder or the owner, at least one soil gas radon grab sample was taken in accordance with the FRRP Standard Measurement Protocols (Williamson and Finkel 1991). The sample was usually extracted from a 1.2 m (4 ft) depth and from as near the center of the projected slab foot print as could be estimated. If the results of this radon grab sample estimated the soil gas radon concentration to be greater than the target value of 1000 pCi/L, then the house site was selected for participation in the project. Only slab-on-grade (SOG) houses were selected for the study. No houses with any portion of the main floor underlain by either a basement or a crawl space were considered for inclusion. Attempts were made to have nearly the same number of MS and SSW foundations. Table 1 is a listing of all fourteen houses selected, giving the builder code, the base living area of the slab, the approximate occupied volume and inside height, the number of stories, and the slab edge detail. As shown, eight builders were used, who constructed from one to four of the houses each. The base area of the slab beneath the living space of the houses varied from 81 m^2 for the only two-story house in the study to from 150 to 200 m^2 for five of the smaller houses to from 215 to 285 m^2 for six of the medium to large houses to over 330 m^2 for the two largest houses in the study. Eight of the houses had MS foundations (one a post-tensioned MS) and six were of SSW construction.

Pre-slab Activities

When the site was prepared for the slab placement, site characterization measurements were made of the

TABLE 1. SUMMARY PARAMETERS OF THE SELECTED HOUSES

House ID	Builder ID	Base Area (m^2)	Occup. Vol. (m^3)	Inside Height (m)	No. Stories	Slab Edge Detail
F-01	S-01	285	957	3.4	1	MS[a]
F-02	S-02	240	659	2.7	1	SSW[a]
F-03	S-01	281	856	3.0	1	SSW
F-04	S-03	182	500	2.7	1	MS
F-05	S-04	215	591	2.7	1	MS
F-06	S-05	170	414	2.4	1	MS
F-07	S-01	339	1135	3.3	1	PTMS[a]
F-08	S-06	343	941	2.7	1	SSW
F-09	S-01	81	445	5.2	2	MS
F-10	S-07	220	603	2.7	1	SSW
F-11	S-07	268	899	3.4	1	SSW
F-12	S-08	151	368	2.4	1	MS
F-13	S-08	167	408	2.4	1	MS
F-14	S-07	196	539	2.8	1	SSW

[a] Monolithic slab (MS), slab-in-stem wall (SSW), post-tensioned monolithic slab (PTMS).

compacted fill and native soils. These measurements consisted soil gas permeability and radon measurements, soil core extractions, and the placement of soil radon flux canisters. The permeability measurements were usually made at two locations near the center of the slab and at two to four others within the slab footprint. These measurements were made at depths of 0.3, 0.6, 0.9, and 1.2 m. Radon grab samples were taken at the 1.2 m depth. In between the two center permeability probe locations, a soil core was extracted of the fill and native soils, usually to at least 1.2 m. These samples were boxed and shipped to the University of Florida (UF) Environmental Radiation Laboratory where they were analyzed for soil radium content and soil radon emanation coefficient. If weather and scheduling permitted, the compacted fill radon flux canisters were placed overnight and collected for shipment to the analysis laboratory the next morning. If rain fall was predicted or if a weekend interfered with a shipment, then the data quality was reduced to the point that deployment and shipment was not reasonable. The ventilation matting was installed for the ASD system, with careful attention to the placement of the exhaust riser to insure that it would be placed in a wall with other plumbing risers or in a chase if one was available. The riser connected to the matting with a toilet flange. The mat and flange were recessed into the fill soil so that the slab thickness was not reduced around the flange. Sub-slab sampling lines were placed, usually with one under each quadrant of the house and one in the installed ventilation matting near the house center. After all of these features and the termite treatment were placed, the proper placement of the vapor barrier was monitored. The primary areas of attention were to insure that an adequate barrier quality was used, correct overlaps were maintained, penetrations and tears were sealed and repaired properly, and that the edge treatment was accomplished correctly. While these activities were being performed on the vapor barrier, slab reinforcement required by the standards at re-entrant corners and at large rectangular openings or penetrations (such as tub or shower traps) was being placed at the appropriate locations.

