1988-34

RADON MITIGATION TECHNIQUES IN CRAWL SPACE, BASEMENT, AND COMBINATION HOUSES IN NASHVILLE, TENNESSEE

by: Bobby E. Pyle
Ashley D. Williamson
Charles S. Fowler
Frank E. Belzer III
Southern Research Institute
Birmingham, Alabama 35255

Michael C. Osborne
AEERL, U. S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

Terry Brennan
Camroden Associates
Rome, New York 13440

ABSTRACT

In an EPA radon mitigation demonstration project, 14 houses in the Nashville, Tennessee area having indoor radon levels ranging from 5.6 to 47.6 pCi/L were mitigated using a variety of techniques. These techniques were designed to be the most cost-effective methods possible to implement and yet adequately reduce the radon levels to less than 4 pCi/L. For the crawl space houses, these techniques included: sealing the openings between the living areas and the crawl space and then passively venting the crawl space, depressurization of the crawl space, depressurization under polyethylene sheeting in the crawl space, and depressurization of the crawl space soil. In the basement and basement/ crawl space combination houses, the techniques used included: sub-slab pressurization and depressurization, block wall depressurization, and combinations of these techniques with some of those above for the exposed soil areas. Post-mitigation worst case radon levels in these houses generally ranged from less than 1 to about 5 pCi/L with one house near 15 pCi/L. These houses are currently being monitored with alpha-track detectors to assess their longterm exposure levels.

This paper has been reviewed in accordance with the United States Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

The State of Tennessee, in cooperation with the U. S. Environmental Protection Agency's (EPA's) State Radon Survey Program, conducted a survey to identify areas within the state having the potential for elevated radon levels in privately owned houses (1). Based on the results of that survey, it was estimated that 84.2% of the houses in the state have radon levels below 4 picocuries per liter (pCi/L), 14.5% have levels between 4 and 20 pCi/L, and 1.3% have levels equal to or greater than 20 pCi/L. The highest level detected in this survey was 99.9 pCi/L. From the geological character of the soils and rocks in the various parts of the state, four levels of risk for indoor radon were developed. The areas of highest risk form a bifurcated band through the central part of the state. This band includes the greater part of Davidson County which also happens to be one of the most populated counties in the state.

Tennessee, Alabama, Mississippi, and Kentucky represent an area in which there exist a large number of houses of a type for which there are very little data regarding the appropriate technique to use for radon mitigation. This construction type, the crawl space house, according to a survey by the National Association of Home Builders-National Research Center (NAHB-NRC) (2), represented from 16 to 32% of the housing starts over the period 1974 to 1983. This represents more than 100,000 houses built in this four state area during this 9-year period alone. Thus, the crawl space house represents a significant fraction of the existing houses in the Midsouth and perhaps in other regions of the United States. In general, crawl space houses can be defined as those in which a part or all of the living area of the house is built over an enclosed area containing exposed earth. Prior to the collection of recent radon data (3), crawl spaces were even considered to be a viable alternative for radon control in new construction (4). Thus, the houses in Davidson County, Tennessee, offered an ideal opportunity to expand the present data base of mitigation methods to include crawl space houses. Another type of house mitigated during this study was the basement house in which the basement was excavated from an existing crawl space. In many of these houses there remain areas of exposed soil in open communication with the basement. This type of construction is also typical of older existing houses in the Midsouth; hence, it offered yet another opportunity to test appropriate mitigation techniques.

The primary purpose of the work described in this paper was to develop cost-effective techniques for radon mitigation in houses in the Nashville metropolitan area (NMA) which would be applicable to similar construction designs in other parts of the country.

HOUSE SELECTION AND DIAGNOSTIC EVALUATION

The houses for this demonstration were selected from respondents to a media announcement for homeowners whose houses had previously been tested and found to contain elevated levels of radon (greater than 4 pCi/L). From approximately 100 respondents, 30 houses were selected for a more extensive house evaluation and possible participation in the mitigation demonstration.

