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Project Summary

Test Cell Studies of Radon Entry

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Although slab edge detail and fill composition are logical factors to consider in radon resistant construction, little research has documented their effects on radon entry into slab-on-grade structures. This study was conducted to contrast the effectiveness of slab-in-stem wall (SSW) with floating slab (FS) construction practices, to measure radon transport and entry for model testing, to develop protocols relevant to depressurized radon measurements, and to determine the effect of high radium fill soil on indoor radon concentrations. The effects of the slab edge details were investigated in two test cells built on 6- x 6-m slabs placed over 8-pCi/g radium soil. The high radium fill study was conducted on two 3- x 3-m poured concrete foundations in which different depths of fill soils could be placed and a movable building put on top. The native soil contained about 0.2 pCi/g radium. The fill soils ranged from 0.2 to 33 pCi/g radium. The indoor radon concentrations in the FS cell were 3.5 times higher than those in the SSW cell. These results agreed with predictions by a radon entry and transport (RAETRAD) model. Whole building stresses and slab area and crack length radon entry were measured, and they yielded comparable results. Experiments in the fill study suggest that the amount of emanating soil radium is a good predictor for radon entry into a structure, indicating that elevated radium fill soil can contribute significantly to indoor radon concentrations.

This Project Summary was developed by the National Risk Management 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

The purpose of the Florida Radon Research Program (FRRP) was the development of building codes and standards for radon resistant buildings and construction standards for mitigation of radon in existing buildings. A working draft of proposed building standards was developed based on fundamental studies. Emphases shifted to field evaluation or validation of specific areas of the proposed standards. These demonstration studies centered primarily on two research components: intense, long-range, controlled studies in a few research structures; and less comprehensive, shorter duration, less controlled measurements in many houses enrolled in new house evaluation studies. The study reported here is part of the research house component.

One objective of these research house studies was to validate the effectiveness of "barrier" construction features, specifically contrasting a floating slab (FS) with a perimeter crack with a slab-in-stem wall (SSW) with no perimeter crack. Another objective was to measure the radon transport and entry required for model testing and validation. The primary model being tested was Rogers & Associates Engineering (RAE) Corporation's radon entry and transport (RAETRAD) code. The third objective was the development of transferable protocols relevant to depressurized radon measurements. The main protocol under investigation in this study was the "stress" test, although several different applications of it were included: whole building, slab area, crack lengths, and short- versus long-term. A final objective of this work was to determine the effect of high radium fill soil placed over a low radium native soil on indoor radon concentrations.

In December 1990, the Florida Department of Community Affairs (DCA) constructed two test cells on the site of the Florida Institute of Phosphate Research (FIPR) in Bartow, FL. These 6- x 6-m structures were built over a spoil bank of sand tailings reclaimed from phosphate mining operations. The soil had moderately low permeability and moderate soil radium levels. The soil gas radon concentrations measured were 3200-3500 pCi/L at 0.9-m depths prior to construction with the soil relatively dry and 5000-12,000 pCi/L at 1.2-m depths after construction when the soil was fairly wet. One of the cells was built with an FS with a significant edge crack, and the second was constructed on an SSW foundation.

In January 1992, plans and construction of a movable building were begun. Two 3- x 3-m foundations were constructed. The site had never been mined, and the native soil was sand with less then 1 pCi/g soil radium. The site was underlain by relatively impermeable clay that prevented soil gas radon produced from deeper and potentially higher radium sources from making its way into the surface sand. Both of these 0.6 m deep poured concrete foundations were built in and surrounded by this low radon potential sand. In one foundation (F1) an additional 0.3 m of native soil was placed, allowing for 0.3 m of fill soil. In the second foundation (F2) 0.6 m of fill soil could be added. The movable building had a pair of fixed floor cracks 1.2 m long and 6 mm wide, 0.3 m from the side walls of the building, and a 75-mm diameter hole in the center of the floor.

Procedure

Sites and Structures

FIPR Cells—

Test cell 1 was built with a floating slab, and test cell 2 had an SSW construction. No polyethylene vapor barrier was placed under either of the 100 mm slabs poured in these two cells. The cells' superstructures were wood frames with stucco over plywood cladding. A 25-mm layer of spray urethane foam was applied inside the plywood surface, in the walls and under the roof, providing both thermal insulation and a considerable degree of air tightness. Each cell had only a single steel door with a foam core opening into the unit with positive magnetic seals on all four edges. Neither cell was built with any other fixed or planned opening. The bottom of the slabs was just above the outside grade. Each test cell was later equipped with a wall-mounted ductless split heat pump for space conditioning. All of the penetrations were sealed with spray urethane and/or caulk and were leak-tested to ensure that the sealing was adequate and complete. Leak tests were performed by depressurizing the whole structure, and using chemical smoke inside the structure to detect infiltration sources.

