United States
Environmental Protection
Agency

Air and Energy Engineering
Research Laboratory
Research Triangle Park NC 27711

Research and Development

EPA/600/S8-90/061 Jan. 1991

EPA

Project Summary

Radon Mitigation Studies: Nashville Demonstration

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In this EPA radon mitigation demonstration project, 14 houses in the Nashville, TN area with indoor radon levels of 5.6 - 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 <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, depressurizing the crawl space, depressurizing under polyethylene sheeting in the crawl space, and depressurizing the crawl space soil itself. For the basement and basement-crawl space combination houses, the techniques included subslab 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 were generally from <1 to about 5 pCi/L with one house near 15 pCi/L. These houses are currently being followed with alpha-track detectors to assess the long term exposure levels.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, 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).

* Readers more familiar with metric units may use the factors listed at the end of this Summary to convert to that system.

Introduction

Purpose

The primary purpose of the work described in this report was to develop cost-effective techniques for radon mitigation in crawl space houses in the Nashville Metropolitan Area. These techniques should also be applicable to crawl space designs in other parts of the country. Other types of houses mitigated during this study were basement houses in which the basement was excavated from an existing crawl space. Unlike many houses with basements and adjoining crawl spaces, 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 the mid-South, offering yet another opportunity to expand the existing data base of radon reduction techniques.

Another purpose for this mitigation demonstration was to train local contractors in the proper techniques of radon mitigation and thereby encourage radon mitigation efforts by the private sector. This will hopefully result in providing sources of cost-effective and successful mitigation installations to homeowners in this region. The results described in this report are the initial results of an ongoing, EPA funded, radon mitigation demonstration in existing houses in the Nashville area.

History

The State of Tennessee, operating through the Tennessee Department of

Health and Environment's (TDHE's) Division of Air Pollution Control and in cooperation with the U.S. Environmental Protection Agency's (EPA's) State Radon Survey Program, conducted a survey to identify areas in Tennessee with the potential for elevated radon levels in privately owned houses. During the months of January through April 1987, approximately 1.787 measurements were carried out in single-family owner-occupied houses Based on the results of that survey, the TDHE estimated that 84.2% of the houses in the state have radon levels <4 picocuries per liter (pCi/L), 14.5% have levels of 4 - 20 pCi/L, and 1.3% have levels ≥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 risk levels for indoor radon were developed (High, Intermediate, Moderate, and Low). The High Risk areas form a two-pronged band through the central part of the state including most of Davidson County, which also happens to be one of the most populated counties in the state

Problem

Tennessee, along with several other states, contain a substantial number of crawl space houses for which there are very little data regarding the appropriate technique to use for radon mitigation. This construction type represented 16 - 28% of the housing starts nationwide between 1963 and 1983. States having a significant fraction of crawl space houses include Oregon, South Carolina, North Carolina, Nevada, Tennessee, Delaware, Arkansas, New Jersey, Idaho, Washington, West Virginia, Alabama, and Virginia. Several other states have <25% each. Thus crawl space houses represent a significant fraction of the existing housing stock in diverse regions of the U.S.

In general, crawl space houses can be defined as those in which a part or all of the living areas of the house are built over an enclosed area containing exposed earth. Prior to the collection of recent radon data, crawl spaces were even considered to be a viable alternative for radon control in new construction.

House Screening and Selection

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 radon levels >4 pCi/L). From about 100 respondents, 30 houses were selected for screening as possible candidates for participation in the radon mitigation demonstration. These 30 houses in Davidson and Williamson Counties (in and near Nashville, TN) were screened between September 8 and 11, 1987, by scientists from EPA, TDHE, Southern Research Institute (SRI), and Camroden Associates. The purpose of the screening effort was to evaluate the houses for possible inclusion in Phase 1 of the Middle Tennessee radon mitigation demonstration.

As a result of the screening, 15 houses were selected for the mitigation demonstration program. The houses selected include nine crawl space houses, three houses with basements converted from crawl spaces, two combination basement/crawl space houses, and one slab-below-grade house. This cross section is representative of the existing houses in the Nashville area and in portions of other states in the mid-south.

