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CAUSES OF ELEVATED POST-MITIGATION RADON CONCENTRATIONS IN BASEMENT HOUSES HAVING EXTREMELY HIGH PRE-MITIGATION LEVELS

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ABSTRACT

Forty basement houses in Pennsylvania which had received EPA-sponsored indoor radon mitigation systems in 1985-87 as part of an earlier project, were re-visited in 1989-90 to permit further testing. These houses had generally had very high pre-mitigation radon concentrations (commonly 50 to 600 pCi/L, or 2 to 22 kBq/m^3); a significant fraction still have residual (post-mitigation) levels greater than EPA's original guideline of 4 pCi/L (148 Bq/m^3), based upon alpha-track detector measurements. The objective of the follow-up testing was to assess why levels were still elevated, and what additional steps would be required in order for these houses to achieve both the original guideline of 4 pCi/L, and a more challenging goal of 2 pCi/L (74 Bq/m^3).

In houses having sub-slab and drain-tile depressurization systems, the primary single cause of elevated residual levels was re-entrainment of the high-radon fan exhaust; airborne radon resulting from radon in well water was an important secondary contributor in some houses. Care in design of the system exhaust, and treatment of the water, would be required to reduce these houses below 2 pCi/L. In only one house with a sub-slab system did the elevated residual levels clearly appear to be due to inadequate depressurization beneath the slab. However, in houses having block-wall depressurization systems, inadequate sub-slab depressurization appeared to be the major cause of the residual levels; exhaust re-entrainment and well-water radon also played a role in some houses with block-wall systems.

Elevated outdoor radon concentrations, and emanation of radon from poured concrete slabs and foundation walls, were not major contributors to the residual indoor concentrations, with each of these factors contributing on the order of 0.2 pCi/L (7 Bq/m^3).

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INTRODUCTION

During the period June 1985 through June 1987, developmental indoor radon reduction systems were installed and tested in a total of 40 houses in the Reading Prong region of eastern Pennsylvania (Reference 1). Most of these installations involved some form of active soil depressurization (ASD), including sub-slab depressurization (SSD), drain-tile depressurization (DTD), and block-wall depressurization (BWD). Other mitigation approaches tested in a few of the houses included active soil pressurization, heat recovery ventilators (HRVs), and radon removal from well water. All of the houses had basements, sometimes with an adjoining slab-on-grade or crawl-space wing. These houses were generally difficult to mitigate, for two primary reasons:

1) The source term was often extremely high, with soil gas concentrations as high as 50,000 pCi/L (1.8 MBq/m^3) measured in one case. As a result, pre-mitigation indoor concentrations were very high, commonly in the range of 50 to 600 pCi/L (about 2 to 22 kBq/m^3). The high source term requires careful treatment of all entry routes, and care in avoiding re-entrainment of ASD exhaust, among other considerations.

2) Communication beneath the basement slabs was sometimes poor or uneven, complicating the application of ASD systems.

The radon concentrations in the basements and living areas of these houses have been measured using alpha-track detectors (ATDs) with 3- to 4-month exposure periods, during each of the winter quarters since the mitigation systems were installed (References 1, 2, and 3). In addition, an annual ATD measurement in the living area was completed during the period December 1988-December 1989 (Reference 4). The average winter-quarter concentrations for each house, and the annual average living-area concentration, are presented in Table 1. As shown in the table, of the 38 houses still participating in the program, the average basement concentration over the past two or three winters has been above 4 pCi/L (148 Bq/m^3) in 18 of them, and above 2 pCi/L (74 Bq/m^3) in 28 of them. The average winter-time living area concentration has been above 4 pCi/L in 11 of the houses (about 30%), and above 2 pCi/L in 22 (about 60%). The annual average readings in the living area are somewhat more favorable than the winter-quarter results, with about one-quarter of the houses above 4 pCi/L and half above 2 pCi/L according to the annual measurement.

Thus, even though the percentage radon reductions were substantial in essentially all of these high-level houses, a significant number have residual (post-mitigation) radon levels greater than EPA's original guideline of 4 pCi/L. An even greater number have residual levels above 2 pCi/L, suggesting that there could be difficulty in achieving the goal of near-ambient indoor concentrations, specified in the Indoor Radon Abatement Act of 1988.

