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TESTING OF INDOOR RADON REDUCTION METHODS IN 16 HOUSES AROUND DAYTON, OHIO

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ABSTRACT

Developmental radon reduction techniques have been installed in 16 houses near Dayton. Sub-slab suction and sump (drain tile) suction have reduced radon levels in five basement houses below 4 picoCuries per liter (pCi/L) -- or 148 Becquerels per cubic meter (Bq/m^3) -- based upon short-term radon measurements. In one of these houses, soil gas flow in the system was only 4 ft^3/min (2 L/sec). In two houses which had a basement plus an adjoining slab on grade, sub-slab suction in the basement alone adequately reduced radon levels in the entire house. Radon was reduced by over 90 percent in each of four slab-on-grade houses using sub-slab suction from outdoors, even though forced-air heating supply ducts under the slabs appeared to prevent effective extension of the suction field under the slab. Forced-air exhaust of the crawl space in four crawl space houses proved more effective in reducing radon in the living area than did natural ventilation of the crawl space. Closure of the wall/floor joint in two basement houses with concrete foundations, and of a sump in one of the houses, gave moderate reductions in the house with a sump, but limited reduction in the other house. Operation of sub-slab ventilation systems in suction proved consistently more effective in reducing radon than did operation of the systems in pressure.

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

INTRODUCTION

As part of the U. S. Environmental Protection Agency (EPA) program to develop and demonstrate cost-effective methods for reducing concentrations of radon inside houses, developmental radon reduction measures have been installed and tested in 16 existing houses in the vicinity of Dayton, Ohio. This project is intended to develop understanding of the design and performance of selected radon reduction systems in selected house substructure types, with geological and house construction characteristics representative of Ohio (as well as other areas of the country). The testing in these 16 houses, conducted under EPA sponsorship by Acres International Corp. and AMERICAN ATCON during the 1987-88 heating season, is envisioned as the first phase of a two-phase radon reduction field project in Ohio.

This test program had five objectives.

1. To verify that traditional sub-slab ventilation systems and sump (drain tile) ventilation systems can provide high radon reductions in "pure" basement houses in Ohio (i.e., basement houses having no adjoining slab on grade or crawl space). These active soil ventilation systems have proven very effective in testing elsewhere[1].

2. To demonstrate whether sub-slab ventilation in the basement only can sufficiently reduce radon levels throughout basement houses with adjoining slabs on grade (i.e., to determine whether separate vent pipes directly treating the adjoining slab can be avoided).

3. To explore alternative mitigation methods for slab-on-grade houses having forced-air heating supply ducts underneath the slab. Methods tested included: operating the central furnace fan to pressurize the sub-slab space using the heating ducts; sealing accessible slab openings; and sub-slab ventilation.

4. To test alternative methods for treating crawl space houses, including: natural ventilation of the crawl space; and forced-air ventilation of the crawl space (with the ventilation fan operating to exhaust air from the crawl space).

5. To test sealing alone as a method for reducing radon in basement houses particularly amenable to sealing (i.e., poured concrete foundation walls, basement unfinished, and slab and walls reasonably free of cracking).

Table 1 lists the 16 study houses, including the results of alpha-track measurements in each house over a 3-month period during the winter, prior to mitigation. Soil gas is the predominant source of the radon in all of the houses; well water and building materials were determined not to be significant radon sources.

MEASUREMENT METHODS

For short-term measurements of mitigation system performance, radon gas is measured using a Pylon Model AB-5 continuous radon monitor equipped with a 17.4 $in.^3$ (285 mL) Lucas scintillation cell. The Pylons are programmed to measure radon hourly. Because of the significant day-to-day variability in indoor radon concentrations observed in the Dayton houses, the short-term radon measurements consisted of at least 48 hours (and sometimes as many as 98 hours) of Pylon readings both before and after the mitigation system was activated. System on/off measurements were made back-to-back, to the extent possible, to reduce temporal variations. Measurements were made in different parts of the house, as indicated in the tables that follow, under closed-house conditions. Much of the monitoring was completed during the heating season, although some of the last measurements were not completed until mid-April 1988.

Diagnostic testing included: sub-slab suction field extension measurements in houses with active soil ventilation systems, both before installation (using a vacuum cleaner to generate the suction) and afterwards; perfluorocarbon tracer measurements of ventilation rate in the crawl space houses, to understand the effects of crawl space ventilation; and suctions and flows in individual pipes associated with the soil ventilation systems.