Intensive Diagnostic Evaluation of Selected Houses

An additional extensive diagnostic visit to each house was conducted between October 21 and 27, 1987 During this visit, measurements and investigations were carried out to develop radon reduction plans that would fit into the overall research objectives of the project. Charcoal canisters (CCs) and alpha track detectors (ATDs) were placed in either the crawl space or the basement and on the first habitable level of each house to obtain a pre-mitigation radon background. In each location, duplicate detectors were collocated to determine the precision of the measurement devices. The CCs were recovered by the homeowner after 48 hours and mailed to the analysis laboratory (Scientific Analysis, Inc., Montgomery, AL). The ATDs were left in the houses until just prior to installation of the mitigation equipment. At that time, they were returned to the supplier for analysis (Terradex Corp., Glenwood, IL). The results from the collocated CC measurements in October 1987 are shown in Table 1.

Development of Mitigation Plans

The mitigation techniques for each of the 15 houses were developed by Camroden Associates and SRI following the diagnostic visits to each of the houses in October 1987. For each of the houses a 2- or 3-phase mitigation strategy was developed following guidelines established by the EPA Project Officer. These guidelines were as follows:

- Phase 1 should be a low-cost alternative (less than $500 if possible) that can be easily removed or turned off
- Phase 2 should be a technique with a high probability of lowering the house radon levels to 4 pCi/L or less and of moderate cost ($500 - $2,000)
- Phase 3 should be as close to a guaranteed reduction method as possible with correspondingly higher cost ($2,000 - $5,000).

During the planning stages it was anticipated that no more than 25% of the houses would require implementation of a Phase 3 system. To obtain the maximum scientific benefit, it was also assumed that Phase 2 systems would be installed and tested even if Phase 1 systems achieved levels <4 pCi/L.

The mitigation strategies for each house were developed using the information obtained during both the screening and diagnostic visits. This information included the type of house construction, condition of the house flooring, whether there was heating and air conditioning ducting in the crawl space, the extent and condition of any existing polyethylene sheeting under the house, the existence of a basement and the condition of the slab, the existence of any exposed soil areas in the basement, and the condition of the soil in the crawl space From these site conditions and a list of the possible mitigation systems that could be applied to the Nashville houses, a matrix of mitigation strategies was developed that would hopefully evaluate, demonstrate and allow comparisons of each technique to arrive at methods that would be both successful and cost-effective for houses similar to those in Nashville. The mitigation matrix is shown in Table 2.

Mitigation of the Nashville Houses

Local contractors in the Nashville area carried out most of the mitigation installations. The houses mitigated during December 1987 were DW 31, DW 43, DW 82, DW 60, DW 66, and DW 90. All of these are crawl space houses except DW 43 which is a basement converted from a crawl space. The remaining houses were mitigated either singularly, or at most, two houses were mitigated concurrently. The only house not mitigated during this first year (1987-88)

Table 1. *Nashville Pre-mitigation Two-day Charcoal Results for October, 1987 (pCi/L)*

House ID (DW)	Crawl Space		Basement		1st Habitable Level	
03	22.0	21.9	NA[a]	NA	9.6	9.5
12	NA	NA	26.4	25.7	20.2	19.1
14	NA	NA	33.2	31.0	16.0	16.0
27	64.1	65.2	NA	NA	39.9	40.3
29	13.2	[b]	NA	NA	5.8	5.7
31	29.0	16.5[c]	NA	NA	22.7	23.2
41	NA	NA	30.1	28.6	18.7	19.2
43	NA	NA	48.3	48.4	16.5	17.0
58	NA	NA	43.0	43.5	36.1	36.0
60	34.8	32.2	NA	NA	20.5	20.5
66	20.0	19.2	NA	NA	12.1	9.9
78	NA	NA	41.2	42.3	21.8	21.4
82	27.3	27.2	NA	NA	15.4	14.2
84	8.9	9.1	NA	NA	5.7	5.5
90	18.0	16.9	NA	NA	8.4	7.7

[a] *Not applicable*
[b] *This detector lost*
[c] *Top left off can in shipment*

of the project was DW 58. This house was scheduled for mitigation during the early part of the second year of the project (1988-89).