Accordingly, during the winter of 1989-90, additional testing was carried out in all of these difficult houses in order to better understand why residual radon levels were still elevated, and what additional steps would be necessary to reduce the indoor levels to near-ambient. Five possible explanations for the elevated residual levels were investigated:

1) failure of the suction fields generated by ASD systems to adequately extend beneath the slab and around the footings, thus leaving some soil gas entry routes inadequately treated;

2) re-entrainment of high-radon exhaust from the ASD systems back into the house;

3) release into the air of radon contained in well water;

4) contribution of ambient (outdoor) radon to indoor levels; and

5) emanation of radon from concrete slabs and foundation walls.

For mitigation approaches not involving ASD, another consideration is possible inherent limitations in the effectiveness of the mitigation approach.

RESULTS

Adequacy of Suction Fields Generated by ASD Systems

The first concern was that the suction fields being generated by the ASD systems might not be adequately extending beneath the slab, and might not adequately be preventing soil gas entry into block walls. In view of the extremely elevated soil gas concentrations at many of these houses, any untreated entry route could have a significant impact on indoor levels.

In each house having an ASD system, between 4 and 22 test holes were drilled through the basement slab and the slab of any adjoining wing, to permit measurements of sub-slab depressurization being created by the system. Usually, a test hole was drilled in each corner of the slab, with a series of additional holes drilled in that quadrant where the depressurization being created by the system appeared to be poorest based upon the results from the corner hole. Sub-slab pressure measurements were made with a micromanometer sensitive to ± 0.001 in. WG (± 0.2 Pa), with all test holes plugged except the one at which the measurement was being made. As a rule of thumb, it is estimated that the sub-slab depressurization at a given point should be at least 0.015 in. WG (about 4 Pa) in order to reliably prevent soil gas flow up through slab openings at that point. This value of 0.015 in. WG approximately equals the theoretical thermal stack depressurization created in the basement of a two-story house during cold weather. It is believed that a sub-slab depressurization of 0.015 in. WG will be overwhelmed only a small percentage of the time by weather effects and by homeowner activities. As an added safety margin, a depressurization of 0.04 in. WG (10 Pa), if maintained, should almost never be overwhelmed.

As a separate measurement of sub-slab communication, the sub-slab depressurizations at these test holes were also measured with the mitigation system off, with suction being generated by an industrial vacuum cleaner. Using a simple mathematical model, the results from these vacuum cleaner diagnostics were used to calculate a "Standard Suction Distance" (SD) for each slab. The SD is nominally the distance over which suction drawn through a 4-in. (10-cm) diameter SSD suction hole would fall to 1% of that being maintained under the slab immediately under the SSD pipe. One percent of the suction under the SSD pipe would typically be about 0.005 to 0.010 in. WG (about 1 to 2 Pa), of the magnitude of the 0.015 in. WG rule of thumb considered above. In general, a SD greater than 1,000 ft (about 300 m) is interpreted as very good communication, suggesting that one SSD suction pipe should easily treat the entire slab. A SD less than 10 ft (3 m) is interpreted as poor communication, indicating the need for multiple SSD pipes.

The results of these measurements are summarized in Table 2 for those houses having ASD systems. As shown, almost all houses having SSD systems have sub-slab depressurizations at all test holes greater than 0.015 in. WG, sometimes by an order of magnitude. In many of the SSD houses, most or all of the sub-slab readings are above the more conservative value of 0.04 in. WG. Of the houses with SSD systems having residual radon levels greater than 2 pCi/L, in only one case -- House 39 -- does the elevated level appear to be due to inadequate distribution of a suction field under the slab by the system. It is noted that effective sub-slab depressurizations are generally being maintained even in houses where the SD is less than 10 ft. This is due to the fact that most of the SSD systems were conservatively designed with multiple suction pipes (usually between three and seven). However, even this number of SSD pipes should be insufficient in the poorest-communication houses, if the SD were in fact an accurate predictor of the distance over which a single pipe can provide treatment. The SD consistently over-predicts the number of SSD pipes actually required.

