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Radon Reduction in Crawl Space House

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Abstract: Radon, a naturally occurring radioactive gas, is drawn from the soil into a house when low air pressure exists in the house. This is a commonplace environmental hazard in the United States, Canada, and northern Europe. The U.S. Environmental Protection Agency (EPA) is developing and demonstrating procedures to use in reducing the radon concentrations in a variety of house types. Until recently, research has focused on basement houses because of their great potential for radon entry; however, other housing substructures also present unique radon problems. Several radon reduction alternatives for crawl space houses are noted, and the successful demonstration of one of these alternatives, subplastic suction, is described in detail. The findings of this study need to be confirmed and supplemented with more measurements, preferably on larger and more complex crawl space houses, and more houses need to be mitigated to provide a statistical test of the subplastic suction technique.

Introduction

Radon, a product of uranium decay, is a naturally occurring radioactive gas. Varying concentrations of radon gas can be found in the soil and in rock formations around the world. As long as the radon remains in the rocks and soil, it is not a serious environmental problem. However, because radon is a gas, it can move from where it is produced in rocks and soils into houses. This transport is powered by air pressure or concentration differentials. Radon traveling through cracks and fissures in rocks and soils or through permeable soils may be drawn into a house when low air pressure exists in the building. Low pressures are induced in houses by the stack effect, winds, and mechanical equipment. The identification of elevated radon concentrations inside houses is commonplace throughout the United States, Canada, and northern Europe.

Over the past three years, the U.S. Environmental Protection Agency (EPA) has developed and demonstrated radon reduction alternatives for houses. The focus of the early efforts by the EPA to reduce radon levels was on houses in Pennsylvania and New Jersey where radon levels were often above the level that the EPA uses to suggest that the homeowner take immediate action to reduce radon concentrations ("A Citizen's Guide to Radon" 1986). The majority of the very elevated radon measurements have been made in houses with basements. Basements provide more avenues of radon entry than other housing substructures because radon can enter through openings in basement

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walls as well as floors that are often "unfinished." The EPA's first two radon reduction reports (Radon Reduction Tech. for Detached Houses 1986, 1988) focused primarily on alternatives for solving the radon problem in basement houses. Although basements may have the greatest potential for radon entry, other housing substructures also present unique radon problems. Nationwide, approximately 50% of the single-family detached houses have basements. Another 35% are of strictly slab-on-grade construction, and 15% have crawl spaces. All of these housing types have been observed to have potential radon problems given sufficient radon in the soil, soil permeability, and access through the building shell.

Crawl space houses have been the last major housing substructure to be evaluated by the EPA for potential radon mitigation. Generally, crawl space houses are throught to be the least likely substructures to present a radon hazard. In fact, one of the alternatives for radon control being evaluated for new construction in Sweden is the conversion of typical basement and slab-on-grade construction practices to crawl space construction (Ericson and Schmied 1986).

One of the first indications that crawl spaces may present a radon problem was a radon survey conducted in Dayton, Ohio (*The Radon Sampling Project Final Report* 1986). The survey included information relating housing substructures to measured radon concentrations. The results showed that crawl space houses in Dayton were a significant share of the elevated radon houses. Additionally, one of the ten demonstration houses in Clinton, New Jersey, combined slab-on-grade and crawl space. Radon measurements in the room immediately above the crawl space of this house were generally higher than those measured above the slab.

Because crawl space houses are common throughout the middle south and portions of the midwest, an evaluation of radon mitigation alternatives for crawl space houses was planned by the EPA. One of the metropolitan areas where radon had been identified as a problem and where crawl space houscs were common is Nashville, Tenn. With the cooperation of the Tennessee Department of Health and Environment, in the summer of 1987, the EPA began a three-phase radon demonstration project in Nashville, with major emphasis on the development and demonstration of radon mitigation options for crawl space houses. Energy Systems, Inc., of Cookeville, Tenn., was employed to complete Phase 1, including the assessment of radon entry mechanisms in five houses and the installation of one radon reduction system. At Phase 2, Southern Research Institute, Birmingham, Ala., with the assistance of Camroden Associates, Rome, N.Y., was employed to design, install, and evaluate a variety of radon mitigation systems in 15 houses including nine with crawl spaces. Following their effort, additional crawl space houses will be mitigated (Phase 3) using the most successful radon mitigation options observed during Phases 1 and 2. Phase 3 will be completed primarily by local building contractors with minimal supervision by Southern Research.

This paper enumerates some of the options being evaluated for crawl space houses with an elevated radon problem and shows how one of these options has been effectively employed. To adequately set the stage for presenting this information, mechanisms for radon entry into crawl spaces must first be explored.

Characteristics of Crawl Spaces

Crawl spaces are typically enclosed by the living area floor, the foundation walls, and exposed earth. Most crawl spaces are 2–4 ft (0.6–1.2 m) high from the earth to the floor framing. Supply plumbing, drain/waste/vent systems, and wiring are located in the crawl space and result in many penetrations into the living area above; furthermore, ducted air distribution systems are often located in crawl spaces. This ductwork is seldom airtight. Return ducts operate at negative pressures of 0.2–0.6 in (0.5–1.5 cm) H_2O, with duct leakage of 150 cfm (255 m^3/h) being common. The duct system is operated more than 3,000 h per year, and, when not in operation, both supply and return ductwork remain at a negative pressure relative to the crawl space.