Additional CC measurements 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 29, 1987, and April 11, 1988. These later measurements occurred primarily during the peak heating season for the Nashville area. These later results are shown in Table 3. In most cases the radon levels were higher than those measured in October (Table 1).

Discussion of Results

One of the objectives of this research project was to develop cost- effective techniques for radon mitigation in crawl space, basement, and combination houses in the Southeastern regions of the U.S. In order to accomplish this task, the houses in this study were not simply mitigated but were used as vehicles to test concepts of the mitigation process. While the same tests were not carried out at each individual house, the results can be grouped by house geometry for comparision and discussion.

Crawl Space Houses

Six mitigation techniques were evaluated in the nine crawl space houses as shown in the mitigation matrix of Table 2. Except for the IPCS (isolate and pressurize the crawl space) and the IDCS (isolate and depressurize the crawl space) methods, all the techniques were applied to two or more houses. The resulting evaluation of these techniques based on continuous radon monitor CRM data is shown in Table 4, and based on CC measurements (pre- and post-mitigation) is shown in Table 5.

ICS - Isolation of Crawl Space

The technique of isolating the living areas from the crawl space and thereby stopping or greatly reducing the radon entry was tried on houses DW 29 and DW 66. In theory the method seemed simple and straightforward. In practice the method was difficult to apply. In the Nashville houses the sub-flooring was typically 1 by 6 in. boards laid diagonally to the floor joists. Air movement, from the crawl space up into the cracks between these boards, could be demonstrated at every location. The air flow was much greater near the points at which the HAC cold air return plenum was constructed between the floor joists. Sealing the cracks between the sub-flooring boards was difficult and achieved only limited success, even in houses that had no insulation under the floor. In houses with insulation, it was more time consuming (and more costly) and even less successful. Attempts to seal the floor, using a variety of spray foams and plastic liners applied or attached to the floor joists, were ruled out as too expensive and therefore not cost-effective. The floor openings that were routinely sealed in these houses were the utility penetrations (electrical wiring, water and gas pipe entries, and waste pipe penetrations for drains and under the bath tub openings) and the larger openings in the box joists used for air return plenums.

In the two Nashville houses (DW 29 and DW 66) where this ICS technique was applied, the results of sealing alone were not impressive. In DW 29 the radon reduction was only about 3% and in DW 66 the levels actually increased by about 15%. These reductions were based on CRM measurements in the living space of the houses as shown in Table 4. No CC measurements were carried out for this technique.

Thus it appeared that attempts at isolating the crawl space from the living areas are a questionable means of reducing the indoor radon levels when used as the only mitigation technique.

IVCS - Isolation and ventilation of crawl space

This technique of isolating the crawl space and opening the existing foundation vents was tried on four houses: DW 03, DW 60, DW 82, and DW 90. The radon reductions ranged from

-60% (an increase) for DW 82, to 75% (decrease) for DW 90 as shown in Table 4. No CC measurements were carried out for the IVCS technique.

In the worst case, DW 82, the garage had been converted to a den and was open to the rest of the living areas. In building the den, the floor was constructed using typical wood floor joist techniques. Unfortunately, the floor joists were so close to the old garage slab that access to this area was impossible. The number of entry points into the den was unknown. For the remainder of the house, the overhead floor was readily accessible from the crawl space. In this area all the major openings (those >0.25 in.) and many of the minor cracks and openings were closed. However, the radon levels in the living area increased.

In summary, for the applications here, it appeared that isolation and passive ventilation of the crawl space alone would not likely reduce the levels of upstairs radon <4 pCi/L level unless the leakage area between the house and crawl space was or could have been reduced to very low values and the ventilation area of the crawl space increased.