These 30 houses in Davidson and Williamson Counties, which comprise the NMA, were screened between September 8 and 11, 1987, by a team of scientists from EPA, Tennessee Department of Health and Environment, Southern Research Institute and Camroden Associates, for possible inclusion in the first phase of the Middle Tennessee radon mitigation demonstration. As a result of these screening visits, 15 houses were selected for the mitigation demonstration program. Table 1 summarizes the selected houses.

An extensive diagnostic visit to each house was conducted between October 21 and 27, 1987. During this visit, each house was subjected to a series of diagnostic tests which included: (1) radon grab and sniffer measurements, both in the lower living areas and in the basement or crawl space, (2) communication tests using smoke and tracer gas to determine the leakage between house and crawl space, (3) infiltration tests using fan doors to quantitate the leakage areas in the house construction, (4) pressure differential measurements between house and crawl space and between the house or crawl space and outdoors, (5) a gamma ray survey of the house, crawl space, and the surrounding lot site, and (6) communication tests of the conditions under the basement slab.

Also during the visit, measurements and investigations were carried out in order to complete the development of house specific radon reduction plans. Tentative mitigation strategies had been previously identified, and additional tests and observations specific to each house mitigation method or combination were temporarily implemented during the diagnostic test week in October. These tests included: soil depressurization in pits excavated in the crawl space soil, sub-polyethylene depressurization using the existing plastic sheeting, and double blower door tests to determine the leakage area of both the house and the crawl space. Also, charcoal canisters (CCs) and alpha track detectors (ATDs) were placed in the crawl space or basement and on the first habitable level above to obtain a premitigation radon background. In each location, duplicate detectors were co-located in an effort to determine the variation that could be expected in these houses.

MITIGATION SYSTEMS

For each of the houses, a staged mitigation strategy was developed such that each phase of the work was as independent of the others as possible. The strategy was such that Stages: 1 be low-cost ($500 or less) and easily removed or turned off if possible; 2 have a high probability of success at moderate cost ($500 - $2000); and 3 be almost a guaranteed reduction method at higher cost ($2000 - $5000). It was anticipated that no more than 25% of the houses would require implementation of Stage 3. To obtain the maximum scientific benefit, Stage 2 would be installed and tested regardless of the results obtained with Stage 1.

The mitigation strategies for each house were developed using the information obtained during both the screening and diagnostic visits: type of house construction, condition of house flooring, existence of heating and air conditioning (HAC) ducting in the crawl space, extent and condition of existing polyethylene sheeting under the house, condition of crawl space soil, existence of a basement and condition of the slab, existence of any exposed soil areas in the basement, and extent to which air flow could be induced under the concrete slab (sub-slab communication). From these site conditions a matrix of mitigation strategies was developed that would evaluate, demonstrate, and allow comparisons of each technique to arrive at those methods that would be both successful and cost-effective for houses similar to those in Nashville. This matrix, shown in Table 2, incorporates at least a two-phase mitigation approach for each house in the study.

CRAWL SPACE HOUSES

The major radon entry points from the crawl space into the house proper are through the numerous electrical and plumbing penetrations in the house floor and via the return air ducting often located in the crawl space. As the pressure in the house decreases relative to the pressure in the crawl space, radon gas emanating from the exposed soil is rapidly drawn into the house. Operation of the HAC system can greatly enhance the normal stack effect produced by temperature differentials between house interior and ambient conditions. Thus, the radon levels can be as much as 2 or 3 times higher in the winter than in the summer.

Isolation of the Crawl Space from the House (ICS)

In this mitigation technique the intent is to seal all possible penetrations between the crawl space and the house in an effort to prevent the passage of radon up into the living areas. The houses selected for this mitigation technique were those with low to moderate leakage between the crawl space and house. Sealing was accomplished using expandable closed-cell foam sealant and one part urethane caulking. Joints in the return air ducts were inspected with a smoke stick while the HAC fan was running. Also, the common practice of constructing return air plenums using the floor joists and the sub-flooring was carefully inspected. This construction technique had multiple leakage points into the crawl space that were impossible to completely seal. No effort was made to seal the crawl space leaks to the outside of the house. Block vents were left to operate in the customary manner, open in the summer and closed in the winter.