ASD systems other than SSD are less effective at depressurizing the sub-slab. Of the five houses (Houses 10, 12, 15, 26, and 27) having exterior DTD systems (i.e., drain tiles outside the footings), three houses have at least one sub-slab reading below 0.015 in. WG. Understandably, the suction being developed around the exterior of the footings is impeded in extending into the sub-slab region. However, all three of the houses with at least one marginal depressurization measurement are below 4 pCi/L, and two are below 2 pCi/L. Thus, it would not appear that inadequate suction field extension is responsible for elevated residual levels in the houses with DTD systems. Testing to be described later tends to confirm that the residual radon in these houses is indeed due to factors other than inadequate sub-slab depressurization. Exterior DTD systems probably function primarily by diverting soil gas away from the footings (preventing entry into the block walls), and perhaps by intercepting the gas before it reaches the immediate sub-slab region; thus, maintenance of high depressurizations immediately under the entire slab might not be necessary for successful performance.

Sub-slab measurements were permitted in five of the houses (Houses 3, 8, 14, 16, and 20) having BWD systems, or systems with a significant BWD component. All five of these houses have multiple readings below 0.015 in. WG (although it is noteworthy that the BWD systems do produce some depressurization of the sub-slab). It is likely that the marginal sub-slab depressurizations in the BWD houses are partly responsible for the elevated residual radon levels in many of these houses. However, inadequate depressurization of the sub-slab is not the only problem. Other testing in some of the BWD houses demonstrated that good depressurization of the sub-slab by an SSD system in those houses was not sufficient, by itself, to provide the desired radon reductions. Thus, part of the problem with the BWD systems (and with the SSD systems that were also tested in some of these houses) is that they were not adequately treating the block walls.

In summary, inadequate depressurization of the sub-slab appears to be largely or partly responsible for the elevated residual levels in SSD House 39, and at least partially responsible in the BWD houses. However, it is not generally responsible for the significant number of still-elevated houses having SSD and DTD systems.

Re-Entrainment of ASD Fan Exhaust

Measurements in the ASD exhaust piping indicated radon concentrations ranging from 10 to 27,000 pCi/L (0.37 to 1,000 kBq/m^3) in the exhaust. Many of the SSD systems had exhaust concentrations exceeding 1,000 to 2,000 pCi/L (37 to 74 kBq/m^3). At these levels, re-entrainment of even a fraction of 1% of the exhaust back into the house could create indoor concentrations exceeding 4 pCi/L.

Based upon the flow rate and radon concentration of the exhaust, and upon the volume and estimated natural ventilation rate of the house, a calculation was made of the indoor radon concentration that would result if only 0.1% (i.e., one one-thousandth) of the exhaust was re-entrained. The calculations indicated that 0.1% re-entrainment would cause an incremental increase of more than 1 pCi/L (37 Bq/m^3) in nine of the houses, and of more than 0.5 pCi/L (18 Bq/m^3) in 14 of them, all having SSD or DTD systems. Most of these "top 14" houses had winter-quarter ATD measurements exceeding 4 pCi/L, suggesting a possible correlation between re-entrainment and elevated residual radon levels.

The majority of these ASD installations have the exhaust fan mounted outside the house at grade level, exhausting straight upward immediately beside the house. This exhaust configuration is conducive to re-entrainment.

Two types of testing were conducted to quantify the effects of re-entrainment on residual indoor levels in these houses. In the first approach, 9 houses from among the top 14 were selected to have their exhaust configurations modified, with Pylon measurements in the house to evaluate the effects of the exhaust modifications on indoor radon. In the second approach, five of the houses were selected for perfluorocarbon tracer (PFT) gas measurements.

The results of the exhaust modification testing are summarized in Table 3. For each house, the alternative exhaust configurations that were tested are listed, along with resulting radon concentrations that were measured in the basement and/or living area. Each radon result is the average of 2 to 4 days of hourly radon measurements with a Pylon continuous radon monitor. As shown, of the nine houses, the exhaust modifications: reduced three of the houses below 2 pCi/L (Houses 22, 25, and 34); reduced another two below 4 but not below 2 pCi/L (Houses 7 and 27); and failed to reduce the other four houses below 4 pCi/L on at least one story (Houses 10, 13, 20, and 24).