Ventilation rates of crawl spaces vary. Foundation vents of less than 100 sq in. (645 cm^2) net flow area are usually installed during construction. A typical 1,500-sq ft (139-m^2) crawl space will have six vents or less. Often, at least one side will have no vents because of high exterior grade levels. In the winter, common practice is to close all vents to reduce energy loss and prevent water line freeze-up. Under closed conditions, crawl spaces then become effective soil gas accumulators. Ductwork, plumbing, drain/waste/vent systems, and wiring all give potential radon entry points into the living area.

The amount of leakage through the floor between the crawl space and the first floor varies considerably from house to house based on house design and construction practices. To quantify this amount of leakage, the effective leakage area (ELA) must be determined. The ELA at a reference pressure (usually 4 Pa) can be determined using a fan door and Eqs. 1 and 2:

$$L = \left(\frac{\rho}{2}\right)^{1/2} K(dPr)^{n-1/2} \quad (1)$$

$$Q = K(dP)^n \quad (2)$$

Taking the logarithm of both sides of Eq. 2 converts it to a linear equation with slope n. The line of best fit can be found through a set of fan door measurements of airflow and pressure difference, allowing for the calculation of K and n (Nitsche et al. 1985).

Procedures

To characterize the leakage in crawl space houses, a series of fan door measurements were made on nine crawl space houses in Nashville, Tenn. Fan depressurization tests were performed on the houses and on the crawl spaces and houses simultaneously so that the pressure differential between the house air and crawl space air was zero. Two fan doors were required to accomplish the simultaneous measurements. By using this approach the leakage area of the floor between the house and crawl space could be determined by subtracting the leakage area of the house–crawl space combined test from the leakage area of the house only. The results are presented in Table 1. The houses themselves are typical in leakage area, averaging 165 sq in. (0.1 m^2) and ranging from 54 to 295 sq in. (0.03 to 0.18 m^2). Subtracting the house leakage area less floor from the house-only leakage area gave an av-

TABLE 1. Leakage Areas of Nine Crawl Space Houses

House number (1)	House ELA (sq in.) (2)	House less floor ELA (sq in.) (3)	Floor ELA (sq in.) (4)	Crawl volume (cu ft) (5)	House volume (cu ft) (6)
DWO3	132	96	36	3,000	8,800
DW27	197	119	78	8,000	16,000
DW29	236	174	62	4,400	15,576
DW31	54	23	31	1,875	9,600
DW60	295	207	88	3,600	9,600
DW66	179	54	125	5,000	14,400
DW82	144	134	10	4,550	12,200
DW84	155	120	35	5,200	16,800
DW90	96	70	26	2,700	10,752
Average	165.3	110.8	55.6	5,258.3	12,636

Note: m^2 = sq in. × 6.45×10^{-4} and m^3 = cu ft × 2.83×10^{-2}.

erage connecting floor leakage area (column 4) of 55 sq in. (0.03 m^2) with a range of from 10 to 125 sq in. (0.006 to 0.08 m^2). The average of 55 is a fairly large hole compared to the average of total leakage area for the houses of 165 sq in. (0.1 m^2). It is clear from these measurements that there are large enough leakage areas in these floors for crawl space air to enter the living space.

An interesting note from these measurements is that houses with air ducts in the crawl spaces have an average of 75 sq in. (0.046 m^2) leakage area through the floor [ranging from 35 to 125 sq in. (0.021 to 0.076 m^2)] and the houses with no ducts in the crawl spaces had a much lower average leakage area of 38 sq in. (0.023 m^2) [ranging from 10 to 88 sq in. (0.006 to 0.054 m^2)]. Although these data are not conclusive evidence that the ductwork presents air routes from the crawl space air to the house air, a stronger case is made when this information is coupled with the observation that smoke sticks showed airflow from the crawl space into the ductwork when the air circulation blower was on.

Radon Reduction Schemes for Crawl Space Houses

A variety of alternative methods have been suggested for reducing the radon level in crawl space houses. The most obvious method and the one offered by the EPA ("Radon Reduction in New Construction" 1987) is by increasing ventilation by increasing the number and/or size of the vents in the crawl space. The Florida Housing Code ("Radiation Standards" 1988) requires a minimum vent area of at least 1 sq ft (0.093 m^2) of opening for each 150 sq ft (13.9 m^2) of floor area for wooden flooring, or at least 1.5 sq ft (0.14 m^2) of opening for each 15 ft (4.57 m) of linear perimeter wall for nonwooden flooring. Additionally, openings are to be placed so that there is one within 3 ft (0.9 m) of the end of each applicable side of the perimeter. Although the use of more or larger openings may be acceptable during warm seasons or where crawl spaces are not subjected to subfreezing temperatures, this approach requires substantial insulation of water pipes and subflooring if the vents are left open during the winter.

Another approach is the depressurization of the crawl space. This requires sealing of all detectable air leaks from the crawl space air to the upstairs part of the house. Additionally, all of the vents and other openings in the crawl space are sealed to outside air, and a fan is installed that draws air from the crawl space and blows it to the outside air. This technique will result in higher radon levels in the crawl space but should also reverse the flow of air from the crawl space into the house. If the fan is reversed, the crawl space would become pressurized, which would reverse the flow of radon gas into the crawl space from the soil and result in significantly reduced radon levels in the crawl space. Pressurization is not recommended, however, because of potential moisture problems resulting from exposure of wood subflooring to large quantities of moist outside air and the potential of blowing other crawl space contaminants (e.g., pesticides and asbestos) into the living space.