Isolation and Passive Ventilation of the Crawl Space (IVCS)

In this modification of the above technique, the leakage points are sealed as before along with all but two or three of the block vents in the foundation wall. These were left open even in the winter in order to allow air to flow through the crawl space, diluting and removing the radon gas. Water and waste pipes near the open vents were wrapped with insulation to prevent freezing. This mitigation method could only be used on those houses with insulated floors and either with no HAC ducts in the crawl space or where the ducts were well insulated beforehand. Attempting to wrap existing ductwork was ruled out as both costly and difficult. For this technique to be effective, not only must the sealing be adequate, but also there must be ample air flow through the block vents. The air flow is greatly influenced by the lot topology and house orientation relative to prevailing winds.

Isolation and Active Depressurization of the Crawl Space (IDCS)

This is a variation on the above technique wherein a fan is placed in the crawl space to actively exhaust the air from underneath the house. The leaks into the living areas have to be sealed as tightly as possible to prevent loss of conditioned air, and hence, constituting an energy loss. Ideally, the block vents are sealed in an effort to produce a negative pressure in the crawl space. Practically, there is sufficient outside air in-leakage to cause the radon soil gas to be diluted in addition to being exhausted.

Isolation and Active Pressurization of the Crawl Space (IPCS)

In this mitigation strategy, the crawl space is isolated from the house and then outside air is actively inducted into the crawl space in order to suppress the radon flux from the soil. As the crawl space becomes pressurized, the excess air is ducted back outside and exhausted. Because of energy considerations, the excess air is exhausted through a heat exchanger to condition the incoming air. Both the inlet and the exhaust are located at roof level with the heat exchanger located in the connecting ductwork to the crawl space (Current Model 300, Current Indoor Air Systems, Inc., Boulder, Colorado).

Sub-Soil Depressurization in the Crawl Space (SSoD)

This mitigation design is novel in that the depressurization is created directly in the soil itself. Four pits approximately 46 cm (18 in.) deep and 61 cm (24 in.) in diameter were dug in the soil, one in each quadrant of the crawl space. Each pit was covered by a 92 cm (3 ft) square piece of treated plywood countersunk into the soil around the pit. The plywood was covered with soil, and a 10 cm (4 in.) PVC pipe was attached through the wood. The pits were connected to a single inline suction fan (Model K4XL, RB Kanalflakt, Inc., Sarasota, Florida) with the exhaust through a block vent in the foundation wall. No effort was made to seal the floor of the house since the radon gas would be removed before it escaped into the crawl space.

Sub-Polyethylene Sheeting Depressurization (SPD)

This mitigation technique is a variation of the successful sub-slab depressurization method used for slab-on or below-grade houses. Many of the nine houses had some existing polyethylene sheeting covering the dirt in the crawl space. This covering is a popular method used to control moisture in the living areas. The existing polyethylene sheeting was supplemented where necessary to completely cover the exposed dirt. This gastight barrier forms a small-volume plenum above the soil in which the radon gas collects. A fan was installed to pull the collected soil gas from under the sheeting and exhaust it outside the house. Initially, no attempts were made to seal the polyethylene to the foundation walls or to any support piers. The sheets were laid directly on the earth so as to produce laps of at least 31 cm (1 ft) at joints. In at least one location, drainage material (Enkadrain Type 9010, BASF Corp., Fibers Div., Enka, North Carolina) was placed under the sheeting to improve air flow. In general, this is not necessary unless the soil surface is excessively hard and smooth or the crawl space area is exceptionally large. When excessive air leaks prevented effective removal of the radon, the joints between sheets were sealed with a bead of caulking. Also, where the number of support piers was large or located close to the suction point, the plastic sheeting was sealed to the piers with caulking and wood strips. In some of the houses, the plastic sheeting was also sealed to the foundation walls to reduce air leaks.