Three-month alpha-track detector measurements were made in the houses prior to mitigation, as reported in Table 1. To measure long-term system performance, 3-month alpha-track measurements will be repeated quarterly for at least 1 year with the systems operating. For quality assurance, these detectors are deployed in clusters of three; in addition, unexposed detectors, and detectors exposed to known radon levels in a chamber, are sent blind to the analytical laboratory.

RESULTS

SUB-SLAB AND SUMP VENTILATION IN BASEMENT HOUSES

Sub-slab ventilation, with a single ventilation pipe inserted down through the slab, was tested in three basement houses. Sump ventilation, where drain tiles entered the sump, was tested in two houses. The results of this testing are summarized in Table 2. The radon levels presented in this table are the short-term Pylon results, since the Pylon results provide back-to-back, system on/off comparisons. The results in the table are with the systems operating in suction, which, as discussed later, is preferred over operation in pressure.

As shown in the table, all five of the houses were reduced to mean radon concentrations below the EPA guideline of 4 pCi/L (148 Bq/m^3). Radon removals were greater than 90 percent in all houses except one. These high radon reductions are consistent with the results observed with sub-slab suction and sump/drain tile suction in other geographic areas.

Pre-installation sub-slab suction field extension measurements had indicated that suction extended effectively beneath these slabs. These diagnostic results led to the decision to install only one 4-in. (10-cm) diameter sub-slab suction pipe in the three houses having sub-slab suction systems, even though one of the basements was large (1850 ft^2, or 170 m^2). Also in view of these diagnostic results, no attempt was made to improve suction by excavating a hole under the slab where the pipe penetrated (other than removal of the several-inch depth of aggregate immediately under the slab penetration). The relatively high radon reductions achieved with only one suction pipe in these houses would seem to verify the apparently favorable diagnostic results. The fans installed on these systems are capable of moving 270 ft^3/min (127 L/sec) of air at zero static pressure, and capable of developing about 1.4 in. of water column suction (350 Pa) before stalling.

The low soil gas flows in two of the sub-slab suction systems (Houses 7 and 43) are of interest (see Table 2). In House 7, the fan was nearly stalled as a result of the suction head. The high radon reductions despite these low flows confirm that high flows are not necessary to achieve good reduction performance with a single suction point, as long as the suction field extends well. The pre-installation (vacuum cleaner) suction field results in all of these houses had suggested that there would be little resistance to gas flow (so that high flows would be expected). Thus, while the pre-installation diagnostics correctly predicted the success of sub-slab suction, there were clearly aspects of the sub-slab condition that the diagnostic testing did not fully reveal. The soil conditions under these houses -- often a hardpan clay directly under the sub-slab aggregate, underlain at some depth with either limestone or gravel -- undoubtedly contributed to the low soil gas flows.

SUB-SLAB VENTILATION IN BASEMENTS OF BASEMENT-PLUS-SLAB HOUSES

In basement houses having an adjoining slab on grade, it would be convenient and less expensive if radon levels in the entire house could be sufficiently reduced through sub-slab ventilation under the basement slab alone. This would avoid the need to insert vent pipes under the adjoining slab. In other studies[1,2], it has sometimes been found necessary to include pipes under the adjoining slab.

The Pylon results from basement treatment of two such houses are presented in Table 3. As with the previous table, these results are with the fans operating in suction. As apparent from the table, radon concentrations were reduced to 4 pCi/L (148 Bq/m^3) or less in both the basement and the living area of both houses with basement treatment alone.

In both houses (and especially in House 11), pre-installation suction field extension measurements had suggested that communication under the basement slab was very good, but that communication between the basement sub-slab and the adjoining slab was questionable. In the case of House 11, one suction pipe in the basement was sufficient to reduce radon levels over the adjoining slab below 4 pCi/L, but levels in the basement were reduced only to 4 pCi/L and not below. Thus, a second basement pipe was added. It is surprising that one pipe was not adequate to reduce the basement below 4 pCi/L, in view of the exceptionally good pre-installation diagnostic results. This result again illustrates that pre-installation suction field extension measurements do not reveal everything about sub-slab conditions. It cannot be confirmed from the post-mitigation diagnostics whether the reductions in upstairs concentrations resulted because the pressure field extended to the adjoining slab, or because reductions in the basement reduced the amount of radon migrating upstairs from the basement.