Slab Placement

Once the pre-slab installations were complete, the site was ready for the slab placement. This activity was closely monitored by SRI at all sites. The project sponsor, the Florida Department of Community Affairs (DCA) required that all concrete was to have high range water reducing admixture (superplasticizer) incorporated in the mix design. The standard required that the added water be kept below a fixed minimum. To insure that the mix design was formulated properly, a quality control specialist from the corporate office of one of the local batch plants was called in to aid the plant in formulating and mixing the design properly. The use of form and grade stakes was a constant difficulty in conforming with the standard properly, but no clear alternative to some of the common practices was found that the contractors would accept and use. The curing and loading practices specified in the standard were monitored carefully.

Post-slab Activities

Metallic penetrations through the slab were treated either with tar, plastic sleeves, or some other interface to separate the metal from the concrete. The use of tar both insulated the pipe from corrosion by the concrete and bonded the pipe to the slab. Sleeves, however, protected against corrosion while often leaving an air gap between the pipe and the slab. Penetrations made of plastic, such as polyvinyl chloride (PVC), unless treated with tar, also left a sub-slab soil gas entry route. Extra measures for sealing these gaps were employed. This penetration sealing was monitored for durability during their curing and loading visits and afterwards when slab cracking was also inspected. After the slab curing process was completed, the slab was inspected periodically for evidence of unplanned slab crack formation. Before the floor coverings were placed, the cracks were mapped on a floor plan of the house, generally with the lengths and widths of the cracks recorded, and measurements were made of selected portions of one or more of the cracks. The measurement protocol followed was similar to that reported by Pugh et al (1992), with the exception of a few modifications to improve the seal of the test chamber to the slab and to insure a more reproducible grab sample of the chamber gas. The measurements were analyzed to determine the crack leakage area and to measure the radon concentration of the gas pulled through it.

Air Handling System and Other Post-framing Installations

The continuation of the ASD piping up a wall or chase into the attic and out the roof required supervision because leaks in this system would be extremely counter-productive to the radon resistance of the house. Once the framing and roofing was complete, the AH system was installed. Specifications of the sealing and placement of plenums, ducts, grills, and boxes were monitored during the installations. The wiring and operation of other exhaust fans in bathrooms, kitchens, attics, etc. were also monitored to insure standard compliance. Table 2 is a summary of the basic construction practices employed in these houses as discussed in the above paragraphs and otherwise required for this study. Certain features were common to all the houses; so these are not enumerated in Table 2. These included the use of ventilation matting for ASD soil gas collection, a 152 μm (6 mil) vapor barrier, superplasticizer in the concrete mix, and acceptable sealing techniques around slab penetrations and in the AH ducts.

TABLE 2. CONSTRUCTION PRACTICES SUMMARY

House ID	Concrete Reinforcement	Slump (mm)	Curing Practice	Loading Delay (d)	AH Location	Air Returns
F-01	fiber	203		7		
F-02		178				
F-03	fiber	127		7		
F-04				4	attic	1
F-05	wire			7		3
F-06	wire	178				
F-07		127		8		
F-08		127		2		
F-09	wire					
F-10	wire				garage	2
F-11	wire				garage (2)	
F-12						
F-13	fiber	127		3		
F-14	wire				garage	

Post-construction Ventilation and Radon Entry Characteristics

After the house shell was completed and the AH system was installed, tested, and powered, testing of the ventilation and radon entry characteristics of the house were conducted. The basic protocol followed was that of