From Table 3, horizontal-at-grade exhausts, directed 90° away from the house, were modified to become vertical-above-the-eave exhausts in two houses (Houses 20 and 24). In both houses, there appeared to be no significant reduction in re-entrainment by converting to the above-eave configuration. In the one other house originally having a horizontal exhaust directed 90° away from the house (House 34), indoor levels were fairly low to begin with (2.4 pCi/L, or 89 Bq/m^3) despite the extremely high concentrations in the exhaust (8,000 pCi/L, or 296 kBq/m^3). Extension of the exhaust piping 15 ft (about 5 m) away from the house was required to achieve a significant additional reduction in indoor levels. Thus, horizontal exhaust at grade might be as acceptable as the above-the-eave method of exhausting ASD systems, especially when radon concentrations in the exhaust are not very high, as long as the horizontal exhaust is directed 90° away from the house. However, from the other results in Table 3, it would never appear appropriate to exhaust horizontally at grade parallel to the house (or at an angle significantly less than 90°), nor would it ever appear appropriate to exhaust vertically at grade immediately beside the house.

The actual reductions in indoor radon concentrations achieved by these exhaust modifications, shown in Table 3, were compared against the calculated increase that 0.1% re-entrainment should contribute to indoor levels, discussed earlier. This comparison should suggest the degree of re-entrainment that was eliminated by re-directing the exhaust. In all cases except House 22, the measured reductions in indoor levels suggested that re-entrainment was reduced on the order of 0.1%. In House 22, the reduction was about 2%, consistent with the high re-entrainment that might have been expected based upon the original exhaust configuration in this house (horizontal at grade parallel to the house, underneath an overhung bay window).

In view of the residual radon levels following the modifications to the system exhausts, it is doubtful that the modifications eliminated all re-entrainment in any of the houses. Rather, re-entrainment was simply reduced to some lesser value.

In an effort to obtain a more quantitative measure of the actual re-entrainment with the different exhaust configurations, PFT tracer gas measurements were made in five of these houses. In each case, one specific PFT gas ("lime") was released into the ASD exhaust piping. To quantify house ventilation rates, "red" PFT was released into the house upstairs, and "gold" PFT was released into the basement. PFT detectors were deployed on both levels. From these results, it should have been possible to quantify the amount of re-entrainment on both stories of the house.

The results from the PFT testing are summarized in Table 4. Unfortunately, some of the detectors were lost during shipment to the analytical laboratory, so that results for some of the exhaust configurations in some of the houses are missing. Table 4 compares basement radon concentration that would be predicted based upon the PFT results, with the actual measured concentration for the particular exhaust configuration, from Table 3. As shown, the PFT-predicted basement levels are always significantly greater that the levels actually measured, suggesting some problem with the technique by which the tracers were used in this study, and preventing any meaningful interpretation of the results.

Contribution of Well Water to Airborne Radon

All but five of the study houses in this project are served by private wells. The radon concentrations in the well water ranges between 530 and 266,000 pCi/L (20 and 9,800 kBq/m^3) from house to house. Much of this waterborne radon is released into the indoor air when water is used in the house.

The widely used rule of thumb -- based upon typical water usage rates, house volumes, and house ventilation rates -- is that 10,000 pCi/L (370 kBq/m^3) of radon in well water will contribute approximately 1 pCi/L (37 Bq/m^3) to the airborne concentration, on the average over time. Using this rule of thumb, the well water in these houses could be contributing between <0.1 and 7.5 pCi/L (<4 and 278 Bq/m^3) to the airborne concentrations (excluding the one house originally having 266,000 pCi/L, which has since been provided with a water treatment unit). Eleven of these houses could have a water contribution to the air levels greater than 1 pCi/L.

To confirm the practical accuracy of this rule of thumb, "temporary" granular activated charcoal (GAC) units were installed to remove the radon from the water in four houses where the water could be contributing more than 1 pCi/L to the air concentrations. To determine the effect of water treatment, radon measurements were made in the basement and upstairs using Pylon monitors, over 2-week periods both immediately before, and immediately after, the GAC units began treating the water.

The "temporary" GAC units consisted of a standard fiberglass water-softener cylinder filled with 0.2 ft^3 (6 L) of charcoal. These units were being marketed locally for organics removal; they were not specifically designed for radon removal, and thus could be subject to a deterioration in radon removal performance over time. However, water radon measurements indicated that these units were providing high radon removals (94 to 99.6%) for the relatively short duration of the current study.