One of the most promising radon mitigation approaches for crawl space houses and the first to be evaluated is soil depressurization under polyethylene. This technique is similar to the most successful basement mitigation technique "subslab suction." Polyethylene sheeting is used to simulate the slab. The thickness of the polyethylene is not important in preventing radon entry but may be important for durability if the crawl space is used for storage or is likely to be entered regularly. Typically, long rolls of polyethylene are run lengthwise between the pillars, and shorter pieces are placed between the pillars, with the object being to cover as much of the exposed earth as possible. The polyethylene may or may not be sealed to the walls or at the edges, but seams should be overlapped by at least 1 ft (0.3 m). For stability, at least the edges of the polyethylene at the end of the crawl space where the door is located should be sealed. A butyl rubber caulk can be used as a sealant between the polyethylene and the concrete and treated 1 × 2 in. (2.54 × 5.08 cm) boards and masonry fasteners used to clamp the edges of the polyethylene to the concrete. This mitigation approach has the advantages of: (1) Eliminating the need to seal multiple radon entry points from the crawl space to the living area; (2) conserving energy by not ventilating the entire crawl space area; and (3) reducing the volume from which the radon must be removed.

A single suction point using 4-in. (20.2-cm) PVC pipe and a blower should be installed in the center of the crawl space to remove soil gas from under the polyethylene and vent it to the outside. A speed control should be added to the fan to permit fine tuning of the system. A pressure gauge is also necessary to allow the homeowner the option of checking periodically to see if the system is working properly. Alternatively, a low pressure switch can be installed to operate a light or a bell, if the pressure drops too low.

A variation on this technique is being tried on at least one house in Nashville, Tenn. Instead of placing polyethylene on the soil, four 24-in. (0.61-m-) diameter by 18-in. (0.46-m) deep suction pits have been dug in the center of each quadrant of the crawl space floor. The holes are covered with four aluminum sheets with holes for 4-in. (10.2-cm) PVC pipes. The pipes are connected to a single centrifugal fan that is exhausted to outside air. Plans are to test this system pulling suction on first two and then all four suction pits. If this technique works, it will eliminate the potential durability problems inherent with polyethylene sheeting which may be a significant problem in often used crawl spaces.

Measurements

Radon grab sampling (GR) and continuous monitoring (CR) measurements were made with a Pylon AB-5 system using four Lucas scintillation cells, a 17.4-cu in. (285-cm^3) flow-through cell, and a 9.9-cu. in. (163-cm^3) flow-through cell used for CR and GR sampling, and two 9.8-cu in. (161-cm^3) cells used only for GR sampling. EPA protocol was followed in the normal GR and CR measurements (Ronca-Battista 1986). The CR data presented in this paper consist of radon levels averaged over 1-hr intervals. The 1-hr intervals were then averaged to give long-term average radon levels. Because of uncertainties in the measurements at low levels, values less than 1.0 pCi/L were considered to be 1.0 in the averaging. Energy Systems, Inc., Cookville, Tennessee, passed the EPA proficiency test in both of these categories. The "walk in" test visit to the Montgomery, Alabama, radon facility also provided an opportunity to fine tune the calibration of the Pylon and scintillation cells.

A radon "short count" technique was used in the living area of the house to examine the radon distribution at a given time and to locate or confirm radon entry points. It was also used in analyzing gas samples taken from under the plastic ground cover. In short count grab sampling, the counting time was the first 15 min after sampling. Counts per minute (corrected for background) were converted to picocuries per liter using a calibration curve. In the presence of thoron, samples were allowed to stand in the scintillation cells for 5 min to allow for thoron decay before counting for radon. When a series of short count measurements were made, it was necessary to correct for disequilibrium in the scintillation cell. The correction was used unless extremes in radon levels from location to location were encountered. Then, it was necessary to change cells.

Soil gas accumulators constructed of capped 4- or 6-in. (10.2- or 15.3-cm) PVC piping with sheet metal skirts were used to test the soils prior to mitigation. The sheet metal skirts were embedded 1–2 in. (2.54–5.08 cm) in the soil, and the accumulator was allowed to stand with access fittings capped for at least 48 h prior to sampling. Grab radon analysis was performed on the soil gas collected from the accumulators.

Activated carbon packets and canisters were used to supplement the Pylon measurements. Test packets obtained from, and analyzed by, Air Chek, Inc., Arden, North Carolina, were employed to test the living area during continuous 48-hr monitoring in the crawl space. Where longer tests were anticipated, activated carbon canisters (supplied and analyzed by Advanced Materials Enterprises, Brentwood, Tennessee) were used. Both suppliers passed the fourth round of the EPA Proficiency Test.

Pressure measurements were made with a Dwyer incline monometer having a scale range of −0.10 to 1.0 in. (−0.254 to 2.54 cm) of water. Resolution of this instrument was 0.01 in. (0.0254 cm) of water.

Subplastic suction exhaust rates were measured by determining the time required to fill a container of known volume. The container was fabricated from a 0.079-in. (2-mm) thick aluminum-coated polyester film attached to a rigid 24-in. (0.61-m) square top. A strip of foam gasketing around the bottom of the base ensured a low leakage seal to an enclosure surrounding the suction system discharge. The inflated volume of the bag was 19.6 cu ft (0.56 m^3). The technique, evaluated at the Mechanical Engineering Department at Tennessee Technological University, Cookeville, Tennessee, using a laminar flowmeter as a standard, was found to be accurate to within ±5%.