BASEMENT OR COMBINATION HOUSES

In a simple basement slab-on-grade, or slab-below-grade house, the major entry points are through openings in and around the slab and/or through the hollow block walls of the structure. Successful mitigation can be achieved by either sealing these openings or actively diverting the radon gas to the outside of the house before it enters the living areas. For the houses of this study in which exposed areas of soil are located in the basement, additional entry routes for radon gas have to be taken into consideration in the mitigation process.

Sub-Slab Depressurization (SSD)

This method has a high probability of success in houses that exhibit good communication under the slab. Sub-slab communication in these houses was poor to nonexistent. Consequently, one aspect of this study was to determine if the technique could be optimized or improved by modification of the pit excavated under the slab. To this end, sub-slab depressurization--with a: wide 61 cm wide(w) x 20 cm deep(d)(24 x 8 in.)(SSD-W), narrow 7.6 cm (w) x 72 cm(d)(3 x 28 in.)(SSD-N), or progressive; zero, 25 cm(w) x 30 cm(d) (10 x 12 in.), 48 cm(w) x 41 cm(d)(19 x 16 in.), and 61 cm(w) x 46 cm(d)(24 x 18 in.)(SSD-P) pit size under the slab-- was carried out in several of the houses. Here, pressure fields were monitored with the suction fan tempoarily installed at the suction point to determine which sub-slab hole shape or size resulted in the best (measurable) pressure field extension under the slab. In some cases, a single suction point was sufficient, while in others, two suction points were installed.

Sub-Slab Plus Block Wall Depressurization (SSBWD)

In some of the houses, high radon levels were measured in the hollow block walls of either the foundation or non-support-bearing walls in the basement. These walls were in direct communication with the underlying soil, and thus required treatment by the mitigation system. This was accomplished using the same sub-slab suction point(s) and simply tying into the wall(s) with the piping.

Sub-Slab Plus Sub-Poly Depressurization (SSSPD)

For houses with exposed soil in the basement, the mitigation system incorporated techniques similar to those used in crawl spaces. The exposed soil areas were covered with poly sheeting and, if necessary, the air between plastic and soil was exhausted using the same suction fan used for the SSD system.

Pressurization of Basement (PB)

In this technique, the basement is pressurized by using a fan to inject outside air into the basement to raise the ambient pressure above the level of depressurization anticipated from the wind and/or stack effect and that produced by air moving equipment. The use of some form of heat exchanger was anticipated to reduce the energy penalty resulting from this technique.

Sub-Slab Pressurization (SSP)

This technique was easily accomplished with any of the SSD systems by simply reversing the fan flow direction.

HOUSE MITIGATION RESULTS

Six houses were mitigated in December 1987: DW 31, DW 43, DW 60, DW 66, DW 82, and DW 90. All of these are crawl space houses except DW 43 which is a basement converted from crawl space. The remaining houses were mitigated over the period January through April 1988. The only house not mitigated during this phase of the project was DW 58, which is scheduled for mitigation during the fall of 1988. Additional pre-mitigation, co-located, CC measurements of the radon levels in both the first habitable level and the basement or crawl space were carried out just prior to mitigation work on each of the houses. These measurements were carried out over either 48- or 72-hour periods between November 28, 1987, and April 11, 1988. These results are shown in Table 3.

The results of implementing the mitigation techniques described in Table 2 are summarized in Table 4 where the average pre- and post-mitigation CC measurements, along with the percentage reduction in radon levels, are tabulated. Notice that the final level of radon in a given house may be the result of one or more phases of mitigation carried out at that house.

In order to compare the amount of reduction achieved for each phase of the mitigation process in each of the houses, the results from continuous radon monitors (CRMs) were used (model AB-5 monitors equipped with model PRD-1 passive cells, Pylon Electronic Development Co., Ltd., Ontario, Canada). In general, a CRM was installed in the living area of the house at least 48 hours before installation of any mitigation devices. The CRM was then either left in operation through the installation or removed and returned after work was completed. The CRM was then allowed to run for at least 48 hours to obtain post-mitigation levels. If more than one phase of mitigation was carried out, the monitoring procedure was repeated. The results of these measurements for each mitigation technique are summarized in Tables 5 and 6, where the percent reduction in the radon levels following each mitigation phase are tabulated for crawl space and basement/combination houses, respectively.