IMC Movable Cell—

A "pad" of relatively uniform sandy soil was mounded in a field that had never been mined. Two 3- x 3-m foundations were dug in this pad about 3 m apart. Concrete stem walls, 0.6 m high and 150 mm thick, were poured in each foundation. Polyvinyl chloride (PVC) access holes and notches for running the sampling lines were placed prior to the pouring. The movable cell itself was constructed of 1.2-m panels made of 0.8-mm aluminum skin bonded to both sides of a 75-mm thick extruded polystyrene (EPS) core. The cell's only major opening was a 3068 insulated steel door with magnetic weatherstripping. The cell was equipped with a wall-mounted ductless split heat pump. The refrigerant lines and electrical wires fed through a single opening in the back wall which was sealed around the feed-through. The floor of this movable cell was constructed of panels 75 mm thick, but the EPS core was only 64 mm thick. Sheets of 11-mm plywood were placed on top of the EPS, and the 0.8 mm aluminum skin was bonded to the EPS on the bottom and to the plywood on the top. In the floor, 0.3 m from each of the two sides, was placed a 1.2 m long fixed floor fault 6 mm wide. In the center of the floor was a 75-mm diameter hole with a 100- x 75-mm closet flange placed on top and bottom. The two 1.2-m edge faults were to simulate perimeter cracks, and the center hole was to represent a plumbing penetration.

Measurements

The critical measurements in the studies were those determining radon concentrations and differential pressures.

Radon Measurements—

Most of the indoor radon was measured in the FIPR test cells with continuous radon monitors (CRMs). Generally, for indoor radon concentration measurements, the CRMs were set up to count for hour intervals and store those counts for later processing. In the IMC movable cell, the indoor radon concentrations were also measured with CRMs, but the counts were fed directly into the data acquisition system (DAS) hardware and into a 286 computer for storage. Another form of critical radon concentration that was measured was grab sampling. A filtered sample of air was drawn into and sealed in a flask or cell that had a zinc sulfide phosphor coating on its interior surface. The flasks were generally counted about 4 hr after filling to allow the short-lived radon decay products to reach equilibrium with the radon. Correction factors were applied to the counting results to compensate for decay during the time between collection and counting. In both continuous monitoring and grab sampling, calibration coefficients were determined for the instruments and flasks used by exposure to known concentrations at the National Air and Radiation Environmental Laboratory (NAREL) in Montgomery, AL. Examples of circumstances in which grab sampling was the measurement of choice include soil gas sampling, sub-slab sampling, and measurements made during the "stress" tests in which the test cells were depressurized at different differential pressures for given time intervals, and the effect on indoor radon concentrations were monitored.

Differential Pressures and Other Measurements—

The third type of critical measurement that was made was that of differential pressures. These measurements were usually made using electronic digital micromanometers. Examples of differential pressure measurements taken during the course of these studies include indoor/outdoor pressures, sub-slab/outdoor pressures, soil/outdoor pressures, stem wall block core hole/outdoor pressures, and pressure drops across an orifice to determine flows when a depressurizing/pressurizing fan was active. A Campbell Scientific, Inc., (CSI) 21X data logger was installed in one of the FIPR test cells for most of the study period. At first it was used primarily to monitor indoor and outdoor temperatures and some of the differential pressures on a continuous, rather than an episodic, basis as with the micromanometers. Later in the project, after all of the components of the weather station were installed, the data logger also stored information on wind speed and direction, barometric pressure, solar flux density, the outdoor air temperature and relative humidity, and rainfall. The data from the CSI 21X were retrieved on a schedule varying from once a day to once every two weeks. In the movable cell, a more powerful DAS was set up. It monitored the pressure drop across the orifice and various pressure differentials, up to 16 thermocouples, three CRMs, and other inputs. Besides receiving, reducing, and storing the data, the DAS also controlled the zeroing functions of the pressure transducers, the switching of the multiplexed transducers and CRMs, and the flushing of the scintillation cells on the quasi-continuous CRMs. Between the two foundations, a weather station was set up that contained a wind speed and direction indicator, a barometer, a rain gage, an outdoor air temperature and relative humidity sensor, and a solar flux density monitor. Signals from these devices fed into the CSI 21X data logger located inside a weatherproof box at the base of the weather station. Also stored in the 21X were soil moisture matric potential data collected from 10 locations.