In House 21, the slab-on-grade portion of the house was underlain by clay, while the basement addition penetrated the clay layer and was underlain by gravel. Probably because it penetrated the impermeable clay layer, this basement had the highest radon levels observed in the Dayton project (83 pCi/L, or 3,080 Bq/m^3). Post-mitigation suction field extension measurements confirmed that suction from the sub-slab system appeared to be extending underneath the entire basement slab; thus, again, it is considered surprising that basement radon levels were reduced only to 4 pCi/L and not less. One hypothesis is that the suction field is not extending under the footings to treat the exterior face of the basement foundation wall, so that radon could still be entering through the seam between the basement stem wall and the adjoining slab. If that is the case, the adjoining slab is not being treated by the basement suction point, and the radon reductions upstairs would be due to reduced migration of radon upstairs from the basement. The low flows in the system in House 21 are interesting, since the slab is underlain by gravel which presumably is permeable.

House 11 has concrete foundation walls; the basement walls in House 21 are block filled with concrete. If the basement suction field were to extend under the adjoining slab, there is a greater likelihood that this would occur with concrete walls (or concrete-filled block walls) than with hollow block walls.

As in Table 2, the installations in Table 3 utilize the 270 ft^3/min fan, 4-in. piping, and no excavation under the slab.

SLAB-ON-GRADE HOUSES

All four of the slab-on-grade houses tested in this study have forced-air heating supply ducts beneath the slab, radiating out from a centrally located down-draft furnace. Under these circumstances, it would be anticipated that a suction field created by a sub-slab suction system would not extend underneath these slabs; presumably, the field would by broken by the ducts, which could provide a supply of indoor air that would neutralize the suction. The apparent presence of clay soil directly under the ducts further reduces the likelihood that a suction field could extend under the ducts. And, as expected, pre-mitigation suction field extension measurements confirmed that the field did not extend between the sub-slab zones created by the ducts.

In view of these concerns about the extension of a suction field, the initial testing addressed approaches other than sub-slab suction. The results of this initial testing are summarized in Table 4.

The first approach was to operate the central furnace fan continuously, in an effort to pressurize the sub-slab region by continuously forc'ng air into these sub-slab supply ducts. As shown in Table 4, furnace fan operation resulted in moderate degrees of radon reduction in Houses 15 and 47, and essentially no reduction in Houses 1 and 31. Sub-slab pressure field measurements confirmed that fan operation appeared to be increasing the sub-slab pressures at all of the test holes. The fact that reductions were not higher than they were indicates that this sub-slab pressurization was not sufficient to keep radon out of the sub-slab space. In House 1 -- the only one of the four slab houses to have a block foundation -- radon could also have still been entering via the block cores.

The next step was to close the major accessible opening through the slab, namely, the opening under the bathtub where the bath plumbing comes up through the slab. It was recognized that this step would likely not be sufficient, by itself, to reduce radon below 4 pCi/L, in view of the other slab openings left unclosed (such as the heating supply vents and the inaccessible wall/floor joint). As shown in Table 4, closing the tub opening gave some apparent reduction in Houses 15 and 31, and essentially no reduction in House 47. (House 1 had no opening under the tub.)

The table shows that -- for the two houses where operation of the central furnace fan had had an effect prior to closing the bathtub opening -- closure of this opening improved the radon reduction effectiveness of fan operation.

Only in the case of House 15 did the above steps reduce radon levels below 4 pCi/L. Thus, additional steps were clearly required. Prior to attempting other measures, it was decided to test a simple sub-slab ventilation approach, even though the diagnostic results as well as intuition indicated that sub-slab suction should not be effective. This simple sub-slab approach involved creation of one sub-slab vent point horizontally through the foundation wall from outdoors below slab level, at one end or at the rear of the house. A hole was cored through the foundation, and the sub-slab ventilation fan was mounted over the hole. No vent pipe was inserted under the slab. As with all of the other sub-slab systems in this project, the fan was capable of moving 270 ft^3/min of gas at zero static pressure.