The effects of the GAC units on airborne radon concentrations are summarized in Table 5. The table includes not only the current results for the four houses tested here, but also the results from two permanent GAC units installed and tested in two other houses in 1986, during the original project.

In four of the six houses in Table 5 (Houses 10, 23, 30, and 34) the ratio of the water radon to its apparent airborne contribution ranges between 7,900:1 and 12,800:1; i.e., within about ± 25% of the 10,000:1 rule of thumb. Thus, this rule of thumb generally appears to be a rough but reasonable predictor of water effects. The expected role of waterborne radon in contributing to the residual airborne levels in these houses is thus confirmed. Except perhaps for House 23, none of these houses could be reduced below 2 pCi/L (74 Bq/m^3) without permanent water treatment.

House 20 is the one house with reliable data where the observed ratio differs from the 10,000:1 rule of thumb by greater than ± 25%. In this house, the apparent actual contribution of waterborne radon (3.1 pCi/L, or 115 Bq/m^3) is only about half of the 7 pCi/L (259 Bq/m^3) that would have been predicted. It is not clear why this should have been the case. The owners have small children, and operate the washing machine frequently; thus, lower-than-usual water usage is not the explanation. The house is somewhat larger than average (about 2,600 ft^2, or 240 m^2), but not sufficiently to explain the significant deviation from the rule of thumb. A higher-than-average natural ventilation rate of the house would also help explain the elevated ratio; it is not known what the ventilation rate of this house is. A reduced fraction of radon released from the water upon use in the house would also help explain this ratio, but there is no reason to expect the release rate from the water to be unusually low.

The apparent ratio in House 2 would also appear to be dramatically different from the 10,000:1 rule of thumb. However, the results from House 2 are so uncertain, for the reasons indicated in the table, that these results are not felt to be meaningful.

Contribution of Outdoor Levels to Indoor Radon

In view of the highly elevated soil gas radon concentrations in some locations, it was considered that higher-than-average ambient (outdoor) radon concentrations could possibly be contributing to the elevated residual indoor levels.

To assess the extent of this contribution, measurements of outdoor concentrations were made near seven of the study houses distributed around the study area. Three alpha-track detectors, shielded by weather-protection cups, were hung from trees near the houses (but well away from the ASD exhausts). The detectors were deployed in December 1989 and returned to the laboratory for analysis in February 1990, after 3 months' exposure. The measured concentrations over this exposure period at the seven sites ranged from 0.0 to 0.8 pCi/L (0 to 30 Bq/m^3). Excluding the one site (near Oley, PA) giving the 0.8 pCi/L, the other six sites averaged 0.2 pCi/L (7 Bq/m^3), definitely no higher than the national average.

Accordingly, it would appear that the ambient levels are not contributing unduly to the indoor concentrations.

Radon Emanation from Building Materials

It was not anticipated that building materials were generally a major contributor to indoor radon. Gamma measurements in all of the houses had shown indoor readings (5 to 13 μR/hr, or 13 to 34 x 10^{-10} C/kg air/hr) somewhat lower than the outdoor readings (averaging between 5 and 20 μR/hr, or between 13 and 52 x 10^{-10} C/kg/hr). On this basis, it would be expected that the concrete slabs and foundation walls did not contain unusually elevated radium concentrations, and should not be contributing an amount of indoor radon significantly greater than might be expected in other parts of the country.

Typical concretes contain roughly 1 pCi of radium per gram of concrete. This radium content will commonly result in an emanation of 10 to 40 pCi of $radon/hr/ft^2$ (4 to 16 $Bq/hr/m^2$). Depending upon the house ventilation rate, and whether the basement has poured concrete foundation walls, this typical emanation could contribute approximately 0.25 pCi/L (approximately 10 Bq/m^3) to indoor levels.