IDCS - Isolation and Depressurization of the Crawl Space

Although three houses were scheduled for mitigation by the technique of isolation and depressurization of the crawl space, only one house (DW 82) actually had the system implemented. The reduction achieved was rather dramatic. Based on the CRM data, the levels in the den were reduced by 90%, and from the pre- and post-mitigation CC measurements the reduction was 96%; however, the levels in the crawl space increased. The levels here rose from 29.8 to 61.7 pCi/L, an increase of 107%. While this posed no problem for this house, it could lead to problems in others. If there were HAC ducts in the crawl space, the increased radon levels could leak into the return ducting and be distributed throughout the house. Also, since the openings between the living area and the crawl space can never be entirely closed, fairly large amounts of conditioned air could be drawn into the crawl space, resulting in a substantial energy penalty for the homeowner. In house DW 82 it was found that the foundation walls had enough leakage areas that the major portion of the air flow into the crawl space was from outdoors. Thus no substantial energy penalty was expected.

IPCS - Isolation and Pressurization of the Crawl Space

The technique of isolation and pressurization of the crawl space was originally scheduled to be tried as a Phase 1 mitigation on house DW 82. However, at the time of installation, there were several uncertainties as to the

Table 2. Mitigation Techniques

Tech-nique	Mitigation Phase by House ID (DW)																	
	03	27	29	31	60	66	82	84	90		43	58	78		12	14		41
ICS			1[a]			1												
IVCS	1	2			1				1									
IDCS		3		2			2											
IPCS							1											
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[b]		2	3		
PB												2	5[b]					
SSP															3			1
DTD																		3

[a] = Numbers refer to phases of mitigation application.
[b] = In house DW 78, two additional phases were scheduled.

ICS = Isolation of Crawl Space.
IVCS = Isolation and Ventilation of Crawl Space.
IDCS = Isolation and Depressurization of Crawl Space.
IPCS = Isolation and Pressurization of Crawl Space.
SSoD = Sub-soil Depressurization.
SPD = Sub-poly Depressurization.
SSD-W = Sub-slab Depressurization Wide Pit.
SSD-N = Sub-slab Depressurization Narrow Pit.
SSD-P = Sub-slab Depressurization Progressive Pit.
SSBWD = Sub-slab + Block Wall Depressurization.
SSSPD = Sub-slab + Sub-poly Depressurization.
PB = Pressurization of Basement.
SSP = Sub-slab Pressurization.
DTD = Drain Tile Depressurization.

Table 3. *Nashville Pre-mitigation Collocated Charcoal Results (Nov'87 to Apr'88) (pCi/L)*

House ID (DW)	Start Date	Stop Date	Crawl Space		Basement		1st Habitable Level	
03	4/08/88	44/11/88	21.6	22.1	NA[a]	NA	7.0	7.1
12	2/05/88	2/08/88	NA	NA	10.3	11.8	7.7	7.8
14	2/08/88	2/10/88	NA	NA	89.9	86.7	47.1	48.1
27	1/22/88	1/25/88	45.7	46.4	NA	NA	32.8	33.0
29	2/19/88	2/22/88	27.1	27.2	NA	NA	15.9	16.2
31	11/29/87	12/1/87	29.4	30.3	NA	NA	26.3	25.7
41	1/22/88	1/25/88	NA	NA	19.2	19.3	13.3	13.4
43	11/29/88	12/1/87	NA	NA	58.6	59.7	23.2	22.9
58	3/29/88	3/31/88	NA	NA	56.2	57.3	20.4	27.4
60	12/01/87	12/3/87	55.2	55.0	NA	NA	27.9	27.8
66	12/01/87	12/3/87	26.1	25.9	NA	NA	12.3	11.9
78	2/19/88	2/22/88	NA	NA	41.2	41.5	19.6	19.9
82	11/29/87	12/1/87	29.5	30.0	NA	NA	14.7	15.1
84	3/28/88	3/30/88	9.4	9.7	NA	NA	1.5	2.3
90	12/01/87	12/3/87	29.6	29.7	NA	NA	15.8	15.8

[a] Not applicable

Table 4. *Percent Radon Reduction for Each Crawl Space Mitigation Scheme (Based on Average Continuous Monitor Data in Living Area)*

	House ID Code (DW)								
Mitigation Technique	*03*	*27*	*29*	*31*	*60*	*66*	*82*	*84*	*90*
Isolate Crawl Space (ICS)			*3*			*-15*[a]			
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 Point		*87*	*84*						
Sub-Soil Dep. (SSoP) 2 Pts				*61*				*58*[b]	
(SSoP) 4 Pts				*84*				*86*[c]	

[a] *Negative values indicate increased radon levels.*
[b] *Worst case condition.*
[c] *House open during part of test.*

correct method of installing the available device (Current Indoor Air Systems, Inc., Boulder, CO, model 300). Consequently, installation of the IPCS technique was cancelled for this house. The device was later installed in another crawl space house, DW 60, but no data as to its operation or effectiveness were available at the time of this report.