Hintenlang et al (1993), with minor adjustments in some of the houses. Generally hourly indoor radon concentrations in one or more rooms, sub-slab concentrations from one of the sub-slab sampling lines, and outside (ambient) concentrations were measured continuously over at least a six-day period. Simultaneously half-hourly indoor/outside, indoor/sub-slab, and room-to-room pressure differential averages and indoor, outside, and other relevant temperatures were recorded. A tracer gas system was operated over the same time frame to monitor the house infiltration rates. Usually sub-slab grab samples were taken before, in between, and after the house ventilation adjustments were made. These house conditions were AH off/interior doors opened, AH on/doors opened, and AH on/doors closed, operated for about two days at a time. Generally this testing was attempted after the house was completed and before the new owners moved. However, a few of the houses were completed when there were break downs in the tracer system, and some of the houses were finished within the same week as another, making for situations in which the owners were already occupying the house before the equipment was available for testing. In those situations, the testing had to be done with the owners' cooperation or scheduled during vacation times.

RESULTS

In each of the 14 houses, there were three distinct sets of diagnostic measurements taken, as described above: site characterization (including site selection measurements), slab crack, and post-construction ventilation and radon entry measurements. Table 3 summarizes some of the averages of the soil, crack, and house measurements in the houses. When the site characterization measurements were being made at house F-04, the permeameter probe was leaking at the weld of the head, and ultimately broke. A replacement could not be found before the slab was placed; so the permeability in the table refers to the average taken during the site selection measurements. Site F-05 had more clay in the native soil and the permeability measurements were lower there than at the other sites. The resulting reduced flow through the radon grab scintillation cell was too little for adequate sampling, leading to low radon concentration measurements during the site characterization there. Rain fall or scheduling problems prevented placement of the radon flux canisters at sites F-02, F-08, F-09, F-10, F-13, and F-14. Some of the other data are missing or not yet analyzed, as indicated by the single dash.

The screening measurements (one or two probes) at sites F-01, F-02, and F-03 were within the standard error of the characterization measurements (average of four to six probes). Those at site F-06 also agree reasonably well (within 20%). The screening sample at site F-05 was taken in a very clayey lens, whose radon concentration was higher than expected, and the characterization measurements were artificially low because of low gas flow. However, the discrepancies between the selection and characterization measurements at sites F-07, F-08, F-12, and F-13 are more difficult to explain. They may reflect the wide range of variability inherent in reclaimed soils; they may be the result of soil mixing that occurred in between the two measurement times; or they may have been influenced by changes in the soil condition, such as moisture content. The recorded radon fluxes do not show any correlation with the soil gas grab radon concentrations, but they are measuring different spaces. The grab samples were all from 1.2 m depths -- well into the native soil in all cases. The flux canisters were placed on top of the compacted fill. The average soil gas permeabilities are all basically within an order of magnitude of one another, with the exception of site F-05, as discussed above. House F-02 had excessive slab cracking, some of which was caused by having to move some plumbing features after the slab had been placed because one of the construction workers had misread the plans. The slab quality overall improved as the project progressed. None of the three major concrete suppliers were familiar with the use of superplasticizer in the concrete mix design. Many of the early mixes were not formulated properly, and a quality assurance officer from one of the home offices was called in to assist in developing the mix design and training the operators in mixing it.