The results with these sub-slab installations are presented in Table 5. As shown, all four houses were reduced below 4 pCi/L, with reductions greater than 90 percent in all cases. It is not understood why these systems were so effective. Sub-slab suction field extension measurements with the systems operating showed no measurable suction being created under the slab by the systems in regions remote from the suction point, consistent with the pre-installation diagnostics.

The results in House 1 -- the one house with a block foundation -- are the most tentative. The performance of the sub-slab system in this house was not measured until after mid-April, at which time the weather had become more mild; in the other three houses, the surprisingly good system performance was measured in March, under more challenging weather conditions. Moreover, continuous operation of the central furnace fan greatly increased radon levels in House 1 (to 10.6 pCi/L, or 390 Bq/m^3), indicating that the sub-slab system might be overwhelmed under some conditions. In the other houses, which all had concrete foundations, operation of the furnace fan did not increase concentrations above 4 pCi/L. A concern is that, in House 1, the block cores could be facilitating the short-circuiting of house air into the sub-slab system, thus reducing the development of suction under the slab.

CRAWL-SPACE HOUSES

The initial testing on the four crawl-space houses in this project involved alternative methods of ventilating the crawl space. Testing to date has addressed: natural ventilation (opening the vents in the foundation wall); and forced-air ventilation, where the fan is mounted to exhaust air from the crawl space. The anticipated advantages of forced crawl-space exhaust are that, in addition to increasing crawl-space ventilation, it would: a) possibly depressurize the crawl space relative to the living area, thus reducing migration of radon from the crawl space into the living space; and b) avoid freezing of water pipes in the crawl space as a result of ventilation during cold weather, since much of the air exhausted by the fan would be warmed house air drawn into the crawl space rather than cold outdoor air. To increase crawl-space depressurization, the foundation vents were closed during forced exhaust ventilation; however, no additional sealing of the crawl-space foundation wall or of the subflooring under the living space was attempted in the tests reported here. Forced-air ventilation of the crawl space, with the fan blowing into the crawl space, will be tested in the future.

The results of the crawl-space ventilation tests are reported in Table 6. As shown, natural ventilation gave radon reductions of 37 to 84 percent in the living area, and usually greater reductions in the crawl space, reducing two of the houses below 4 pCi/L in the living area. Crawl-space concentrations, which were roughly twice the living area concentrations with the vents closed, tended to become closer to the living area concentrations with the vents open.

By comparison with natural ventilation, forced-air exhaust gave distinctly greater radon reductions in the living area in all of the houses (although still only two are below 4 pCi/L). However, reductions in the crawl spaces are much less with forced exhaust, as would be expected; in depressurizing the crawl space, this approach draws more soil gas into the crawl space, largely offsetting the benefits of increased ventilation. The potential of the crawl-space depressurization mechanism is demonstrated by the fact that concentrations in the living area can be substantially decreased while the crawl-space concentrations are being decreased only slightly to moderately. Whereas natural ventilation functions by diluting the radon in the crawl space before it enters the house (and possibly by reducing the driving force for soil gas entry by neutralizing the pressure in the crawl space), crawl-space depressurization functions by reversing the direction of flow between the crawl space and the living area.

To assess the effects of natural and forced-air crawl space ventilation on the ventilation rates in the crawl space and the living area (and on the movement of air between these two zones), perfluorocarbon tracer measurements were made in all of these houses. The results of the tracer gas measurements were inconclusive.

SEALING IN BASEMENT HOUSES

For proof of principle concerning the effectiveness of sealing, the two basement houses selected for sealing tests were as close as possible to being "textbook cases." Both had poured concrete foundation walls, thus avoiding entry routes associated with the cores and the porous faces involved with block walls. In addition, the basements were unfinished, providing reasonably convenient access to all apparent entry routes -- specifically, the wall/floor joint, cracks in the slab and walls, and, in the case of House 32, the sump.

The results of this testing are summarized in Table 7. Moderate reductions were achieved in House 32, perhaps because of the significance of the sump in that house as a source. The reductions in House 49 were less significant; in fact, considering the low concentrations involved, it is not clear that the sealing effort in that house had a real effect at all.