SSoD - Sub-Soil Depressurization

The technique of depressurizing the soil directly was implemented on two houses, DW 31 and DW 84. The soil in the crawl space of DW 31 was fairly loose and permeable to air movement (as measured during the diagnostic visits in October 1987). The soil under house DW 84 was quite different. The surface of this soil was very hard and had large desiccation cracks up to 0.5 in. wide throughout. The system installed in each house was basically identical. Four, evenly spaced, suction pits about 24 in. wide and 12 - 18 in. deep were dug in the soil and connected to a single fan (model K6, R.B. Kanalflakt, Inc., Sarasota, FL) exhausting to the outdoors. The area of the crawl space under DW 31 was about 780 ft^2 and under DW 84 was about 1360 ft^2. Thus the number of suction points per square foot of soil was one per 195 ft^2 for DW 31 and one per 340 ft^2 for DW 84.

The pressure field extension in the soil was measured by carefully drilling a series of 3/8-in. diameter holes into the soil. These holes were generally 12 - 18 in. deep, although in some instances the soil was sufficiently loose that it tended to slide into the bottom of the hole. In those cases it was difficult to estimate the depth of the test hole. The test holes were located at varying distances from a suction pit. In carrying out the measurements, a 12 in. length of 1/8 in. diameter steel tubing was carefully inserted into the hole. The top of the hole was sealed as tightly as possible by means of a rubber stopper at the top of the tube. The steel tube was connected to an electronic manometer (Neotronics, Gainesville, GA, model EDM-I) with a sensitivity of 0.001 in. of water.

The depressurization in the soil could reliably be measured at distances of up to 6 ft from the suction pit, and in several cases up to 12 ft. For House DW 31, the pressure field dropped to about 10% of the pit pressures within 2 ft and around 1% at distances of about 6 ft. In the soil under House DW 84, the pressure decrease was even more drastic. Here, the pressure dropped to approximately 1% of the pit pressure within 2 ft, although some pressures were measured as far out as 6 ft.

These results were consistent with the observed nature of the soils under the two houses. The soil under DW 31 was moderately loose and should have had a higher permeability than the soil under DW 84, which was hard packed clay. Thus, each suction point of the system was capable of producing a measurable soil depressurization over an area of at least 113 ft^2 and perhaps as large as 452 ft^2.

In terms of the reduction of the radon levels in the living space, the SSoD technique achieved reductions of approximately 85% as seen in Table 4 for the CRM measurements, and up to 92% based on the CC measurements as shown in Table 5. Unfortunately, the method has been applied to only two houses. If the technique is to be used on any large scale it should be tested for other types of soils and at different locations.

SPD - Sub-Poly Depressurization

The technique of depressurizing the soil under a plastic membrane had the widest application in the current group of houses. Six of the nine crawl space houses had an SPD system installed and evaluated. This mitigation technique is a variation of the successful sub-slab depressurization method used for slab-on- or below-grade houses. In many of the nine houses there was at least some polyethylene sheeting covering the dirt in the crawl space. This covering is a popular method used to control moisture in living areas. The intent of this technique was to supplement the existing sheeting with new 6 mil sheeting to completely cover the exposed dirt. This gastight barrier formed a small-volume plenum above the soil in which the radon gas collected. At one or more suction points, a shallow pit approximately 24 in. wide and 12 in. deep was dug in the soil. Each hole was then covered with a 36 by 36 in. piece of treated plywood. The 4 in. diameter polyvinyl chloride (PVC) suction pipe was mounted through the plywood and the sheeting sealed around the pipe and plywood. A fan was installed to pull the collected soil gas from under the sheeting and exhaust it outdoors. Initially, no attempts were made to seal the sheeting to the foundation walls or to any support piers located in the crawl space. The sheets were laid directly on the earth in most cases overlapping at least 1 ft at the joints.