Several other types of measurements were made at the test cells associated with specific tests or experiments. One of these is the soil permeability, including measurement of soil gas radon concentration at the deepest penetration. After each test cell was leak-tested with chemical smoke and all the infiltration sites were sealed as well as possible with urethane foam or caulk, air infiltration was determined using a modified “blower door” approach. A computer program modified from the actual blower door code was used to estimate the equivalent leakage area (ELA) of each test cell. Later in the project, when sufficient sources and detectors could be obtained, the Brookhaven National Laboratory Air Infiltration Measurement System (BNL/AIMS) was used to monitor infiltration integrated over longer time periods. Air leakage was also measured in the movable cell, generally after each move. The BNL system was not used in the movable cell. When the soil permeabilities were being measured, an auger core near each test cell was extracted for analyses by other laboratories both for additional documentation of the site for this study and also in support of other related projects in the FRRP. Samples were analyzed for soil moisture percent, soil radium concentration, and radon emanation percentage in accordance with the FRRP Standard Protocols.

Model Predictions

Information from the RAETRAD model generic predictions was useful in the planning and design phases of the FIPR project. At that time a variety of “reasonable” parameters representing some of the ranges that may be expected were used as hypothetical starting points. Later, as actual data were collected, the models were refined to reflect the conditions of the test cells and their environment more realistically. Similar iterations were made with other input parameters. The model could deal with only one fixed crack. When the slabs produced unplanned settling cracks where they could not be easily modeled, new estimates of the slab permeability had to be used to approximate the “effective” permeability of the intact and cracked slab. Soil and slab parameters such as densities, permeabilities, saturation fractions, and porosities, were similarly first approximated and later corrected if necessary as more data were collected. Models of radon entry were run for smaller footprint structures to ensure that we could go to the 3- x 3-m foundations of the movable cell without undue loss in generality. The model predictions proved similar to those of larger structures. Most of the data required as input for the movable cell runs were well characterized before the runs were needed; so the iterative process described above for the FIPR cells was not required.

Radon Entry Theory and Applications

The total amount of radon in a given volume is VC, where V is the volume of the space and C is the radon concentration. V is constant for the structure, and C generally varies with time. This quantity of radon changes as radon enters and leaves the volume. It is assumed that the radon enters at some fixed entry rate, I, for any given pressure applied in the building. Radon exits by way of the exfiltration of the structure air, represented by QC, where Q is the exfiltration rate and is assumed to be constant at a given building condition of closure and applied pressure. The net rate of change in the radon quantity is

$$\frac{d(VC)}{dt} = V\frac{dc}{dt} = I - QC \qquad (1)$$

This is the governing differential equation describing the change in radon. The assumed initial condition for solving this equation will be that the concentration at time zero will be zero: C(0) = 0. Other initial conditions can be accommodated fairly easily. A solution that satisfies the governing equation and initial condition is

$$C(t) = C_S(1 - e^{-\lambda t}) \qquad (2)$$

where C_s is the steady-state (long time equilibrium) radon concentration, and λ is the ratio of the exfiltration rate to the volume

$$\lambda = \frac{Q}{V} \qquad (3)$$

The radon entry rate, I, (assumed to be constant for a given structure condition) must equal the equilibrium radon exfiltration rate after a sufficiently long time for the indoor concentration to stabilize, or

$$I = QCs \qquad (4)$$

Study Design

This project was implemented in phases such that similar study objectives were addressed in slightly to very different environments. The initial activity in the FIPR test cells was performed prior to any planned compromise of the slab integrity. Necessary modifications such as sealing and installation of ports, openings, and sampling tubes were accomplished before altering the slabs. A full battery of experiments was conducted, with as much instrumentation as possible in place. After the operation in the cells with the slabs relatively intact was accomplished, three 100-mm slab cores were removed from each cell. Sections of 100-mm PVC pipes were caulked into these core holes so that they could be capped off or opened with some degree of control. Additional 10-mm holes were drilled through the slabs along other radials, and stainless steel tubes were placed to depths of 0.3-1.2 m and sealed so that differential pressure or sub-slab radon measurements could be checked in other directions. Many experiments and measurements similar to those made with the intact slabs were repeated. Finally, after the tests and experiments were completed, samples were taken to characterize the sub-slab soil. These included soil permeability and soil gas radon samples and soil cores from approximately 0 to 1 m deep. At the movable cell site, similar characterizations of the site and structure to those made at the FIPR site were made of each of the fill soil configurations being tested.

Stress Tests

One of the objectives of this work was to develop transferable protocols relevant to depressurized radon measurements. The specific protocols relevant to the other objectives of this project dealing with radon entry and barrier effectiveness are the whole structure and zonal "stress tests." These were developed for both short- and long-term measurements. The radon entry rates were approximated by the change in concentration at constant flow over the time period. These radon entry rates were expressed as a function of cell depressurization where appropriate. Usually as the levels reached a plateau, the entry rate would become proportional to the exhaust flow rate.