TABLE 3. SITE SOIL AND HOUSE MEASUREMENTS

House ID	Soil Gas Radon Concentrations Screening (pCi/L)	Characterization	Radon Flux through Fill ($\mathrm{pCi/m^2s}$)	Soil Gas Permeability ($\mathrm{cm^2}$)	Slab Crack Length (m)	Natural Infiltration Rate (ach)
F-01	5508± 72	4982±624	1.1±0.1	1.1(±0.4) x 10^{-7}	21.0	-[a]
F-02	1481± 92	1502±152	-	8.8(±0.8) x 10^{-8}	35.4	0.16±0.02
F-03	2626± 12	2367±455	4.8±1.3	8.4(±0.8) x 10^{-8}	30.2	0.17±0.01
F-04	5185±389	-	6.1±0.9	2.2(±0.1) x 10^{-8}	7.6	-
F-05	19,894± 60	2706[b]	1.4±0.2	3.0(±0.6) x 10^{-9}	5.3	0.16±0.01
F-06	3049± 85	3761±389	3.0±0.7	6.4(±1.4) x 10^{-8}	0	0.16±0.02
F-07	2692± 25	5322±288	1.2±0.2	2.4(±0.7) x 10^{-7}	-	-
F-08	1308± 10	3021±486	-	1.1(±0.2) x 10^{-7}	24.8	-
F-09	14,324± 98	-	-	-	0	-
F-10	2927± 39	-	-	3.1 x 10^{-8}	-	0.19±0.01
F-11	-	-	1.1±0.3	-	-	-
F-12	5700± 8	3694±523	1.0±0.4	5.0(±1.0) x 10^{-8}	0	0.15±0.01
F-13	5989± 60	3782±366	-	9.8(±0.6) x 10^{-8}	5.9	-
F-14	-	-	-	-	0	-

[a] - Indicates that the data are not available or not yet analyzed.

[b] Insufficient air flow for a good sample.

Table 3 summarizes most of the site screening and characterization measurements, with the exception of the soil core radiological analyses performed by UF. Table 4 provides the summary results of those analyses. The soil radium content of both the surface soils on these sites and in the lower profiles were all well in excess of the recommended radium concentrations for foundation back fill material of 0.8 pCi/g (Rogers, and Nielson 1991), with the lone exception of site F-02. It appears that high radium fill may have been imported to site F-11, or it would have been below the recommended concentration. At six other sites, the fill or top horizon of the prepared base was higher in radium content than the lower horizons of the native soil. At sites F-01 and F-07 the fill was tested and found to be higher than any of the lower horizons, and at sites F-03, F-08, F-10, and F-14 it is suspected that imported fill may have contributed to higher radium contents in the uppermost layer of prepared soil. Site F-02 was the only one where low concentration fill was known to have been imported, but it appears that lower concentration fill than the native soil may have been used at F-05, F-12, and F-13. At site the fill had 7 pCi/g radium concentration, about what the native soil had. At site F-04 the soil radium concentration was very high from the surface down to 1.5 m. The radon flux through the compacted base from Table 3 corresponds very well with the soil radium concentrations in either the fill soil or in the uppermost horizon, which is a reasonable correspondence.

After the house shells were completed, the house ventilation and radon entry measurements were made as discussed earlier. Table 5 summarizes the results of the house ventilation and radon measurements taken in the fourteen houses under the three house conditions: A/H off, interior doors opened; A/H on, doors opened; and A/H on, doors closed. The data have not been collected in house F-09 and are still being analyzed for house F-10. A portable computer hard disk failure was the cause for the loss of the doors closed data from house F-11, and an extremely high sub-slab moisture problem in house F-14 prevented an accurate estimate of the radon concentrations there. In ten of the twelve houses for which most of the data are available, the indoor concentrations exhibit the following pattern: AH off ≥ AH on, doors opened ≥ AH on, doors closed. In the two houses in which this pattern was not observed, there were some possible explanations that may have contributed to the deviation from the norm. In house F-04, there was some evidence that workers and/or owners may have entered the house when the measurements were being made, especially during the AH off condition. In house F-06, there appeared to have been a strong rainfall event that led to elevated indoor (and sub-slab) radon concentrations during the AH on, doors opened condition. House F-04 had the highest sub-slab radon concentrations (and radon flux and soil radium content) and also had the highest indoor concentrations, while house F-02 had the lowest sub-slab concentrations and some of the lowest indoor concentrations. The others houses had intermediate sub-slab and indoor concentrations with no clear pattern of correlation.