Only one house had any type of perforated pipe or ducting network installed under the sheeting. In house DW 27, drainage material (Enkadrain Type 9010, BASF Corp. Fibers Div., Enka, NC) was placed under the sheeting to improve air flow. In general, this is necessary only where the soil surface is excessively hard and smooth or the crawl space area is exceptionally large (DW 27). When excessive air leaks prevented effective removal of the radon, the joints between the sheets were sealed with a bead of caulking (DW 27). Also, where the number of support piers was large or located close to the suction point (within 12 ft) the sheeting was sealed to the piers nearest the suction points with caulking and wood strips (DW 03, DW 29, and DW 60). In one house (DW 27) the sheeting was also sealed to the foundation walls to reduce air leaks.

Pressure under the sheeting was measured in all but one house (DW 27). Measurements utilized an electronic micromanometer (Neotronics, Gainesville, GA, model EDM-I) with a sensitivity of 0.001 in. of water column. In each house, measurable pressures were detected at distances of up to 6 ft from the suction point, and in some cases up to 12 ft. Farther away, the pressures were not measurable with the manometer but, in most cases, air flow under the sheeting was observed using a smoke tracer.

In two houses (DW 27 and DW 29), a second suction point was added to increase the extension of the depressurization under the sheeting. These two houses had the largest crawl space area of any of the houses. In both cases, the same fan was used for both suction points.

Based upon the CRM data, the SPD technique achieved reductions ranging from 60 - 92% (Table 4). Based on pre- and post-mitigation CC measurements (Table 5), the reductions range from 45 - 85%.

In summary, the SPD technique was the most widely used and appears to be the most applicable to crawl space houses in which the upstairs levels are in the 10 - 30 pCi/L. There are questions regarding the technique that have not been fully answered in this study. In the SPD installations, the material used for the houses in this study was standard, builder-grade, 6 mil polyethylene sheeting. The properties of this material (thickness, puncture resistance, permeability, and resistance to ultraviolet light and temperature degradation) vary from location to location in a single sheet and perhaps from source to source. Also, the tear and puncture resistance are not believed to be sufficiently high to withstand normal traffic (such as by service personnel from utility companies, termite control organizations, or the homeowner) that might be expected in a crawl space. Other materials such as cross-laminated high-density polyethylene films or lagoon liners need to be examined for use in these applications. Other questions that have not been addressed include, the amount of energy penalty resulting from the SPD system withdrawing house air down into the crawl space, and the effects of the system upon the house frame as a result of moisture removal from the crawl space.

Basement or Combination Houses

One- or two-point sub-slab depressurization (SSD) systems were installed in five basement/combination houses. Measurements of the pressure field extension under the slab showed a wide, shallow pit in the soil where the pipe penetrated the slab to be more effective than a narrow, deep pit. The surface area of soil exposed in the pit was found to be more important than the shape of the pit. Sub-slab pressure, measured at a fixed distance from the suction hole, increased dramatically as the size of the hole in the soil under the slab penetration was increased. In mapping the pressure field extension as a function of the distance from the suction point, the pressure became unmeasurable farther than 20 - 25 ft from the suction point.

The radon reductions achieved were 28 - 98%, as shown by the CRM data 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 (less than 100 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

Table 5. Nashville Radon Reduction Summary (Based on Charcoal Canister Measurements in pCi/L)