As a more quantitative estimate of the emanation from the concretes of these houses, a flux test was conducted on the slab and concrete foundation wall of Houses 33 and 34 under the current project. Inverted stainless steel bowls having a volume of 0.2 ft^3 (6 L) were sealed over the slab and wall, and the increase in radon concentration was measured inside the bowls after 1 hour. For the dimensions of these bowls, an increase of 1 pCi/L/hr (37 $Bq/m^3/hr$) inside the bowl would correspond to a radon emanation rate of 8 $pCi/hr/ft^2$ (3.2 $Bq/hr/m^2$). The changes in radon concentration in the bowl over 1 hour during this testing were small, in the range of 1 pCi/L, indicating approximate emanation rates of 2.3 $pCi/hr/ft^2$ (1 $Bq/hr/m^2$) from the slab, and 12 $pCi/hr/ft^2$ (5 $Bq/hr/m^2$) from the walls in House 33. In House 34, emanation from the slab was comparable to House 33, and emanation from the walls was slightly higher (28 pCi/hr/ft^2, or 12 Bq/hr/m^2). Because of the short duration of the test and the small concentration increases/low emanation rates, the uncertainties in these emanation rates are large, about ± 10 pCi/hr/ft^2 (± 4 Bq/hr/m^2). However, it is clear that the emanation rates are not elevated compared to rates from slabs in other parts of the country. In both houses, the emanation rates would suggest that the concrete is contributing less than 0.2 pCi/L (7 Bq/m^3) to the indoor concentrations.

In conclusion, it would appear that building materials are not a significant contributor to the residual indoor radon concentrations in these houses.

Inherent Limitations of Certain Mitigation Approaches

In several of the houses not having ASD systems, the failure of the house to have been reduced below 2 pCi/L (74 Bq/m^3) is felt to be the result of inherent limitations in the effectiveness of the selected mitigation approaches.

All three of the houses having block-wall pressurization systems (Houses 2, 5, and 9) have basement and living-area ATD results greater than 4 pCi/L (148 Bq/m^3). These results suggest an inherent problem of wall pressurization systems in establishing an effective pressure/flow field to prevent soil gas entry into the block cores, or through slab cracks.

Two of the three houses having HRVs have residual concentrations of greater than 4 pCi/L on at least one story (Houses 17 and 18); the third HRV house (House 28) is above 2 pCi/L. These results reflect the fact that ventilation techniques such as HRVs are inherently limited to achieving no greater than moderate (50 to 75%) radon reductions.

The one house being treated solely with a GAC well water removal unit (House 30) is still above 2 pCi/L. This result simply reflects that, while water treatment can be very effective at reducing the waterborne source of radon, it cannot address soil-gas-related entry mechanisms.

CONCLUSIONS

Based upon the testing and assessment conducted during the 1989-90 measurements in the Pennsylvania study houses, it is believed that we now understand the reasons for the residual radon concentrations in all of the houses having residual levels greater than 2 pCi/L (74 Bq/m^3). These reasons are summarized in Table 6.

For SSD and DTD systems, the primary single cause of residual elevated levels is re-entrainment of high-radon fan exhaust, followed in some houses by airborne radon resulting from well water. Care in the design of the exhaust, and treatment of the water, would be required to reduce these houses below 2 pCi/L. In only one house with a SSD system did the elevated residual levels clearly appear to be due to inadequate depressurization beneath the slab.

For BWD systems, inadequate depressurization beneath the slab by the BWD system is probably the major contributor. Re-entrainment and well-water contributions are probably also playing some role in some of the houses.

For other than ASD systems, inherent limitations in the systems are commonly the primary single cause of the elevated residual levels.

Elevated outdoor radon concentrations, and radon emanation from the poured concrete slabs and foundation walls (where present), do not appear to be significant contributors to the elevated residual indoor levels. These factors apparently contribute on the order of 0.2 pCi/L (7 Bq/m^3) each to the indoor concentrations.