Premitigation Testing

The residence which was selected for a detailed mitigation study was relatively free of complicating factors. The house is located in Hermitage, Tennessee, and is an 1,100-sq ft (102.2-m^2) ranch style house built in 1962. It is a brick structure with a hollow core block foundation. The height of the foundation wall varies from 24 to 40 in. (0.61 to 1.02 m). The house is heated by a radiant heat system in the ceiling and cooled by a window air conditioner (no ductwork). Foundation vent cover plates and a tight-fitting access door allow good sealing of the crawl space area. Major radon entry points into the living area from the crawl space are limited to plumbing penetrations, including a 6 × 10-in. (15.2 × 25.4-cm) hole under the bathroom tub and electrical penetrations. A diagram of the crawl space is shown in Fig. 1.

Bare soil was exposed in the crawl space (no moisture barrier). It is A and B horizon Maury loam, a phosphatic, clayey-silty soil derived from the Middle Ordovician Bigby-Cannon formation. Desiccation cracks up to 1/4 in. (0.64 cm) wide are present in parts of the crawl space.

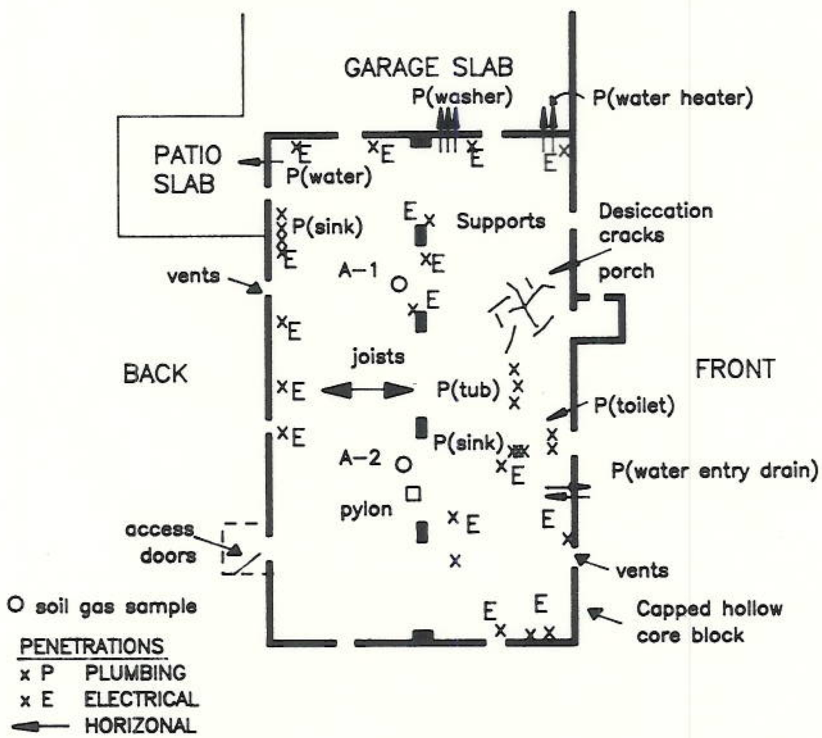

FIG. 1. Diagram of a Crawl Space

This house was originally tested as part of the joint EPA/Tennessee radon survey. A screening test in the den showed 23.7 pCi/L in February, 1986. Crawl space vents had been closed, which is the typical winter position. Premitigation measurements were made in early August, 1987. The crawl space vents had been opened for the summer but were closed 24 h prior to testing. The testing consisted of a 63-h continuous monitor (CR) run in the crawl space and simultaneous charcoal tests in the living area. Two soil accumulators were left in the crawl space during the CR test and sampled at the end of the run. A soil gas sample was collected from a desiccation crack by placing a 3-ft square piece of plastic over the crack and sampling through a hole in the plastic. Finally, six short count grab samples were collected in the living area at the end of the CR test.

The CR test showed an average radon level of 25.3 pCi/L in the crawl space, with a low of 18.1 pCi/L and a high of 33.7 pCi/L (Fig. 2). The Pylon intake was 1 ft above the crawl space floor. The soil samples showed 130.5 and 143.2 pCi/L. The sample from the desiccation crack showed 42.2 pCi/L. Short count grab samples and activated carbon tests of the living area showed 3.0 pCi/L or less. A slightly higher value was found in the bathroom linen closet (3.3 pCi/L) and extracted from an electrical outlet in a closed-off bedroom (4.3 pCi/L).

Radon Mitigation

In the test house, the crawl space floor [930 sq ft (86.4 m^2)] was covered with 0.158-in. (4-mm) polyethylene plastic and tightly sealed where sheets overlapped and around support pillars. Overlapping sheets of plastic were sealed by placing a strip of double-faced carpet tape on the first (bottom) sheet, then folding under the second (top) sheet to give an edge that just covered the tape. The plastic was pressed together, and then a 2-in. (5.08-cm) strip of transparent box sealing tape was used to cover the edge of the seam.

Plastic was sealed around posts by a sheet metal apron of 3 × 3-in. (7.62 × 7.62-cm) metal angles tabbed to fit around the posts. Silicone caulk and polyurethene foam were used to seal the apron to the post. The plastic film was cut to fit around the posts and then sealed to the horizontal part of the apron with double-sided tape covered by box sealing tape.