	Crawl Space			Basement			1st Floor			
House ID (DW)[a]	Pre	Post	%Red	Pre	Post	%Red	Pre	Post	%Red	Notes
03	21.9	ND[b]	ND	NA[c]	NA	NA	7.1	2.6	64	1,10
27	46.1	9.2	80	NA	NA	NA	32.9	5.3	84	2
29	27.2	5.7	79	NA	NA	NA	16.1	7.0	56	1
		2.8	90	NA	NA	NA		3.0	82	3
31	29.9	2.0	93	NA	NA	NA	26.0	2.2	92	4
60	55.1	23.3	58	NA	NA	NA	27.91	15.2	45	1
66	26.0	7.6	71	NA	NA	NA	12.1	2.8	77	1
82	29.8	61.7	-107[d]	NA	NA	NA	14.9	0.7	96	5
84	9.6	ND	ND	NA	NA	NA	1.9	ND	ND	4,11
90	29.7	7.1	76	NA	NA	NA	15.8	2.4	85	1
43	NA	NA	NA	59.2	4.8	92	23.1	1.4	94	6
58	NA	NA	NA	56.8	ND	ND	23.9	ND	ND	12
78	NA	NA	NA	41.4	2.8	93	19.8	1.5	92	6,13
12	NA	NA	NA	11.1	4.4	61	7.8	4.8	39	8
14	NA	NA	NA	88.3	11.3	87	47.6	3.8	92	9,14
					3.0	97				9,15
41	NA	NA	NA	19.3	1.4	93	13.4	1.0	93	7

[a] See Table 2 for mitigation codes
[b] No Data
[c] Not Applicable
[d] Negative values indicate increased radon levels

Notes:
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 4 ft from floor and 6 ft from C/S wall

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 of 42 - 60%. Because of the high porosity of the block comprising the wall, acceptable reductions were not achieved until the wall was coated with a sealer (SurWall Brand). The final reduction for this house was 92%.

For house DW 12 the exposed soil in the crawl space was covered with 6 mil polyethylene sheeting but no depressurization under the sheeting was implemented. Final reduction for this house was 92%.

The exposed soil in the crawl space of house DW 14 was covered with 6 mil sheeting sealed to the surrounding walls. Depressurization under the sheeting was accomplished by breaking through the adjoining wall (and under the sheeting) 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 treated 2 x 12 in. boards 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 the crawl space in this house (600 ft^2) was roughly twice the area of the slab (300 ft^2) and was probably the major source for radon entry into the basement. After covering the soil with 6 mil sheeting 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 sheeting covering the soil. The

Table 6. Percent Radon Reduction for Each Basement Type Mitigation Scheme (Based on Continuous Monitor Data in Basement)

Mitigation Technique	*House ID (DW)*					
	43	*58*	*78*	*12*	*14*	*41*
Sub-Slab Pressurization (SSP)						*70*[a]
Sub-Slab Depressurization (SSD)[b]	*28*[c]		*78*	*92*	*70*	*98*[c]
SSD + Block Wall Depress.(BWD)	*42-60*				*85*	
SSD + BWD + Seal Exposed Soil			*93*		*93*[d]	
SSD + BWD + Seal Wall Face	*92*					

[a] *Single sub-slab depressurization point*
[b] *Unless specified otherwise, all SSD systems include two suction points*
[c] *Single sub-slab pressurization point*
[d] *Top of wall sealed*

final reduction was 93% as measured in the basement with 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 termaticide (aldrin) in two rooms of the basement were increased from premitigation concentrations of 0.3 and 0.12 μg/m³ to levels of 1.40 and 1.03 μg/m³ 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 <0.066 μg/m³. Thus, while SSP can be effective in lowering radon levels, it could also lead to other problems for the homeowner.

Conclusions and Recommendations

Several techniques have been tested in crawl space and combination houses typical of the Southeast. Based on the results described in this report, the following conclusions can be drawn.