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TABLE 1. SUMMARY OF POST-MITIGATION ALPHA-TRACK DETECTOR RESULTS FROM PENNSYLVANIA STUDY HOUSES

House No.	Mitigation System[1]	Pre-Mitigation Radon (pCi/L)[2,3]	Post-Mitigation Radon (pCi/L)		
			Winter-Quarter Averages[4]		Annual Average
			Basement	Living Area	(Living Area)
2	Wall press.	413	4.3	6.9	[5]
3	BWD + SSD	350	3.3	2.1	1.8
4	SSD	25	1.0	0.9	0.5
5	Wall press.	110	4.8	4.4	4.0
6	SSD	60	3.5	3.6	2.3
7	SSD	402	4.5	3.3	[5]
8	BWD	183	3.4	1.4	1.1
9	Wall press.	533	11.5	14.8	[5]
10	DTD	626	11.5	8.4	12.1
12	DTD	11	2.5	2.3	1.3
13	SSD + DTD	64	2.5	2.9	[5]
14	BWD	36	0.8	1.0	[5]
15	DTD	18	1.2	1.2	0.9
16	BWD	395	5.3	1.8	1.5
17	HRV	9	8.1	5.1	2.7
18	HRV	12	11.7	3.5	3.6
19	BWD	32	31.3	0.7	[5]
20	SSD + BWD + DTD	210	6.9	9.7	10.0
21	SSD	172	2.3	2.7	3.7
22	SSD	24	9.0	3.8	[5]
23	SSD	98	2.5	1.6	1.6
24	SSD	66	4.1	4.0	3.2
25	SSD	122	6.8	4.8	6.4
26	DTD	89	1.3	1.4	1.0
27	DTD	21	4.5	2.2	3.9
28	HRV	21	3.6	4.9	3.6
29	DTD + SLD	61	1.9	1.9	3.0
30	Water	17	3.6	1.7	1.9
31	SSD	485	2.3	7.0	[5]
32	SSD	6	0.9	3.6	4.0
33	SSD	82	5.6	1.0	0.6
34	SSD	470	5.3	4.9	5.8
35	SSD	144	1.4	0.9	0.7
36	SSD	300	1.2	0.8	0.7
37	SSD	87	0.9	1.0	0.9
38	SSD	309	7.8	7.2	6.6
39	SSD	111	7.5	1.8	4.1
40	SSD	148	1.9	1.2	[5]

Footnotes for Table 1

[1] SSD = sub-slab depressurization; DTD = drain-tile depressurization; BWD = block-wall depressurization; SLD = sub-liner depressurization (crawl spaces); HRV = heat recovery ventilator; wall press. = block-wall pressurization.

[2] 1 pCi/L = 37 Bq/m^3

[3] Pre-mitigation measurements were usually made in the basement by the Pennsylvania Department of Environmental Resources using ATDs, prior to the mitigation project.

Each reported radon value is the average of winter-quarter ATD measurements, usually for two or three winters.

[5] Annual average ATD measurement was not successfully completed in this house, usually because system was turned off, or was not fully operational, during part of the measurement period.

TABLE 2. SUB-SLAB DEPRESSURIZATIONS CREATED BY MITIGATION SYSTEMS (HOUSES WITH ASD SYSTEMS ONLY)

House No.	Mitigation System	No. of SSD Pipes	Range of Sub-Slab Depressurizations Created by System (in. WG)[1,2]	Range of SD (ft)[1,3]
3	BWD + SSD	1[4]	0.004-0.012	1,600 to >30,000
4	SSD	6	0.008-0.234	0.3 to 6
6	SSD	3	0.129-0.194	2 to 45
7	SSD	7	0.093-0.375	90 to >30,000
8	BWD	0[4]	0.004-0.007	3,900 to >30,000
10	DTD	0[5]	0.056-0.085	>30,000
12	DTD	0[5]	0.014-0.018	8,800 to >30,000
13	SSD + DTD	4	0.109-0.605	3 to >30,000
14	BWD	0[4]	0.006-0.012	110 to >30,000
15	DTD	0[5]	0.014-0.072	1 to 580
16	BWD	0[4]	0.001-0.006	3,300 to >30,000
19	BWD	0[4]	Owner did not permit measurements.	
20	SSD + BWD + DTD	5[4]	0.008-0.202	1 to 25
21	SSD	1	0.117-0.169	>30,000
22	SSD	4	0.322-0.399	170 to 2,200
23	SSD	4	0.669-0.706	45 to >30,000
24	SSD	3	0.847-1.109	75 to 190
25	SSD	4	0.020-0.274	6 to 270
26	DTD	0[5]	Pos.-0.008	2 to 990
27	DTD	0[5]	0.056-0.081	>10,000
29	DTD + SLD	0[5]	0.625-0.685	>30,000
31	SSD	6	0.113-0.738	5 to 380
32	SSD	7	0.282-0.706	2 to 4
33	SSD	1	0.322-0.637	6,100 to >30,000
34	SSD	6	0.685-1.391	1 to 40
35	SSD	4	0.014-0.171	1 to 30
36	SSD	5	0.056-0.181	80 to >30,000
37	SSD	6	0.968-1.012	>30,000
38	SSD	2	0.044-0.258	45 to >30,000
39	SSD	3	0.001-0.102	0.7 to 2
40	SSD	20	0.001-0.256	1 to 3