The outer edge of the plastic was "sealed" to the soil with a continuous length of water-filled plastic tubing 0.39 in. (1.0 cm) thick and 2.54 in. (6.45 cm) in diameter [4-in. (10.2-cm) wide "flat tubing"]. PVC end caps [2 in. (5.08 cm)] were uscd to plug the tubing. The tubing was sealed to the end caps with band clamps and a protective strip of rubber. One end cap was fitted with a 3/4-in. (1.9-cm) boiler drain valve to facilitate attachment of a garden hose used for filling. Where possible, a shallow trench 2–3 in. (5.08–7.62 cm) deep was dug along the base of the foundation wall to keep the tubing in place as close to the wall as possible.

Later in the study, 0.158-in. (4-mm) polyethylene plastic was used to cover the foundation walls, from the sill plate to the floor. The plastic was sealed to the sill by running duct tape along the sill, pressing the bottom half of the tape to the wood, and then folding the top half down and under to form a tube of tape. The top edge of the plastic was folded over and pressed on the duct tape tube and then stapled through the tube to the sill. The bottom

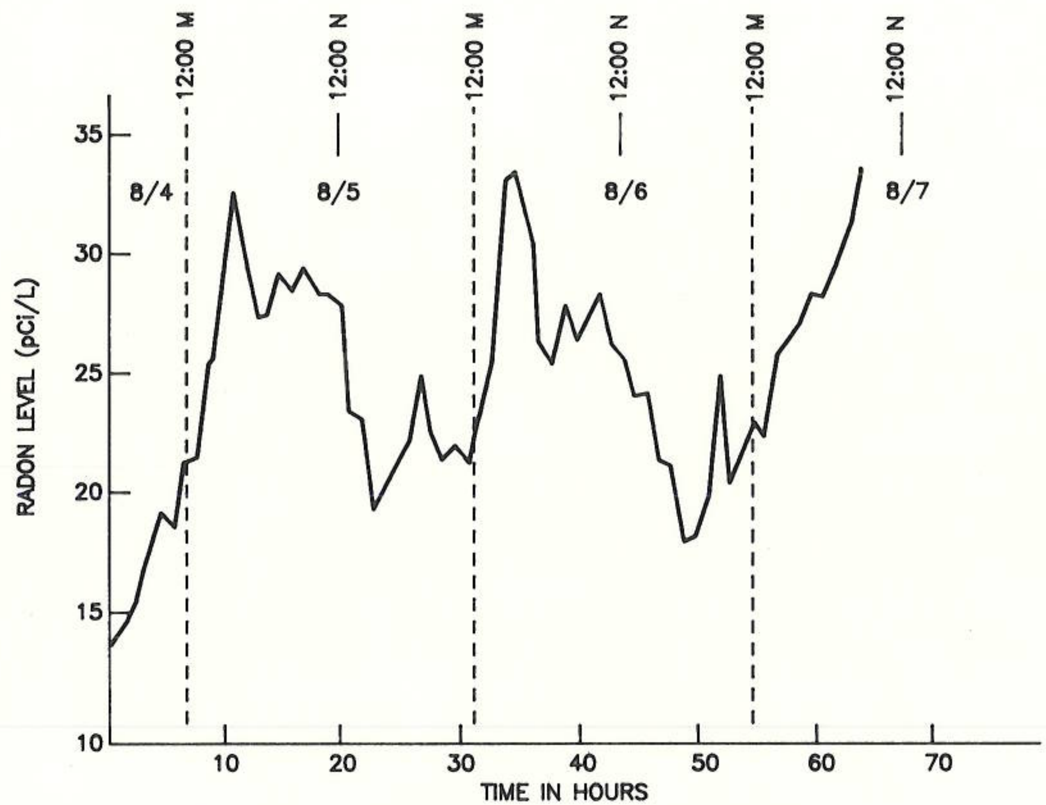

FIG. 2. Premitigation Radon Levels, Crawl Space

of the plastic film was taped to the plastic ground cover with box sealing tape.

The transition from the plastic film covering the ground to the mitigation exhaust system was 6-in. (15.24-cm) cone flashing. The corners of the flashing were bent down to form legs so that the vent opening was 2–3 in. (5.08–7.62 cm) off the floor. The plastic film was sealed to the flashing with double-sided tape and box sealing tape.

A 30-gauge, 6-in. (15.24-cm) round duct was run vertically from the cone flashing through a hall closet into the attic. About 2 ft (0.61 m) into the attic, the duct was routed horizontally for 5 ft (1.52 m), transitioned to a 4-ft (1.22-m) section of 6-in. (15.24-cm) flexible aluminum duct, then connected to the fan inlet. The fan, a Dayton #4C666, was vented vertically through the roof. All joints and seams in the duct system were carefully sealed with high quality duct tape.

Results

The mitigation system was evaluated by examining radon levels in the crawl space rather than in the house itself. Results of continuous monitoring measurements in the crawl space under varying test conditions are summarized in Table 2.

The first step in implementing the mitigation system was to completely cover the crawl space floor with polyethylene. The plastic film was left on the floor in an unsealed, unvented condition for four days, duplicating the plastic "moisture barriers" found in many crawl space homes. A grab sample collected under the plastic at the end of four days showed 1924 pCI/L of radon. This represents a large radon buildup when compared to the average premitigation soil gas level of 137 pCi/L. Unfortunately, the radon levels in the crawl space were not measured with the unvented ground cover in place.