CRAWL SPACE HOUSES

In some cases (ICS and IVCS), there were negative reductions (increases) in the radon levels. These are thought to be due to both the difficulty in sealing between the living areas and the crawl space and the variability in air flow through the crawl space. Sealing was especially difficult due to the numerous cracks and crevices in the sub-flooring. To completely seal the house from the crawl space would have required major structural changes to the house such as installing a continuous vapor barrier below the sub-floor or floor joists. Also, the amount of surface area available for ventilation using existing block vents was insufficient in view of the low prevailing winds. Thus, isolation alone or isolation and passive ventilation of the crawl space appears to be a questionable technique for radon mitigation.

While the technique of isolation and depressurization of the crawl space (IDCS) achieved a 90% reduction of the radon levels in the living space, it also doubled the radon levels in the crawl space (as seen in Table 4). Thus, this method would not be applicable to houses in which the crawl space is entered on a regular basis. Also, the sealing between house and crawl space must be sufficient to prevent drawing an excessive amount of conditioned air from the living areas. If there are HAC ducts in the crawl space, this method could lead to problems later if leaks develop in the return air ducts.

Isolation and pressurization of the crawl space (IPCS) has been initiated in one house (DW 60), but no data reflecting the effectiveness of this technique are available. This technique will be evaluated in the near future, and the results reported later.

The technique of depressurization under a polyethylene sheet covering the soil (SPD) has had the broadest application in this study. It appears to be the most general approach to mitigating crawl space houses. It has the advantage of being relatively inexpensive and can in most cases be done by skilled or semi-skilled labor. Measurable depressurization under the polyethylene sheeting was observed at distances from the suction point of up to 1.8 m (6 ft) in all cases and up to 3.7 m (12 ft) for some of the installations. Smoke movement under the polyethylene sheeting was observed at even greater distances. In some houses the plastic sheeting had to be sealed to the foundation walls (DW 27) and to some (DW 03, DW 29, DW 60) or all (DW 27) of the house support piers. This required additional efforts to ensure a good seal and mechanical attachment to the concrete blocks. In the Nashville area many houses have foundation walls made of cut stone. Attempts to attach the plastic sheets to such irregular surfaces have had very limited success.

Depressurization of the soil in the crawl space appears to be a rather simple technique. However, it has been tried in only two houses (DW 31 and DW 84), one of which (DW 31) had fairly loose soil compared to the other eight crawl space houses. In the second house (DW 84), the soil was more typical (hard-packed clay). Tests with smoke and with an electronic micromanometer showed air flow into and depressurization of the soil at distances up to 3.7 m (12 ft) from the suction point in both houses. However, the post-mitigation radon data for house DW 84 are of questionable quality. Reevaluation of this house is planned for the winter of 1988. A fair assessment of this technique should be obtained during the upcoming winter.

BASEMENT OR COMBINATION HOUSES

One- or two-point sub-slab depressurization systems (SSD) were installed in five basement or combination houses. Measurements of the pressure field extension under the slab showed the wide shallow pit to be more effective than the narrow deep pit. The surface area of soil exposed in the pit was found to be more important than the shape of the pit. The radon reductions achieved ranged from 28 to 98%, as shown in Table 6. The house with the greatest reduction (DW 41) had a single suction point installed near the edge of the slab under the front foyer. The slab had good communication which allowed the sub-slab area to be ventilated from a single point. Also, the area of exposed soil located under the front porch was small [< 8.4 m^2 (90 ft^2)] and was easily isolated from the living areas by construction of a treated plywood barrier wall with a sealed access door.