Results and Discussion

Characterization and Other Measurements

Test Cell Air Infiltration Measurements—

The cells were depressurized with an exhaust fan, and the resulting pressures and flows were measured similar to blower door tests. Because of the low flows in these tight cells and the resulting larger impact of wind effects, the precision of the calculated leakage areas and infiltration could not be tightly controlled. The ELA leakage area calculated for test cell 1 varied from 580 to 1290 mm^2, while that of cell 2 ranged from 390 to 840 mm^2. It was thought that the perimeter crack in the FS of cell 1 was the source of some, if not all, of the additional leakage found there. From the pressure-flow data, one could also calculate the infiltration in air changes per hour (ACH). Applying these calculations to the test cell 1 measurements indicated 0.02-0.06 ACH at 4 Pa in cell 1 and 0.02-0.04 ACH at 4 Pa in cell 2. At 50 Pa depressurization, the results were 0.17-0.25 and 0.11-0.20 ACH in cells 1 and 2, respectively. From the analyses of the BNL data collected in two weeks in July, the infiltration at 20 Pa and 4.7 L/s flow for both cells was about 0.2 ACH. When the cells were operated under no mechanically induced depressurization and with all known openings closed tightly, the infiltration was 0.028 ACH in cell 1 and 0.024 in cell 2. Also, placing other tracers at the base of the footings in both cells allowed for the estimation of the fraction of their emissions that were found in the test cells under both conditions. In cell 1, 45-57% of the emissions from the buried tracers were detected when the cell was depressurized at 20 Pa, while 2.7-3.9% was detected indoors when the cell was not mechanically depressurized. For cell 2, the corresponding numbers were 23-32% and 1.0-2.5%.

Soil Radium, Radon Emanation, Moisture, and Other Characteristics—

During construction of the test cells, GEOMET gathered samples of the soils and sent them to UF for analyses. Later Southern sent some deeper samples to UF and two entire cores to RAE for somewhat similar analyses. In both test cells the fill soils were slightly lower in soil radium content, but higher in emanation percentage. During late June 1991, tensiometers were placed in the soil around the test cells to measure the matric potential of the soil moisture. Generally the soil matric potential increased with depth and varied fairly little over the time the measurements were made. Since there were regular and frequent rains, the 0.3-m depth generally had higher moisture concentration. In late July, after the slabs had been penetrated, three tensiometers were placed through the slab and into the subslab soil of each test cell. Generally, the soil matric potentials there decreased with depth and proximity to the edge of the slab. Over a relatively short time period, the moisture was effectively constant under the slabs, and those from the outdoor tensiometers showed little change from the previous month.

Stress Tests and Related Radon Entry Calculations

Radon Flux and Stress Test Measurements—

The 0.382 m^3 "zonal plenum" was used to measure the buildup of radon over a 0.8 m^2 area of intact exposed slab in both cells. A CRM was placed under the sealed plenum, and the radon in that space was measured over time. A form of Eq. (2) seemed to describe the observed behavior fairly well. The zonal plenum was also used to conduct a depressurized stress on 0.8 m^2 of slab area in both test cells. The plenum was placed at -20 Pa and about 0.5 L/min regulated flow through a bleed valve. The radon entry rate for cells 1 and 2 seemed to be about 2.5 and 2.4 pCi/min, respectively. The second kind of area plenum used was a crack plenum. It was used to measure the radon concentrations pulled through the perimeter crack around the floating slab in test cell 1. It was found that -1 Pa at 0.2 L/min flow was a stable, reproducible setting. When the measured radon concentrations were fit to entry Eq. (4), the radon entry rate was found to be about 11.1 pCi/s, or 24.3 pCi/s per meter of perimeter crack. With no depressurization, the radon entry rate appeared to be between 0.6 and 2.2 pCi/s or about 1.3 to 4.6 pCi/s per meter of crack depending on the portion of the crack measured. This crack plenum was also placed over 0.45 m lengths of the unplanned settling cracks that occurred in the slabs of both test cells. The radon entry rates in cell 1 estimated by three applications of Eq. (2) were 2.3 pCi/s for -40 Pa, 0.22 L/min flow, 2.2 pCi/s when the flow was increased to 0.26 L/min with bleed air, and 0.14 pCi/s for the "passive" case with no imposed depressurization. In cell 2 the radon entry rate was calculated to be about 0.3 pCi/s with no depressurization and 10.9 pCi/s at -40 Pa and about 0.2 L/min flow.

Whole Building Radon Measurements and Long Term Stresses—

Measurements of the indoor concentrations in the test cells were started May 31, 1991. Radon entry rates were calculated by fitting Eq. (2) for several controlled conditions for each cell. These conditions included "passive" modes, in which no depressurization was applied to the cell, and a number of states during which a variety of depressurizations were applied at various flow rates of make up air. Cell 1 maintained higher indoor radon concentrations and entry rates than cell 2 when they were operated in the same condition. Radon entry rates for both cells were also calculated over a time when significant rainfall, high winds, and a drop in barometric pressure made the cells behave differently from their controlled conditions. The sub-slab pressures were elevated at this time, perhaps spiked by the drop in barometric pressure, the pumping action of the rain, and/or some contribution from the increased wind. As the cells "relaxed," they returned to more normal entry rates, but only after several days. The cells were also operated at various depressurizations and flows, with fixed openings at various placements in the slab. The radon entry rates of the two cells were much closer to each other with a fixed hole open. Radon entry rates were calculated in cell 1 for several months after cell 2 was being used for another project.