Next, the plastic film was sealed over the crawl space floor and the sub-plastic suction system installed. When suction was applied to the system, radon levels in the crawl space (foundation vents closed) were reduced from

TABLE 2. Continuous Radon Monitoring Results for Residence Crawl Space (Aug. 4–Oct. 5, 1987)

Tests (1)	Plastic on floor (2)	Plastic on walls (3)	Wall vents (4)	Exhaust fan (5)	Test duration (h) (6)	RADON LEVEL (pCi/L) High (7)	Low (8)	Average (9)	Percent reduction (10)
1	No	No	Closed	None	63	33.7	18.1	25.3	—
2	Yes	No	Open	On	40	2.9	<1	1.5	94.1
3	Yes	No	Closed	On	87	4.7	<1	2.2	91.3
4	Yes	No	Closed	Off	68	8.9	1.4	3.5	86.2
5	Yes	Yes	Closed	Off	73	9.8	<1	5.0	80.2
6	Yes	Yes	Closed	On	92	3.9	<1	1.6	93.7
7	Yes	Yes	Open	On	94	2.1	<1	1.1	95.7
8[a]	—	—	—	—	70	6.3	1.4	2.7	89.3

[a]Same as number 6 with house depressurization. [Static pressure difference between living area and crawl space of 0.07 in. of water (17.5 Pa).]

the premitigation average of 25.3 pCi/L to an average of 2.2 pCi/L (Fig. 3). With the foundation vents open, the radon level was lowered further, averaging 1.5 pCI/L.

The exhaust rate and static pressures in the vent system and below the plastic film were measured after 72 h of continuous fan operation. The exhaust rate, measured on the roof with an air bag, was 36.3 cfm (61.7 m^3/hr), well below the maximum capacity of the fan. The static pressure in the exhaust vent, measured in the attic at the fan inlet, was 0.96 in. (2.34 cm) of water. Pressure in the vent 2 ft (0.61 m) above the crawl space floor had dropped to 0.92 in. (2.34 cm) of water and held at 0.92 in. (2.34 cm) of water in the gap just below the suction vent. Static pressures under the plastic film showed a sharp drop from the vent, declining to less than 0.01 in. (0.254 mm) of water at distances of 8–10 ft (2.44–3.05 m) from the vent. A subplastic pressure diagram is shown in Fig. 4.

Radon under the plastic film was sampled after the suction fan had been operating for six days. This sampling showed that the radon levels had been reduced from 1924 pCi/L to an average of 24 pCi/L.

Following the tests with the suction system in operation, the fan was shut off and radon levels in the crawl space and below the plastic film were remeasured (passive ventilation conditions). The CR test in the crawl space was interrupted by an instrument malfunction, but the radon levels over a total monitoring time of 68 h with the foundation vents closed were an average of 3.5 pCi/L, or about 86% of the premitigation level. Radon levels measured under the plastic ten days after the fan had been shut off showed a surprisingly small buildup, increasing to an average of 96 pCi/L. Both radon levels were slightly lower near the exhaust vent and showed a sharp drop near the perimeter of the ground cover.

Small amounts of radon persisted in the crawl space following the mitigation. Diurnal highs reached about 4 pCi/L with the subplastic suction in operation and climbed to about 8 pCi/L with the system in a passive mode. In an attempt to locate the source of these daily buildups, the foundation walls were tested for radon. Holes were drilled into the voids in the hollow core block and samples extracted with the Pylon AB-5, which were then analyzed for radon. Samples collected from the back wall and along the garage side showed 19.3 and 22.9 pCi/L of radon. Samples collected along the front wall showed lower radon levels, between 2.3 and 4.8 pCi/L.

In order to block any possible radon influx into the crawl space through the foundation walls, the walls were covered with 0.158-in. (4-mm) polyethylene sealed to the sill plate and plastic ground cover. Crawl space measurements were repeated with the wall covering in place. Under passive ventilation conditions, the radon level increased from the previous 3.5 pCi/L to 5.0 pCi/L with the foundation wall covering in place. With the subplastic suction in operation, however, average levels were lowered from 2.2 to 1.6 pCi/L.

One test was conducted with the plastic covering on the foundation walls and the foundation vents open. The ground cover had been partly pulled from under the water-filled perimeter tubing to allow communication between the outside air and the gap below the plastic ground cover. Subplastic suction applied to the system under these conditions resulted in the lowest crawl space radon levels of all of the tests, an average of 1.1 pCi/L.