The lowest reduction for SSD was also achieved using a single suction point (DW 43). However, in this house the communication under the slab was poor so that an additional suction point was required. Also, this house had a cement-capped perimeter shelf around most of the basement. This shelf was constructed of coarse cinder blocks which allowed radon gas to enter the basement through their face openings. Incorporating block wall suction achieved a reduction in the range of 42 to 60%. Because of the high porosity of the blocks comprising the wall, acceptable reductions were not achieved until the wall was coated wtih a sealer (SurWall brand). The final reduction for this house was 92%.

For house DW 12, the exposed soil was contained behind a 46 cm (18 in.) thick cut stone wall. This area was covered with 0.46 mm (6 mil) polyethylene sheeting but no depressurization under the sheeting was implemented. Final reduction for this house was 92%

The exposed soil in house DW 14 was located behind a concrete block wall. This area was covered with 6 mil polyethylene sheeting sealed to the surrounding walls. Depressurization under the polyethylene was accomplished by breaking through the adjoining wall (and under the polyethylene) with the sub-slab system. The open block tops of the wall were filled with expanding closed-cell foam. This combination achieved a reduction of 85%. After the top of the wall was covered with a treated 5 x 30 cm (2 x 12 in.) board sealed to the top of the blocks with urethane sealant, a final reduction of 93% was achieved.

The remaining basement/combination house (DW 78) had a two-point sub-slab suction system installed and achieved a radon reduction of 78%. The area of exposed soil in th's house 56 m^2 (600 ft^2) was roughly twice the area of the slab 28 m^2 (300 ft^2) and consequently represented the major source for radon entry into the basement. After covering the soil with 6 mil polyethylene sealed to the slab perimeter wall and sealing the open block tops of that wall with expandable foam, the SSD system was extended into the wall and thus under the polyethylene covering the soil. The final reduction was 93% as measured in the basement wtih the CRM.

The only house in which the SSP technique was implemented was DW 41. Here the fan was initially installed to force outside air under the slab. The reduction achieved (70%) was surprising in view of the fact that a polystyrene foam beadboard at the edge of the slab allowed air from under the slab to easily enter the basement interior via the finished walls and baseboards. This entry was verified by use of a smoke bottle and was confirmed by the homeowner as an increase in humidity and odor in the basement. Concurrently, measurements of the levels of insecticide (aldrin) in two rooms of the basement were increased from pre-mitigation concentrations of 0.3 and 0.12 ug/m^3 to levels of 1.40 and 1.03 ug/m^3 with pressurization under the slab. Subsequent measurements in these two rooms after the system was run in the sub-slab depressurization mode for approximately 10 weeks showed the levels of aldrin (and dieldrin) to be less than 0.066 ug/m^3. Thus, while SSP can be effective in lowering the radon levels, it could also lead to other problems for the homeowner.

CONCLUSIONS

Several different techniques have been tested in crawl space and combination houses typical of the Southeast. It was difficult to prevent radon gas from entering the living areas with only passive measures. A more logical approach would be to use active devices to remove the radon before it can get into the house. Two such techniques (IDCS and SPD) have been successfully demonstrated, while a third method (SSoD) requires additional evaluation. In basement houses with exposed soil and poor sub-slab communication, the SSD technique has been shown to be effective if sufficient soil surface area is exposed under the suction point and the open soil areas in the basement are treated appropriately.

REFERENCES

1. "Summary Report of the Tennessee Radon Survey." Tennessee Department of Health and Environment, Division of Air Pollution Control, Nashville, Tennessee, August 1987.

2. "Single Family Detached Housing Construction Characteristics." National Association of Home Builders-National Research Center, report prepared for American ATCON, Inc., October 1985.

3. "The Radon Sampling Project Final Report." Regional Air Pollution Control Agency: Dayton, Ohio, December 1986, pp. 15-21.

4. Ericson, S. and H. Schmied. "Modified Design in New Construction Prevents Infiltration of Soil Gas Carrying Radon." Proceedings of the ACS Symposium on Radon and Its Decay Products: Occurrence, Properties, and Health Effects, April 1986, pp 5-6.