Pressure Field Extension Measurements and Model Comparisons

After the slabs had been penetrated on July 10, the test cells were depressurized with one hole open in the cap of the center core hole. The pressure field extension was then measured at each of the slab tubes and at the soil tubes placed outside the structure earlier. The RAETRAD model was run to predict the pressures and radon concentrations expected. It was found that, because of the extensive cracking and some detected subsidence under the slab in cell 1, adjustments had to be made in some of the parameters for the model to fit the measured values. The primary adjustments were to make the slab and the stem wall more "porous" to the applied pressures. With such adjustments made, the model was made to agree fairly well with the values observed during the pressure field extension measurements. The model predictions are in good agreement under and within 0.3 m of the slab, but the agreement is not as good 1.8 m from the slab. Some of this discrepancy may relate to the fact that the model predicts for a cylindrical approximation rather than for a square structure. The RAETRAD model also predicts soil gas radon concentrations. Some of these were taken as grab samples over the course of the study. The samples were taken over a wide range of time, conditions, and states of operation, leading to some fairly wide ranges of values. The model seems to predict values relatively close to those ranges.

Studies of Radon Entry from "Hot" Fill Using Movable Test Cell

In March 1992, the experimental studies of the effects of "hot" fill soil began on the second host site using the movable test structure described earlier. The first series of tests were performed on the foundation designed for 0.3 m depth of fill, but used the native soil for a control soil. A week of depressurized operation was performed, followed by a week of passive recovery and a second week of depressurized operation. As expected from the low soil radium level, the soil gas and indoor radon levels were low. The indoor radon concentrations averaged little more than 1 pCi/L. Some trends are clear in this data set which are observed in the higher-radium fill soils. During the period of 20 Pa depressurization, a slow drop in sub-slab radon concentrations is seen which may be interpreted as depletion of soil gas radon under the structure. Under passive operation, the sub-slab radon appears to recover somewhat and approach previous levels. Similarly, a trend toward higher indoor radon is noted. A layer of 0.6 m of moderate radium fill was placed in F2 on May 15. This fill consisted of sand tailings with a measured radium level of 4.12 pCi/g, and emanation fraction of 14%. The cell was moved onto this foundation on May 22 and left in passive operation through June 4. The cell was depressurized approximately 7.5 Pa with approximately 2.5 L/s average exhaust flow rate, then left passive. The pattern seen in the earlier period was demonstrated again, but with a greater signal/noise ratio. The sub-slab radon built up to a steady state value after a week of passive operation, then dropped by one-third during the 4-day depressurization, and began to recover during the final 3 days of the experimental cycle. The indoor radon quickly reached a steady state value of about 3 pCi/L under depressurization, then climbed over a several day period when mechanical exhaust ventilation was removed. Between June 12 and October 15, the cell was mounted over foundation F1, which was filled with scrap concentrate to represent a probable upper limit to the range of radioactive fill soil likely to be encountered. This material contained 32.9 pCi/g radium with an emanation fraction of 11%. The indoor radon in the cell was allowed to equilibrate under passive conditions; then it was depressurized at 10 Pa for 2 days, then allowed to remain under passive conditions. The ratio of the indoor radon to the sub-slab radon concentration was used to compare the data. During periods where the sub-slab radon is changing slowly relative to the indoor ventilation rate, this ratio gives a measure of relative soil gas entry. During the periods of passive operation, the ratio approaches comparable steady-state values even though the indoor and/or the sub-slab concentrations may not have attained comparable degrees of steady state.

On October 16, the cell was moved to foundation F2 for the final fill condition. This fill consisted of a layered "cold over hot" soil. The lower 0.3-m layer at the bottom of the foundation consisted of the same scrap concentrate hot fill used in the previous test series. This was covered with a 0.3 m layer of the base soil from the site. The cell was left passive until October 20, when it was depressurized to 12 Pa with an exhaust flow rate of 4.7 L/s. After October 23, a series of experiments were conducted with the center and edge openings alternately opened and closed. This range of conditions allowed radon entry and depletion to be measured beneath the slab for different locations of opening.