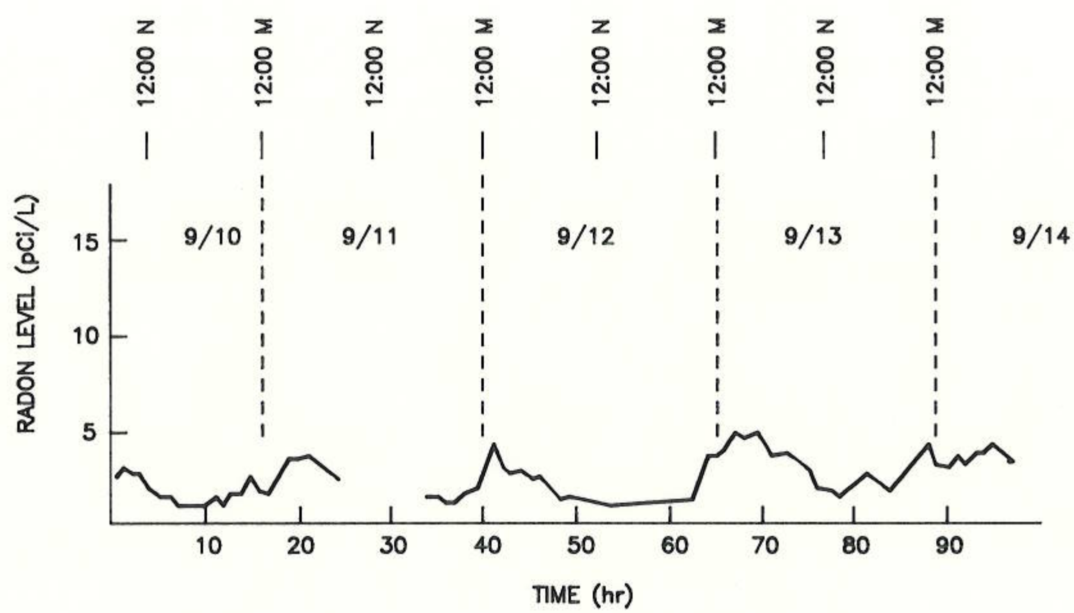

FIG. 3. **Radon Levels, Crawl Space, Subplastic Suction, Foundation Vents Closed**

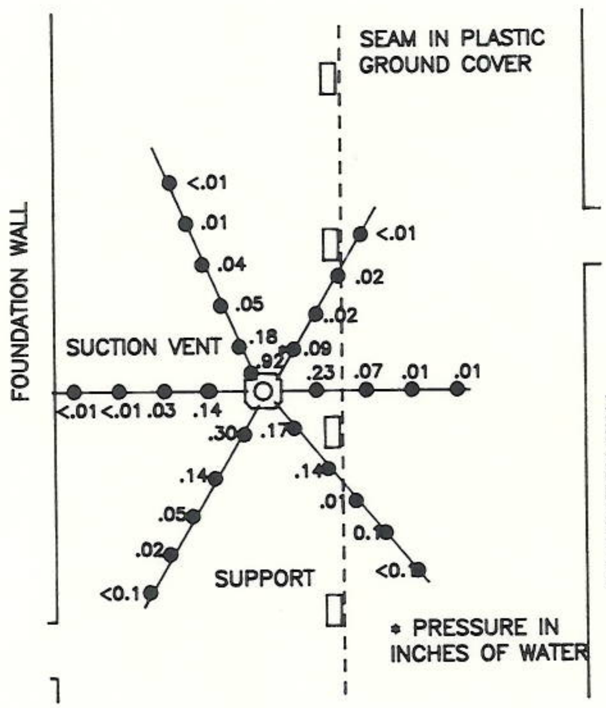

FIG. 4. Subplastic Depressurization, Crawl Space

Finally, in an attempt to simulate winter conditions, the house was depressurized using an exhaust fan system mounted in a front bedroom window. The system, capable of moving nearly 850 cfm (1,444 m^3/hr) at 0.1 in. (0.254 cm) of water external static pressure, produced a pressure difference between the living area and crawl space of 0.07 in. (0.178 cm) of water. During this test, randon levels in the crawl space ranged from a high of 7.3 to a low of 1.4 pCi/L and averaged 2.7 pCi/L. Highs did not follow the normal diurnal pattern seen in other tests.

Activated carbon tests in the living area conducted in conjunction with the crawl space CR tests all showed less than 2.0 pCi/L with the mitigation system in operation, even during the house depressurization test.

INTERPRETATION

The most serious problem with the mitigation system was the puncture and tear resistance of the plastic ground cover. Small pinhole punctures and tears were repaired when observed, but almost certainly other holes went unnoticed.

The continuous length of water-filled tubing around the perimeter of the crawl space was a very rapid and efficient method of weighing down the edge of the plastic film; however, due to irregularities in the crawl space floor, the seal was not airtight. Also, a few small, but troublesome, leaks developed along creases in the tubing when it was filled with water.

The foundation wall covering had the advantage of acting as a thermal barrier which cut energy loss from the crawl space and allowed outside air to move under the plastic ground cover, increasing the effectiveness of the subplastic ventilation. Unfortunately, with the vents open, the foundation wall plastic billowed in the wind; however, the effectiveness of the system was not impaired. Prolonged wind exposure through the vents could certainly damage the system.

The exhaust fan flow rate of less than 40 cfm (68 m^3/hr) produced a negative pressure of 0.92 in. (2.34 cm) of water at the subplastic suction point and resulted in a radon reduction of more than 90%.

The materials cost was $275, with most material readily available. Installation by two experienced workers should take less than two days. Laying and sealing of the plastic barrier requires care, but not a great deal of skill. However, running an exhaust system with a fan from the crawl space to the roof may tax the ability of most homeowners. An exhaust system would be easier to install through a foundation vent but could produce locally elevated radon levels unless exhausted above the eaves. Some homeowners may consider an outside vent system an unsightly addition to their houses.

The subplastic suction mitigation system effectively reduced radon levels in the crawl space. In five separate tests, levels were lowered from a premitigation average of 25.3–2.7 pCi/L or less. It is assumed that the radon reduction in the crawl space correlates with reductions in the living area of the house, but this could not be confirmed because radon did not enter the house during the summer testing period.