TABLE 4. RADIOLOGICAL ANALYSES OF FILL AND SOIL SAMPLES

House ID	Depth (m)	Ra-226 (pCi/g)	Emanation (%)	Emanating Ra (pCi/g)	Moisture (%)
F-01	fill	4.5 ± 0.09	21 ± 7	0.96 ± 0.28	6 ± 0.3
	0.00-0.30	3.0 ± 0.05	4	0.13	5
	0.30-1.57	0.9 ± 0.05	16 ± 4	0.16 ± 0.04	5 ± 0.8
F-02	fill	0.5 ± 0.1	13 ± 8	0.08 ± 0.05	5 ± 1
	0.00-0.91	1.2 ± 0.1	12 ± 4	0.14 ± 0.06	6 ± 0.9
	0.91-1.52	0.5 ± 0.05	8 ± 8	0.04 ± 0.04	4 ± 1
F-03	0.00-0.91	10.0 ± 3.1	17 ± 7	1.67 ± 0.54	4 ± 1
	0.91-1.22	6.6 ± 0.1	23	1.53	3
	1.22-1.52	1.4 ± 0.04	14	0.19	4
F-04	0.00-1.52	13.9 ± 1.2	12 ± 2	1.76 ± 0.41	6 ± 0.9
F-05	0.00-0.30	6.3 ± 0.08	20	1.24	6
	0.30-1.22	15.3 ± 0.9	4 ± 2	0.66 ± 0.37	8 ± 2
	1.22-1.52	6.6 ± 0.09	20	1.32	18
F-06	fill	7.0 ± 0.08	12	0.82	5
	0.00-0.91	7.3 ± 1.0	16 ± 5	1.25 ± 0.70	6 ± 1
	0.91-1.52	5.5 ± 0.05	17 ± 2	0.92 ± 0.14	3
F-07	fill	5.3 ± 0.08	10	0.55	6
	0.00-0.25	4.2 ± 0.08	15	0.63	6
	0.25-1.52	2.2 ± 0.06	25 ± 2	0.53 ± 0.03	11 ± 0.4
F-08	0.00-0.30	4.2 ± 0.09	18	0.76	9
	0.30-0.91	2.6 ± 0.2	18 ± 3	0.48 ± 0.11	10 ± 0.3
	0.91-1.52	1.1 ± 0.1	16 ± 10	0.18 ± 0.13	7 ± 0.5
F-09	0.00-1.52	5.0 ± 1.0	25 ± 7	1.23 ± 0.32	11 ± 0.8
F-10	0.00-0.79	4.6 ± 0.5	13 ± 2	0.59 ± 0.03	12 ± 5
	0.79-1.55	1.2 ± 0.03	14 ± 3	0.16 ± 0.04	4 ± 2
F-11	0.00-0.25	5.0 ± 0.07	8	0.40	7
	0.25-1.30	0.6 ± 0.09	4 ± 3	0.02 ± 0.02	7 ± 2
F-12	0.00-0.25	4.2 ± 0.07	18	0.76	9
	0.25-0.41	8.8 ± 0.11	26	2.28	11
	0.41-0.91	7.6 ± 0.1	10 ± 0.3	0.73 ± 0.03	4 ± 0.3
	0.91-1.52	6.4 ± 0.1	8	0.51 ± 0.03	5 ± 2
F-13	0.00-0.30	3.7 ± 0.07	17	0.61	9
	0.30-0.46	11.6 ± 0.12	22	2.52	14
	0.46-1.52	6.7 ± 0.2	7 ± 1	0.47 ± 0.11	4 ± 0.2
F-14	0.00-0.56	6.9 ± 0.05	2	0.14 ± 0.01	9
	0.56-0.66	4.1 ± 0.13	17	0.70	14
	0.66-1.22	0.8 ± 0.1	11 ± 4	0.09 ± 0.04	10 ± 2
	1.22-1.52	6.7 ± 0.1	99	6.64	20