Radon Entry and Slab Edge Details

There were 10 periods of time when both the FIPR test cells were operated at no applied depressurization. The indoor radon concentrations were recorded and fitted to the infiltration equation, and equilibrium radon concentrations and radon entry rates were calculated. In every instance the indoor radon concentrations in cell 1 greatly exceeded those measured in cell 2. In fact, the equilibrium concentrations ranged from being 2.2 to 5.4 times higher and the radon entry rates from 2.3 to 5.0 times higher in the FS cell than in the SSW cell. While sub-slab radon concentrations indicate that the source potential was as much as 40 to 50% higher under cell 1 than under cell 2 because of the lateral variability of the site, this does not account for the three to fourfold increase in indoor concentrations. When the cells were depressurized at various levels, the ratio of the steady state concentrations and entry rates reduced to less than the factor of 3 to 4. The use of the box plenum over areas of an intact slab in both passive and depressurized modes indicated that 1 to 2 pCi/s radon entry came through the intact concrete in either test cell. The crack plenum was similarly used over the perimeter crack in cell 1. Radon entry was calculated at a rate of 30 to 600 pCi/s, depending on the degree of depressurization. This plenum was also used on the settling/shrinkage cracks in both cells, and rates of 4-60 pCi/s and 8-300 pCi/s were estimated to enter cells 1 and 2, respectively. The perimeter crack of the FS seemed to be the primary contributor to the cell's radon entry. With practically no depressurization, there would be as much as 35 pCi/s radon entry in cell 1 and about 10 pCi/s in cell 2. The observed passive state usually resulted in radon entry rates from 54 to 200 pCi/s in cell 1 and from 15 to 53 pCi/s in cell 2. When the various plenum measurements under depressurized conditions were extrapolated, estimated cell 1 radon entry rates of as much as 660 pCi/s were reached. Whole cell depressurization of 10 to 20 Pa produced calculated entry rates of 540 pCi/s. The cumulative plenum depressurizations in cell 2 extrapolated cell entry rates to the 300 pCi/s range, while experimental observations produced entry rates from 135 to 340 pCi/s when the cell was depressurized from 10 to 20 Pa. These observations indicate that the various plenum measurements seem to have potential for estimating the whole building entry rates.

Long-term Trends in Radon Entry

As experiments were conducted over time in the FIPR cells, the radon concentrations seemed to increase for the same cell under the same conditions over time. The slabs were still in the process of aging and settling. This possibility was substantiated by the slow appearance of settling/shrinkage cracks 5 to 6 months after the slabs were placed. The slabs did not have vapor barriers exacerbating the effects of the cracks. In addition to these naturally occurring faults, the work that was done in the later phases also compromised these slabs. Each of these alterations was sealed, caulked, and repaired as well as possible, but the resulting barriers may not have been as substantial as the initial 100 mm of concrete. The two parameters that tended to indicate most strongly the changes over time were the calculated equilibrium radon concentrations and radon entry rates for the cells with no applied depressurization. Linear regression calculations indicate that the equilibrium concentrations and entry rates were increasing significantly over the time periods of observation. The equilibrium radon concentrations and radon entry rates were also calculated and recorded for the experiments in which the cells were depressurized. For cell 1, the equilibrium concentration for the nominal 2.4 Pa depressurization was averaged to be 131±33 pCi/L, while the average entry rate for these passive runs was 104±47 pCi/s. For cell 2, the corresponding concentration was 33±15 pCi/L, and the entry rate was 31±13 pCi/s. Both the equilibrium concentration and the entry rate increased with depressurization. The radon entry rate is expected to be linear with applied depressurization and seemed to be quite significant with slopes of 30±2 and 11±2 pCi/s/Pa for cells 1 and 2, respectively. The consistent increase in the equilibrium concentrations is expected in these tight structures. Since the contribution of leakage air through the superstructure was minimal, the dilution of the indoor radon was primarily limited by the flow control valve, effectively reducing the leakage area as the applied pressure was increased. The ratio of the cell 1 (5.1±0.5 pCi/L/Pa) to cell 2 (1.1±0.1 pCi/L/Pa) slopes of the equilibrium concentration regression lines was 4.6, and that of the radon entry rates was 2.7. These ratios are reasonably close to the factor of three to four observed in relative radon concentrations between the two cells. As stated above, we attribute this difference primarily to the perimeter crack.

Hot Fill Effects on Radon Entry

During the course of the hot fill phase of the study in 1992, radon entry rates from four combinations of fill were studied under passive and mechanically depressurized conditions. These experimental results were compared with predictions of radon entry using the RAETRAD model and figures of merit based on soil properties. The model provides satisfactory fits to the experimental data and predictions of the effect of further variation of key parameters. First, the measured radon entry at 10 Pa depressurization was compared with predicted entry rates for each fill studied. The experimental data were about 30% higher than the RAETRAD predictions for the fills studied. However, not all the depressurization experiments were carried to steady-state with respect to depletion of the sub-slab radon as assumed by RAETRAD. Had steady-state been achieved experimentally, the experimental numbers would be lower, and in closer agreement with the model. The experimental and model results were compared with a basic figure of merit: the total emanating radium under the slab. This number is calculated by multiplying the measured soil radium times the emanation fraction times the calculated mass of the soil layer in the 0.9-m layer immediately under the footprint of the slab within the foundation walls. A strong correlation with the experimental and modeled entry was noted.