TABLE 1. HOUSES SELECTED FOR THE NASHVILLE RADON DEMONSTRATION

House ID No.	Area m^2	(ft^2)	Description
			Crawl Space Houses
DW 03	116	(1250)	No HAC ducts, good poly sheeting on soil (95%)
DW 27	181	(1950)	Walk-in with gas furnace and ducts, no poly cover
DW 29	205	(2200)	HAC ducts with large leaks, 70% covered with poly
DW 31	74	(800)	No HAC ducts, no poly, moderately loose soil
DW 60	91	(975)	No HAC ducts, 35% covered with poly
DW 66	140	(1500)	HAC ducts in crawl space, 50% covered with poor poly
DW 82	149	(1600)	No HAC ducts, no poly, with inaccessible areas
DW 84	140	(1500)	HAC ducts installed on soil, no poly
DW 90	102	(1100)	No HAC ducts, 90% covered with poly
			Basements Converted From Crawl Space
DW 43	65	(700)	Slab with cement capped shelf around perimeter
DW 58	93	(1000)	All exposed soil, small slab under furnace
DW 78	28	(300)	Slab with approximately 56 m^2 (600 ft^2) exposed soil
			Combination Basement/Crawl Space
DW 12	105	(1125)	Slab with cut stone walls, 19 m^2 (200 ft^2) exposed soil
DW 14	177	(1900)	Slab with block walls, 26 m^2 (280 ft^2) exposed soil
			Slab-Below-Grade
DW 41	140	(1500)	Finished basement with 56 m^2 (600 ft^2) slab-on-grade, some exposed soil

TABLE 2. MATRIX OF MITIGATION TECHNIQUES

Technique	House ID No. (grouped by substructure type)														
	DW 03	DW 27	DW 29	DW 31	DW 60	DW 66	DW 82	DW 84	DW 90	DW 43	DW 58	DW 78	DW 12	DW 14	DW 41
ICS			1			1									
IVCS	1	2			1		1		1						
IDCS		3		2			2								
IPCS					3#										
SSoD				1				1							
SPD	2	1	2		2	2		2	2						
SSD-W										2	1	2			2
SSD-N										1		1			
SSD-P													1	1	
SSBWD										3		3		2	
SSSPD												4		3	3
PB											2	5			
SSP													2		1

NOTES: # Installation added as an alternate technique

ICS = Isolate crawl
IVCS = Isolate-vent crawl
IDCS = Isolate-depress. crawl
IPCS = Isolate-press. crawl
SSoD = Sub-soil depress.
SPD = Sub-poly depress.
SSD-W = Sub-slab depress. wide pit
SSD-N = Sub-slab depress. narrow pit
SSD-P = Sub-slab depress. progressive pit
SSBWD = Sub-slab + block wall depress.
SSSPD = Sub-slab + sub-poly depress.
PB = Press. of basement
SSP = Sub-slab press.

TABLE 3. NASHVILLE PRE-MITIGATION DUPLICATE CHARCOAL RESULTS (pCi/L)
November 1987 to April 1988

House ID No.	Start Date	Stop Date	Crawl Space		Basement		1st Floor	
DW 03	4/8/88	4/11/88	21.6	22.1			7.0	7.1
DW 12	2/5/88	2/8/88			10.3	11.8	7.7	7.8
DW 14	2/8/88	2/10/88			89.9	86.7	47.1	48.1
DW 27	1/22/88	1/25/88	45.7	46.4			32.8	33.0
DW 29	2/19/88	2/22/88	27.1	27.2			15.9	16.2
DW 31	11/29/87	12/1/87	29.4	30.3			26.3	25.7
DW 41	1/22/88	1/25/88			19.2	19.3	13.3	13.4
DW 43	11/29/87	12/1/87			58.6	59.7	23.2	22.9
DW 58	3/29/88	3/31/88			56.2	57.3	20.4	27.4
DW 60	12/1/87	12/3/87	55.2	55.0			27.9	27.8
DW 66	12/1/87	12/3/87	26.1	25.9			12.3	11.9
DW 78	2/22/88	2/24/88			41.2	41.5	19.6	19.9
DW 82	11/29/87	12/1/87	29.5	30.0			14.7	15.1
DW 84	3/28/88	3/30/88	9.4	9.7			1.5	2.3*
DW 90	12/1/87	12/3/87	29.6	29.7			15.8	15.8