TABLE 5. HOUSE VENTILATION AND RADON MEASUREMENTS

House ID	AH Off, DO[a]				AH On, DO				AH On, DC[a]			
	Vent.[b] (ach)	C_{in}[c]	C_{out}[c] (pCi/L)	C_{sub}[c]	Vent. (ach)	C_{in}	C_{out} (pCi/L)	C_{sub}	Vent. (ach)	C_{in}	C_{out} (pCi/L)	C_{sub}
F-01	-	1.6	0.2	4312	-	0.9	0.2	4893	-	0.9	0.2	4510
F-02	0.17	1.6	1.1	886	0.17	1.6	1.2	946	0.13	0.9	0.3	753
F-03	0.17	3.8	0.4	5993	0.17	2.1	0.7	5905	0.16	1.9	1.0	6971
F-04	-	4.1	1.1	12,121	-	4.6	0.9	12,017	-	4.9	0.9	11,783
F-05	0.17	1.5	0.1	4490	0.17	1.5	0.6	4423	0.15	0.8	0.1	4315
F-06	0.16	1.6	0.8	4524	0.17	2.7	0.7	4713	0.17	1.9	1.1	4636
F-07	-	1.4	0.2	4242	-	1.0	0.2	4275	-	0.6	0.1	4317
F-08	-	3.3	0.4	4004	-	3.1	0.6	4295	-	3.0	0.5	4390
F-10	0.20	8.0	1.3	5577	0.20	5.5	0.9	4582	0.16	4.1	0.9	4582
F-11	-	1.9	0.2	4184	-	1.3	0.2	4150	-	-	-	-
F-12	0.15	2.7	0.4	6478	0.16	2.6	0.2	7816	0.14	2.3	0.1	5865
F-13	-	2.5	1.1	6208	-	2.5	0.2	5639	-	1.5	0.4	5725
F-14	-	3.1	1.1	-	-	2.4	1.1	-	-	2.1	1.1	-
Mean	0.17	2.3	0.6	5222	0.17	2.2	0.6	5370	0.15	1.9	0.5	5327
±S.D.	±0.02	±1.0	±0.4	±2737	±0.01	±1.0	±0.4	±2748	±0.01	±1.2	±0.4	±2785

[a] Air handler (A/H), interior doors opened (DO), interior doors closed (DC).

[b] House ventilation rate from blower door measurements (air changes per hour).

[c] Inside (C_{in}), outdoor (C_{out}), and sub-slab (C_{sub}) radon concentrations (picocuries per liter).

DISCUSSION

From the hourly inside and outdoor radon measurements, the net radon (C_{net}) was calculated by subtraction, as outlined by Nielson et al (1993a). The radon entry rate (RER) was then calculated by rearranging one of their equations

$$RER = C_{net} * \lambda_h * V_h / 3.6$$

where λ_h is the rate of house ventilation by outdoor air and V_h is the interior house volume. Table 6 lists the RER for each of the houses for which data have been collected and analyzed, as well as two other measures of the slab's effectiveness as a radon barrier, the radon entry velocity (or conductance) (REV), and the radon concentration ratio (CR). The REV was calculated by lumping several of the velocity terms of Nielson et al (1993a) into one variable in the equation

$$REV = RER / (A_h * C_s)$$

where A_h is the house area and C_s is the sub-slab radon concentration. CR was calculated simply by taking the ratio C_{net}/C_s, similar to those listed by Nielson et al (1993b). The means of these various measures of slab barrier effectiveness (C_{net}, RER, REV, and CR) for the two type of slab edge details were compared statistically. The net indoor radon concentrations in the two groups of houses showed no significant differences. The RER, which takes into account the house ventilation rates and house volumes, showed definite differences between the two slab types, but the variability within and between the groups was so great that these differences were not significant at a 10% significance level. The REV, taking into account the house slab area and the sub-slab radon concentrations, and the CR, taking into account the sub-slab radon concentrations, produce very highly significant results for the AH off condition, as indicated in Table 6. With this small sample size and the high variability in the measured and calculated parameters, it was difficult to show much significance in the analyses. It is expected that an increased sample size would reduce the variability in some of these parameters, increase the power of the comparisons, and indicate more significance in the results.