Further parametric modeling was studied using RAETRAD for each of the four experimental soil configurations as well as a few hypothetical extensions of these conditions. The first effect studied was the presence of sub-slab void spaces. Indications of void spaces under the slab were seen not only in the movable cell but also under the FIPR cells and in past diagnostic studies in existing houses. In order to test the effects of void spaces, RAETRAD calculations were repeated with no void spaces and with a “worst case” void 9 mm thick extending under the entire slab. The presence of this gap increased the radon entry by 10-20% over the pressures studied. Increases of the same magnitude were noted for other fill soils and geometries. The second parameter studied was the position of the penetrations or openings under the slab. Most of our experiments were performed with both center and edge penetrations open. The few studies performed with one location closed indicated little difference in radon entry between the center only, edge only, or both open conditions. While the experiments were not conclusive, these results would be expected if a significant sub-slab void exists and if the primary resistance to soil gas flow is the soil itself rather than either penetration. Investigation indicated that for each geometry the ratio of radon entry between the two channels varies only weakly with pressure above roughly 1-2 Pa depressurization. As one might anticipate, entry through the side channels is greater under pressure-driven flow conditions, while the proportion entering the center increases in the presence of the sub-slab gap and/or at lower pressures. Since both of these conditions are common, if not typical, we expect central penetrations to be as significant a factor as edge penetrations in general slab-on-grade housing stock.

We would anticipate that the different fill geometries studied would have different response to applied depressurization. In order to test these assumptions, calculations were performed over a pressure range of 0.2-20 Pa, extending over an order of magnitude below and above typical depressurization levels. Calculations were performed for the four fill cases studied: The “base” case (low radium soil), the 0.6-m layer of 4.12 pCi/g “warm” fill, the 0.3-m layer of 32.9 pCi/g “hot” fill, and the 0.3-m layer of hot fill covered by 0.3 m of base soil. In addition, calculations were performed on a fifth case for comparison. This case, 0.6 m “hot,” was identical to the 0.6 m “warm” case except for substitution of the “hot” fill. For consistency, the “gap” geometry was used for all cases. Inspection of this comparison showed a similar trend for all fill cases. At the lowest pressures, the radon entry approaches a constant value characteristic of diffusive transport without convection. At higher pressures, the entry rate increases with roughly a power-law dependence, then appears to approach an upper asymptotic limit which we would assume to be determined by the limit on the production rate of the radon source. The pressure dependencies of all cases are similar, but not identical. The radon entry rate of each fill case was normalized to its rate for a 0.2-Pa depressurization. The differences among the cases can be rationalized as follows: where the radium-bearing soil extends farther from the slab entry point. greater depressurization is required to collect an equivalent fraction of the available radon and is likewise less subject to depletion at higher pressures.

To extend the conclusions of the test cell studies to new residential construction, RAETRAD calculations were extended to the elliptical geometry of the "reference" house used in other modeling studies for the FRRP. The ratio of the yard area to house area modeled is 6.25:1. We tested the dependence on crack position for a base scenario consisting of 0.6 m of elevated, sandy fill over sandy base soil. The radon entering the house through the slab crack increases almost linearly with crack position to a maximum of 3.7 and 4.3 m from the center; for larger radii, radon entry decreases slightly until the perimeter is reached. The total radon entry also includes roughly 23 pCi/s attributable to direct transport through the slab; the magnitude of this portion is essentially independent of crack position. It was found that the radon entry rate per unit crack length varied by less than 3.5% for cracks in the annular region 0.9 m or more from both the center and edge of the slab. The soil gas flow varies by 4.4% over this range, increasing monotonically with the radius. These results indicate that model conclusions using perimeter cracks should be applicable to interior cracks as well.

Calculations at 0.9- and 4.9-m radius for cracks of 2.5- and 10-mm width were also made. The calculated soil gas and radon entry values were essentially invariant over this factor of four variation in crack width, indicating that crack length rather than area is the proper normalizing factor for cracks of this size. In evaluating the effect of a hot fill it is convenient to postulate that the contribution of fill soil at all depths within the slab footing is roughly constant and that the total emanating radium within this layer will largely determine the indoor radon. A series of studies was performed to investigate this hypothesis. Assumed radium contents of 2, 4, 8, and 16 pCi/g were used in the fill layer. Emanation fractions of 50, 55, 50, and 50% were assumed, in accordance with the findings of others for soils in a five-county area of Central Florida. Data generated suggest that the indoor radon may indeed scale with the total fill radium. For each assumed fill radium content, the rate of increase in indoor radon with fill thickness falls off with increasing thickness, suggesting that the deeper fill layers do not contribute quite as much as the top layer. The incremental added radon attributable to each new layer falls off at a rate of 52%/m in the top 0.6 m.