Methods Applied to Crawl Space Houses

- Isolation of the crawl space from the living areas of the house was found to be difficult if not impossible to achieve and its use as the only mitigation technique is risky, questionable, and not recommended.
- Isolation and passive ventilation of the crawl space using only the existing foundation vents was found to be ineffective due to the limited area of the vents installed in most houses. This technique is not recommended as the sole mitigation method even if it is combined with covering the soil in the crawl space with some type of plastic film. Without active ventilation under the film, the radon levels in the living areas will, in all likelihood, not be reduced to acceptable limits.
- Isolation and depressurization of the crawl space was found to be an effective method of reducing the radon levels in the living areas of one house. However, this technique can substantially increase the levels in the crawl space. This technique may be difficult to apply when there are cold air return ducts in the crawl space and could also incur an energy loss from the conditioned air space above.
- Sub-soil depressurization was found to be an effective technique for two houses in this study. Its effectiveness is greatly influenced by the soil conditions in the crawl space and should be used with caution until additional results from other geographic locations and soil conditions become available.
- Sub-membrane depressurization in the crawl space was the most widely applicable technique in this study and proved a reliable method of removing radon before it enters the crawl space. The number of suction points needed under the membrane will depend on both the crawl space area and the condition of the soil. For areas >1,200 ft² or crawl space with execssively damp soil conditions, at least two suction points should be installed at opposite ends of the crawl space. The membrane used in these houses was standard 6 mil clear builder's polyethylene. However, due to its limited puncture and tear resistance and its instability to ultraviolet (UV) light degradation, it is not recommended for more general use. Instead, a cross-laminated, high density polyethylene material with UV stabilizers is recommended. Sealing of the membrane lap joints and to the surrounding foundation walls and support piers is recommended at locations within 12 ft of the suction point(s) and at all locations if the crawl space is exceptionally large. In this case it may even be necessary to install some type of drainage system under the membrane to improve the air flow.

Methods Applied to Basement or Combination Houses

- Sub-slab pressurization was found to be somewhat effective for radon reduction in one house but not as effective as depressurization of the sub-slab region. It also can produce other problems such as increased moisture or even increased levels of termaticide in the basement. It may be difficult to apply when sub-slab communication is poor.
- Sub-slab depressurization (or sub-slab ventilation) was found to be an effective technique in the five houses studied even when the sub-slab communication was not very good. In these cases, more than one suction hole will likely be required. The soil under the slab, at the suction point should be excavated to at least a diameter of about 36 in. and to a depth of about 12 - 18 in. The amount

of soil surface area exposed in the pit is more important than the depth or shape of the pit. Filling the pit with crushed stone was not found to be necessary.

- Block wall depressurization was found to improve the effectiviness of sub-slab systems in the three houses in which it was applied. In these houses, large areas of the block wall were either below grade or separated the crawl space from the basement. Sealing of the wall was found to be necessary in one case in which the porous blocks short-circuited the negative pressures generated under the slab.
- Consideration of the exposed soil in direct communication with the basement was found to be essential to lowering the radon levels to acceptable limits. The methods used for these areas are similar to those for crawl spaces above.

Mitigation Costs

The actual contractor costs for installing the systems in the crawl space houses of this study were $850 - $1,859 with an average of $1,282. For the basement and basement-combination houses, the costs were $785 -$1,995 with an average of $1,496. However, these costs do not include any time spent in diagnostics or in design of the mitigation systems. The expenses incurred by private mitigators for diagnostics and design could increase the costs by as much as 50%.

Recommendations for Additional Research

Questions need to be addressed in future studies of mitigation using the techniques described above. In the sub-poly depressurization technique, the material used for these houses was standard builder's grade 6 mil polyethylene sheeting. The properties of this material (thickness, puncture resistance, permeability) vary from location to location in a single sheet. Also, the tear and puncture resistance is not believed to be sufficiently high to withstand normal traffic (such as by service personnel from utility companies, termite control organizations, or the homeowner) that might be expected in a crawl space. Other materials such as cross-laminated high-density polyethylene films or lagoon liners need to be examined for use in these applications.

In houses where sub-slab depressurization cannot be made to function cost-effectively, other techniques such as basement pressurization need to be developed and demonstrated.

Conversion Factors

Readers more familiar with metric units may use the following factors to convert nonmetric units used in this Summary to their metric equivalents.

Nonmetric	*Multiplied by*	*Yields Metric*
ft	0.305	*m*
ft^2	0.093	*m^2*
in.	2.54	*cm*
in. H_2O	0.249	*kPa*
mil	25.4	*μm*
pCi/L	37.0	*Bq/m^3*

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The complete report, entitled "Radon Mitigation Studies: Nashville Demonstration," (Order No. PB 90-257 791/AS; Cost: $31.00, subject to change) will be available only from:
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