NOTES: * Levels in October 1987 were 5.6 pCi/L

TABLE 4. NASHVILLE RADON REDUCTION SUMMARY
(Based on Charcoal Canister Measurements in pCi/L)

House*	Crawl Space			Basement			1st Floor			
ID No.	Pre	Post	%Red.	Pre	Post	%Red.	Pre	Post	%Red.	Notes
DW 03	21.9						7.1	2.6	64	1,10
DW 27	46.1	9.2	80				32.9	5.3	84	2
DW 29	27.2	5.7	79				16.1	7.0	56	1
		2.8	90					3.0	82	3
DW 31	29.9	2.0	93				26.0	2.2	92	4
DW 60	55.1	23.3	58				27.9	15.2	45	1
DW 66	26.0	7.6	71				12.1	2.8	77	1
DW 82	29.8	61.7	-107				14.9	0.7	96	5
DW 84	9.6						1.9			4,11
DW 90	29.7	7.1	76				15.8	2.4	85	1
DW 43				59.2	4.8	92	23.1	1.4	94	6
DW 58				56.8			23.9			12
DW 78				41.4	2.8	93	19.8	1.5	92	6,13
DW 12				11.1	4.4	61	7.8	4.8	39	8
DW 14				88.3	11.3	87	47.6	3.8	92	9,14
					3.0	97				9,15
DW 41				19.3	1.4	93	13.4	1.0	93	7

*Grouped according to substructure

NOTES: (See Table 2 for mitigation codes)
Negative value indicates increased radon levels
1. ICS+SPD
2. Two point SPD
3. ICS+two point SPD
4. Four pit SSoD
5. IDCS
6. Two point SSBWD
7. SSD-W
8. Two point SSD-W
9. Two point SSBWD+SSSPD
10. No measurements in crawl space
11. No post-mitigation CC measurements
12. House not mitigated
13. No duplicate done upstairs
14. Basement readings on top of crawl space wall
15. Basement readings 1.2 m (4 ft) from floor 1.8 m (6 ft) from crawl space wall

TABLE 5. PERCENT RADON REDUCTION FOR EACH CRAWL SPACE MITIGATION SCHEME (Based on Continuous Monitor Data in Living Area)

Mitigation Technique	House ID No.								
	DW 03	DW 27	DW 29	DW 31	DW 60	DW 66	DW 82	DW 84	DW 90
Isolate Crawl Space (ICS)			3			-15			
Isolate Vent C/S (IVCS)	18				27		-60		75
Isolate Dep. C/S (IDCS)							90		
Isolate Pres. C/S (IPCS)									
Sub-poly Dep.-									
(SPD)1 Point*	69	60	64		77	72			92
(SPD)2 Points**		87	84						
Sub-soil Dep.-									
(SSoP)2 Pits#				61				58+	
(SSoP)4 Pits##				84				86++	

NOTES: Negative values indicate increased radon levels

* For one suction point

** For two suction points

\# For two suction pits

\## For four suction pits

\+ Worst case cond.

++ House open during part of test

TABLE 6. PERCENT RADON REDUCTION FOR EACH BASEMENT TYPE MITIGATION SCHEME (Based on Continuous Monitor Data in Basement)

Mitigation Technique	House ID No.					
	DW 43	DW 58+	DW 78	DW 12	DW 14	DW 41
Sub-slab press. (SSP)						70#
Sub-slab depress. (SSD)	28*		78	92	70	98*
SSD + block wall depress. (BWD)	42-60				85	
SSD + BWD + seal exposed soil			93		93**	
SSD + BWD + seal wall face	92					

NOTES: Unless specified otherwise, all SSD systems include two suction points

\+ Post-mitigation data not yet available

* Single sub-slab depressurization point

** Top of wall sealed

\# Single sub-slab pressurization point