To extend the predictions of this study to a range of conditions, calculations were made with a range of base and fill soil types. For those studies, a 0.6-m fill layer was assumed over a radium-free base soil of the same soil class as the fill. Three facts were revealed. First, the variation of indoor radon is completely correlated with the emanating radium content of the fill for each soil type. This must of necessity be the case within the numerical precision of RAETRAD due to the structure of the equations used in the model. Second, there is an intercept of roughly 0.06 pCi/L across the range of soil types. Third, the slopes of the lines do not vary by more than a factor of two across the range of soil types used. More insight into this result, which might at first seem surprising, can be gathered from calculating results from the 4 pCi/g soil radium cases in various soils. The predicted total radon entry for this available radium content varies from 79 to 166 pCi/s across the soils studied. The portion of radon which enters through the crack shows a much stronger relative relationship varying from 10 to 143 pCi/s. The remaining radon entry route, direct transport across the slab, accounts for most of the radon entry for the less permeable soil types. This rate drops off for coarser soils as more of the radon immediately under the slab is able to diffuse to lower depths or is drawn into the building through the crack; both of these factors decrease the concentration gradient that drives the diffusive transport.

When the calculations are extended to non-uniform soils, the results are less easily visualized. In fact, the variability of the results is partly explained by the variation of direct entry through the slab. For fill soils coarser than clay the diffusive transport through the slab decreases as the coarseness of the fill and/or the underlying base soil increases. The same mechanisms operate to decrease the sub-slab radon available for transport through the crack, but are generally overwhelmed by the orders of magnitude increase in soil gas flow as the coarseness of base and/or fill soil is increased. Thus, for a given base soil type, radon entry generally increases as the coarseness of the fill is increased. For a given fill soil type, the radon entry generally increases strongly as the base soil coarseness is increased to that of the fill, then levels off and often will decrease with further increases of base coarseness. As one might predict, the crack entry rates collapse into a tight trend when radon entry is made a function of soil gas entry. There is more scatter in the total entry rate, but, for a given soil gas entry rate, the radon entry rates are clustered within about ±15% of one another. While the soil gas entry rate is not generally measurable for a given house, a surrogate parameterization is to define an effective total permeability, $K_{eff,}$ as a weighted average of the fill and base permeabilities. The effective permeability reflects the resistance to flow that would be experienced by a streamline passing 150 mm from the footing boundaries. A comparison of the analysis with this parameter rather than soil gas entry indicates that K_{eff} does indeed serve as reasonable surrogate for soil flow rate.

Conclusions and Recommendations

One objective of this research was to validate the effectiveness of "barrier" construction features, specifically contrasting the "floating" slab construction of test cell 1 with the slab-in-stem wall foundation of test cell 2. The observed indoor radon concentrations of test cell 1 generally were about three times higher than those of cell 2 when the two cells were operated under equivalent conditions. Calculated radon entry rates for the structures tended to show this same general relationship of a threefold or greater entry rate with the floating slab. Specific measurements were made estimating the radon entry through the perimeter crack of the floating slab, and as the modelers predicted, most of the radon entry appeared to come through the perimeter crack.

Another objective was to make detailed measurements relevant to radon transport and entry for model testing and validation. Many measurements were made and compared with the predictions of the Rogers & Associates' RAETRAD model. It was discovered that several adjustments to assumed parameters were necessary to bring about good agreement. Some of these were made because insufficient information was available initially about the actual conditions. Others were required because imperfections in the actual slabs and fill preparations caused them not to perform as the modeled slab and fill base predicted. Overall, the modeled pressure fields and sub-slab radon concentrations were brought into good agreement with the observed measurements. Both horizontal and vertical variability in the soil radium content input parameter was observed and incorporated in the model. The model was able to accommodate most of the variability that was detected.

Another objective was to develop transferable protocols relevant to depressurized radon measurements. A solution to the basic differential equation accounting for the mass balance of radon within the structure was found to explain fairly well the radon concentration changes observed when the cells or zones of the cells were subjected to depressurized stresses. Overall the modeling applications were very useful and informative and showed good potential for further use in this type of research.

The final objective was to demonstrate and quantify the effect on indoor radon from high radium fill soil. The data collected from a number of experiments with the movable cell placed over different thicknesses of fill soils with different concentrations of soil radium are presented with an analysis of which parameters affect the indoor radon concentrations most strongly and what some target "safe" values might be. A framework for a possible radiological standard for fill soil is presented.

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The complete report, entitled "Test Cell Studies of Radon Entry," (Order No. PB96-153549; Cost: $27.00, subject to change) will be available only from:
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