The test results, summarized in Table 2, show that the greatest reductions were obtained with the foundation vents open. Natural ventilation of the crawl space through open vents helps prevent radon buildup and may be an adequate mitigation technique during the summer. However, in the winter, foundation vents are typically closed to reduced energy loss and to prevent water lines from freezing. In fact, from an energy conservation point of view, the foundation vents should be closed during the summer cooling season as well.

It is apparent that an energy efficient mitigation system must function effectively with the foundation vents closed. Tests conducted with the vents closed showed reductions of 91% and 94%, with average radon levels well below 4.0 pCi/L, the EPA recommended action level. These results suggest the possibility of designing an effective radon mitigation system that would conserve energy and could even reduce energy use.

All tests at this house were conducted in the summer, a period of typically low indoor radon levels. The depressurization, or winter simulation, test was, therefore, critical to the evaluation of the system. A pressure drop from the living area to the crawl space of 0.07 in. of water (17.5 Pa) probably exceeds the natural cold weather depressurization generated in the house and represents a good test of the system. Under these conditions, radon was reduced from the premitigation level by 89%, to an average of 2.7 pCi/L. This indicates that the mitigation system will maintain low radon levels during the winter, but long-term alpha track tests will be conducted as confirmation.

Tests conducted with the mitigation system in a passive mode (suction fan off) showed a surprising reduction in the crawl space radon levels. Reductions of 80.2% and 86.2% were observed with no suction applied to the system. This strongly suggests the possibility of designing an effective, passive mitigation technique that would be energy efficient and possibly maintenance free.

Results of the CR tests with the foundation walls sealed are not definitive. In the passive mode, crawl space levels were slightly higher after the walls were sealed. This suggests little radon influx through the walls. With the subplastic suction in operation, however; radon levels were lower with the walls sealed. This reduction could reflect an influx of outside air through the foundation walls. With the sealed plastic in place, this air would tend to move under the plastic ground cover and dilute the radon-bearing soil gas.

Radon levels in the crawl space showed regular diurnal variation with highs early in the morning and lows late in the afternoon. The diurnal fluctuations were more pronounced with the mitigation system in a passive ventilation mode. The amplitude of the variations ranged from about 2 to 10.

Radon levels in the hollow core block foundation walls were highest adjacent to the garage slab and near the back-patio slab. This implies a radon buildup under the slabs and movement of some radon into the foundation walls. Samples collected along the front wall and the side wall opposite the garage showed lower radon levels. The fairly low radon levels in the interior walls suggest natural ventilation of the block. The walls were tested prior to installation of the sealed plastic wall covering. Sealing of the walls could result in an increase in the radon contained within the walls.

The large buildup (1,924 pCi/L) under the unvented plastic ground cover suggests that the moisture barriers found in many crawl spaces could act as radon-rich reservoirs capable of contaminating a crawl space and house during periods of depressurization.

With the exhaust components of the mitigation system in place, radon levels below the plastic decreased by more than 95% under both passive conditions and with the suction fan operating.

Although the number of subplastic measurements is limited, the data allow some preliminary interpretations. First, there is significant radon reduction under passively vented plastic (fan off). Lower levels near the edge of the plastic suggest dilution by outside air. Lower levels near the vent suggest more rapid exhausting of the soil gas through the vent (less radon buildup).

Second, under active ventilation conditions (fan on) radon under the plastic is reduced even further. There is a pronounced increase in the radon levels near the vent. This correlates with the increase in depressurization as the vent is approached. The measurements suggest that outside air is drawn under the plastic, where it mixes with radon-bearing gas moving out of the soil. The radon levels are fairly uniform from the edge of the plastic to about 10 ft (3.05 m) from the vent. Near the vent, stronger depressurization draws more soil gas under the plastic, resulting in the higher radon levels.

Lowering of radon levels under the plastic ground cover appears to correlate with lowering levels in the crawl space. It follows that a detailed examination of the static pressure and dynamics of radon movement under a vented ground cover could result in improvements in mitigation techniques.

Conclusions

In a crawl space house, a subplastic suction radon mitigation technique has been successfully demonstrated at moderate cost from readily available building materials. A combination of ventilation and depressurization under the plastic prevented radon buildup in both the crawl space and the house. The findings of this study need to be confirmed and supplemented with more measurements, preferably on larger and more complex crawl space houses, and more houses need to be mitigated to provide a statistical test of the subplastic suction technique.

Reduced radon levels in the crawl space under conditions of passive ventilation suggest the possibility of designing a passive mitigation system for crawl space houses. Such a system would have no energy impact, would be a low maintenance system, and probably would be a low cost system. The design and application of a passive mitigation system for crawl space houses is currently being funded by the EPA because of the projected potential of such a system.

Appendix I. References

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Appendix II. Notation

The following symbols are used in this paper:

dP = indoor-outdoor pressure difference [lb/sq ft (Pa)];
dPr = reference induced pressure difference [0.084 lb/sq ft (4 Pa)];
K = flow coefficient [cu ft/sec × lb^n ($m^3/s \times Pa^n$)];
L = ELA at 4 Pa [sq ft (m^2)];
n = flow exponent which has a range of $0.5 < n < 1.0$; and
Q = airflow [ft/sec (m/s)] = density of air [lb/sq ft (kg/m^2)).