TABLE 6. COMPARISON OF CALCULATED ENTRY PARAMETERS BY SLAB TYPE

	AH Off, DO			AH On, DO			AH On, DC		
House ID	RER[a] pCi/s	REV[a] mm/s	CR[a] -	RER pCi/s	REV mm/s	CR -	RER pCi/s	REV mm/s	CR -
				houses with monolithic slabs					
		($x10^{-5}$)	($x10^{-4}$)		($x10^{-5}$)	($x10^{-4}$)		($x10^{-5}$)	($x10^{-4}$)
F-01	95	7.8	3.2	51	3.7	1.4	46	3.6	1.6
F-04	104	4.8	2.5	128	3.5	3.1	139	6.9	3.4
F-05	41	4.4	3.3	31	3.3	2.5	20	2.2	1.9
F-06	19	2.4	2.2	42	4.8	4.2	19	2.4	2.2
F-07[b]	92	6.5	2.7	60	4.1	1.8	35	2.4	1.0
F-12	33	3.4	3.2	39	3.4	3.1	32	3.5	3.8
F-13	49	4.3	2.7	68	7.5	3.5	32	3.3	1.9
GMean[c]	53	4.5***	2.8***	54	4.2	2.7	37	3.2	2.1
GSD[c]	1.89	1.48	1.17	1.59	1.34	1.50	1.95	1.48	1.52
				houses with slabs-in-stem wall					
F-02	29	13.5	10.2	34	14.8	11.6	14	8.1	8.0
F-03	151	8.9	6.2	40	2.4	1.4	38	2.2	1.2
F-08	195	14.1	7.5	165	11.2	5.8	165	11.0	5.7
F-10	223	18.2	12.0	158	15.7	10.3	86	8.6	7.0
F-11	106	9.5	4.1	68	6.1	2.6	-	-	-
F-14	76	-	-	50	-	-	40	-	-
GMean	107	12.4***	7.4***	70	8.2	4.7	50	6.3	4.6
GSD	2.12	1.35	1.53	2.00	2.29	2.62	2.53	2.11	2.21

[a] Radon entry rate (RER), radon entry velocity (REV), and concentration ratio (CR = C_{net}/C_{sub}).

[b] House F-07 has a post-tensioned monolithic slab.

[c] Geometric mean (GMean), geometric standard deviation (GSD).

*** Very highly significant difference (statistically significant at the 0.1% significance level).

Nielson et al (1993b) collected the measured radon and house data from Tyson and Withers (1993) from their study based on houses from the same general area as those reported here and calculated CRs based both on the measurements and on their lumped parameter model calculations. For MS houses in that study, the overall geometric means of their measured and calculated CRs for houses with the ASD system installed but either capped or passive was 5-6x10^{-4}. For SSW houses the corresponding geometric means ranged from 7 to 9x10^{-4}. Table 6 lists the respective CRs from this study to be 2-3x10^{-4} and 4-7x10^{-4}. These reductions are assumed to be attributable to the improved sealing procedures enforced in this year's study. One other comparison between the slab types that did show a highly significant difference was the amount of slab cracking. The MS foundations averaged less than 6 m of slab crack length per slab, while the SSW houses had over 22 m of cracks per slab. However, house F-02, which had the alterations in the plan design after the original slab was placed, was a SSW foundation. The moving of some of the plumbing penetrations required breaking the slab, which caused some additional cracking. This activity biased the slab cracking data in favor of the MS foundations, but it did not account for all of the difference.

CONCLUSIONS

The results from this study demonstrated that houses built over MS foundations show less slab cracking and greater resistance to radon entry than did those built over SSW foundations, in accordance with previous findings. But both types of slabs were shown to be effective at retarding radon entry, even in houses built over relatively high radon potential soils (1000-5000 pCi/L or higher). The performance of these slabs was evaluated using measures such as REV and CR. When compared with CRs from previous studies in the same area of the State, those from this year's houses were lower by about half. Most of the improvement is attributed to stricter enforcement of the sealing of slab penetrations.

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