Initial efforts reported here focused on closure of the wall/floor joint (and of the sump in House 32). Attempts to use flowable caulks on the wall/floor joint were not successful; the caulk either disappeared down the crack, or puddled on top of the slab, without closing the crack. The joint was thus closed using non-flowable, gun-grade polyurethane caulk (sometimes tooled, sometimes not). The concrete surfaces were wire-brushed, and special care was used in removing dust from the surfaces before applying the caulk. In House 49, a primer was used prior to final caulking. In both cases, the caulk bead appeared visually to be adhering well to both the slab and the wall.

The effectiveness of the closures was tested by taping sheets of plastic over segments of the caulked wall/floor joint, and over the sump in House 32, and by measuring radon under the sheets after 24 hours. Significantly elevated radon concentrations under the sheets indicated that radon was still entering through the closed joints. One hypothesis is that the radon might be bypassing the caulk bead, moving through the porous surface of the concrete ("laitance") near the base of the foundation wall. If this hypothesis is correct, and if a suitable primer will not close the laitance, then the reductions that can be achieved using the type of sealing effort that homeowners could reasonably perform themselves will be limited. In the case of House 49, the residual radon could also be partially due to hairline slab and wall cracks which have not yet been treated.

PRESSURIZATION VERSUS SUCTION IN SUB-SLAB VENTILATION SYSTEMS

Sub-slab ventilation systems have most commonly been operated with the fans drawing suction under the slab. Certain advantages would result (e.g., avoidance of a high-radon exhaust) if the fans could be operated instead to pressurize the sub-slab.

Table 8 presents the results in eight of the houses in this study where the sub-slab system was tested in both suction and pressure. As shown, in every case, pressurization was less effective than suction, sometimes substantially so.

It is believed that, for sub-slab pressurization to be effective, the system must create sufficient flows of air under the slab to dilute the radon in the sub-slab gas (which will be forced up into the house by the system). Establishing a pressure field is not sufficient by itself. As discussed previously, flows in the sub-slab systems in Dayton were sometimes unusually low, possibly explaining the lower effectiveness of pressurization.

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TABLE 1. SUMMARY OF HOUSES SELECTED FOR TESTING IN DAYTON

House No.	Foundation Wall	Pre-mitigation Alpha-Track Results (pCi/L) Basement	Living Area	Crawl Space
Objective 1 - Sub-slab/drain tile ventilation in basement houses				
4	Block	24.5	20.7	--
7	Concrete	10.1	9.5	--
32	Concrete	23.2	17.4 (1st) 17.6 (2nd)	--
43	Concrete	11.3 (1st) 8.0 (2nd)	6.3	--
45	Concrete	19.2	8.5	--
Objective 2 - Basement sub-slab ventilation in basement + slab-on-grade houses				
11	Concrete	28.9	17.3	--
21	Concrete	98.6	12.7	--
Objective 3 - Alternative methods in pure slab-on-grade houses				
1	Block	--	17.5 (Ktchn) 20.9 (BR)	--
15	Concrete	--	16.3 (BR)	--
31	Concrete	--	12.6 (Ktchn) 14.0 (BR)	--
47	Concrete	--	22.9 (Ktchn) 24.1 (BR)	--
Objective 4 - Alternative methods in pure crawl-space houses				
22	Block	--	15.0	25.6
24	Block	--	11.2	21.1
28	Concrete	--	13.4	20.7
33	Block	--	8.4	17.6
Objective 5 - Sealing alone in pure basement houses				
32	Concrete	23.2	17.4 (1st) 17.6 (2nd)	--
49	Concrete	4.8	4.0	--

1. Alpha-track detectors exposed during the period December 1987 through March 1988, prior to completion of mitigation systems. Detectors exposed in clusters of three; figures shown here are averages of the three. Replicate clusters denoted 1st, 2nd.

2. Living area is defined as: story above basement (basement houses); ground level (slab-on-grade houses); slab-on-grade portion of basement + slab houses; rooms above crawl space (crawl-space houses).

TABLE 2. RESULTS WITH SUB-SLAB SUCTION AND SUMP (DRAIN TILE) SUCTION IN BASEMENT HOUSES (OBJECTIVE 1)

House No.	Radon Concentrations in Basement (pCi/L)				% Reduction in Mean	Comments
	System Off		System On			
	Range	Mean	Range	Mean		
4	1-247	35.8	0-2	0.5	99	Sump suction; drain tile visible entering sump crock. Fan at reduced speed, draws 0.35 in. WC suction on sump, flow 126 ft^3/min out of sump.
7	1-29	10.9	1-6	2.6	76	One sub-slab suction pipe, approx. centrally located in basement slab (one pipe per 1150 ft^2 of slab area). Fan at high speed draws 1.4 in. WC, 4 ft^3/min.
32	12-37	27.0	0.5-2	1.2	96	Sump suction; two drain tiles enter sump, suggesting substantial loop. Fan at low speed, 0.3-0.5 in. WC suction, 123-162 ft^3/min.
43	7-25	14.3	0-1	0.5	96	One sub-slab suction pipe, located toward one end of basement (one pipe per 1850 ft^2). Fan at low speed draws 0.55 in. WC, 22 ft^3/min. Floor drain, connected to interior drain tile loop, trapped.
45	7-30	18.2	1-3	1.5	92	One sub-slab suction pipe, approx. centrally located (one pipe per 970 ft^2). Fan at low speed draws 0.55 in. WC, 91 ft^3/min. Floor drain, connected to drain tiles, trapped.

TABLE 3. RESULTS WITH BASEMENT SUB-SLAB SUCTION IN BASEMENT PLUS SLAB-ON-GRADE HOUSES (OBJECTIVE 2)

House No.	Average Radon Level in Basement (pCi/L)		Average Radon Level, Slab on Grade (pCi/L)		% Reduction		Comments
	System Off	System On	System Off	System On	Basement	Slab	
11	9.2	1.2	5.1	1.1	87	78	Two suction pipes centrally located in basement (one pipe per 450 ft^2 of basement, or per 900 ft^2 of basement plus slab). Fan at high speed draws 1.0 in. WC, 71 ft^3/min.
21	83.4	4.0	15.4	0.9	95	94	One suction pipe in one corner of basement (one pipe per 325 ft^2 of basement, or per 1200 ft^2 of basement + slab). Fan at high speed draws 1.1 in. WC, 12 ft^3/min.

Conversion factors: Bq/m^3 = 37 x value in pCi/L; L/sec = 0.47 x value in ft^3/min; Pascals = 248 x value in inches of water column (in. WC); m^2 = 0.093 x value in ft^2

TABLE 4. RESULTS WITH CENTRAL FURNACE FAN OPERATION AND SEALING IN SLAB-ON-GRADE HOUSES (OBJECTIVE 3)

House No.	Pre-mitigation Radon (pCi/L)		Central Fan Operation Radon (pCi/L)		Central Fan Operation	Sealing* Radon (pCi/L)		Sealing*	Central Fan + Sealing Radon (pCi/L)		Central Fan + Sealing
	Range	Mean	Range	Mean	% Reduction	Range	Mean	% Reduction	Range	Mean	% Reduction
1	14-32	20.2	15-27	21.2	(-5)	—	—	—	—	—	—
15	6-42	17.9	2- 8	4.6	74	1-21	9.1	49	0- 2	1.1	94
31	7-27	14.7	8-19	12.8	13	5-20	9.8	33	9-18	13.0	12
47	20-39	29.6	10-20	14.5	51	17-32	25.2	15	7-13	9.7	67

* Sealing consisted of closing the slab opening under the bathtub using foam. House 1 did not have an opening under the bathtub.

TABLE 5. RESULTS WITH SUB-SLAB SUCTION IN SLAB-ON-GRADE HOUSES (OBJECTIVE 3)

House No.	Radon Concentrations (pCi/L) System Off		Radon Concentrations (pCi/L) System On		% Reduction in Mean	Comments
	Range	Mean	Range	Mean		
1	14-32	20.2	0-3	1.3**	94	One sub-slab suction point, through foundation wall from outside, in middle of rear of house (one suction point per 2050 ft^2 of slab area). Continuous operation of central furnace fan increased levels to 10.6 pCi/L.
15	6-42	17.9	0-1	0.5	97	One sub-slab suction point, through wall from outside, at one end of house (one point per 975 ft^2). Fan on high speed draws 1.2 in. WC, 43 ft^3/min. Continuous operation of central furnace fan has no apparent effect on system's radon reduction performance.
31	7-27	14.7	0-2	0.8	95	One sub-slab suction point, through wall from outside, in middle of rear of house (one point per 1000 ft^2). Fan on high speed draws about 0.8 in. WC, 62 ft^3/min. Continuous operation of central furnace fan increased indoor radon levels to 3.1 pCi/L.
47	20-39	29.6	0-2	0.9	97	One sub-slab suction point, through wall from outside, at one end of house (one point per 1075 ft^2). Fan on high speed draws 1.2 in. WC, 69 ft^3/min. Continuous operation of central furnace fan has no apparent effect.

** Post-mitigation measurements made during mild weather. This could be improving apparent performance.

All measurements presented in Tables 4 and 5 were made in living area, on slab on grade.

TABLE 6. RESULTS WITH CRAWL SPACE VENTILATION IN CRAWL-SPACE HOUSES (OBJECTIVE 4)

House No.	Foundation Vents Closed (Pre-mitigation)		Foundation Vents Open (Natural Ventilation)				Forced-Air Exhaust			
	Mean Radon Level (pCi/L)		Mean Radon Level (pCi/L)		% Reduction		Mean Radon Level (pCi/L)		% Reduction	
	Living Area	Crawl Space	Living Area	Crawl Space	Living	Crawl	Living Area	Crawl Space	Living	Crawl
22	14.4	25.8	9.1	10.7	37	58	4.4	23.8	69	8
24	17.4	34.1	6.8	15.1	61	56	4.8	17.6	72	48
28	5.0	31.1	2.7	4.2	46	86	0.8	26.1	84	16
33	18.2	43.9	2.9	3.8	84	91	1.3	21.9	93	50

House 22 had 6 foundation vents; House 24 had 5 vents; House 28 had 7 vents; House 33 had 5 vents.

TABLE 7. RESULTS WITH SEALING IN BASEMENT HOUSES HAVING POURED CONCRETE FOUNDATION WALLS (OBJECTIVE 5)

House No.	Radon Concentration in Basement (pCi/L)				% Reduction in Mean	Comments
	Before Sealing		After Sealing			
	Range	Mean	Range	Mean		
32	12-37	27.0	3-18	10.2	62	Lucite cover sealed over sump. Entire wall/floor joint (1/32 to 3/16 in. wide) closed using non-tooled, gun-grade polyurethane caulk after wire-brushing, carefully cleaning surface. Seal around pipe penetrations through slab using flowable polyurethane caulk. One interior slab crack caulked; slab, walls otherwise had only minimal cracking.
49	3- 8	5.8	3- 7	4.4	24	Wall/floor joint (1/16 to 1/8 in. wide) closed using gun-grade polyurethane caulk with a primer, after wire-brushing and carefully cleaning surface. In some places, caulk was tooled. Significant number of hairline cracks in slab and walls were not treated.

Conversion factors: Bq/m^3 = 37 x value in pCi/L
mm = 25.4 x value in inches

TABLE 8. EFFECTS OF PRESSURIZATION VERSUS SUCTION IN ACTIVE SOIL VENTILATION SYSTEMS

House No.	House Substructure/ Mitigation System	Average Radon Concentration (pCi/L) Pre-mitigation	Post-mitigation Suction	Post-mitigation Pressure	% Reduction Suction	% Reduction Pressure
4	Basement/sump vent	35.8	0.5	1.7	99	95
7	Basement/sub-slab vent	10.9	2.2	5.8	80	47
11	Basement+slab/ basement sub-slab vent	18.7	3.5	9.1	81	51
15	Slab on grade/ sub-slab vent	17.9	0.4	1.8	98	90
31	Slab on grade/ sub-slab vent	14.7	0.4	4.3	97	71
32	Basement/sump vent	27.0	1.3	2.9	95	89
43	Basement/sub-slab vent	14.3	0.5	5.3	96	63
47	Slab on grade/ sub-slab vent	29.6	2.9	16.0	90	46

Note: The average post-mitigation radon concentrations shown in this table for the systems operating in suction, in some cases differ from the comparable values presented in earlier tables. The radon levels shown here for the systems in suction represent 48 to 98 hours of hourly Pylon readings in suction, taken just before or just after the system was tested under pressure, and under the same conditions as the pressure test. These levels are felt to provide the best back-to-back comparison of operation under suction versus pressure. However, the suction tests conducted in conjunction with the pressure testing are not always representative of the final system conditions (e.g., the fan speed might have been different). The radon concentrations shown in the earlier tables are those which best reflect the performance of the system in suction under final design and operating conditions.