Footnotes for Table 2

[1] The range of depressurizations and 1% suction distances (SDs) reflect the range of results from the different test holes.

[2] 1 in. WG = 248 Pa

[3] 1 ft = 0.30 m

[4] House has a block-wall depressurization system only, or a SSD system with a major BWD component; thus, depressurization beneath the slab will be low in comparison with typical SSD systems.

[5] House has a drain-tile depressurization system. In all cases except House 29, the drain tiles are outside the footings; thus, sub-slab depressurizations will be low in comparison with typical SSD systems.

TABLE 3. PYLON RESULTS FROM MODIFICATION OF ASD EXHAUST CONFIGURATIONS

House No.	Radon in Exhaust (pCi/L)	Exhaust Configuration	Average Pylon Result (pCi/L)	
			Basement	Living
7	3,500	1. Vertical at grade, immediately beside house (original configuration).	5.2	--
		2. Stack extended up to eaves; elbow directs exhaust horizontally, 90° away from house, at eave level.	4.9	--
		3. As in 2 above, except stack ends vertically above eaves.	2.1	--
10	2,300	1. Vertical at grade, immediately beside house (original config.) Incl. water treatment.	9.4	5.8
		2. Elbow on fan outlet directs exhaust horizontally at grade level, at a 20° angle away from house (i.e., almost parallel). Water treatment.	2.1	10.8
13	580	1. DTD fan exhausting vertically at grade (original configuration). SSD system off.	7.3	--
		2. Elbow on DTD fan outlet directs exhaust horizontally at grade level, at 60° angle away from house, toward corner of house. SSD off.	15.6	--
20	2,200	1. Horizontal at grade, directed 90° away from house (original config.). Incl. water treatment.	4.6	~5-10
		2. Stack extended up outside house, vertical discharge above eaves. Incl. water treatment.	--	5.2
22	1,550	1. Vertical at grade, immediately beside house (original configuration).	14.5	--
		2. Elbow on fan outlet directs exhaust horizontally at grade level, 90° away from house; hose on horizontal outlet of elbow leads exhaust 10 ft away from house.	1.6	--

(continued)

TABLE 3 (continued)

House No.	Radon in Exhaust (pCi/L)	Exhaust Configuration	Average Pylon Result (pCi/L)	
			Basement	Living
24	2,000	1. Horizontal at grade, directed 90° away from house (original configuration). (Fan reduced.)	5.4	--
		2. Stack extended up outside house, vertical discharge above eaves. (Fan reduced.)	4.9	--
25	1,200	1. Horizontal at grade, parallel to house, under deck (original configuration).	4.6	--
		2. Horizontal at grade, directed 90° away from house, with exhaust pipe extending 10 ft away from house (to end of deck).	0.5	--
27	650	1. Vertical at grade, immediately beside side of house (original configuration).	6.9	--
		2. Horizontal at grade, directed 90° away from rear of house, with exhaust pipe extending 4 ft away from rear of house (under deck stairs).	2.7	--
		3. Stack extended up outside of house, vertical discharge above eaves.	2.4	--
34	8,000	1. Horizontal at grade, directed 90° away from rear of house by sliding glass door (original configuration). (Temporary well water treatment system also operating.)	2.4	3.4
		2. Horizontal at grade; 90° elbow on fan outlet directs exhaust parallel to rear of house, with a 14-ft length of pipe directing the exhaust to the corner of the house, where it is discharged parallel to the rear but 90° away from the side of the house. (Temporary water treatment system operating.)	3.5	--
		3. As in 2 above, except horizontal exhaust piping extended an additional 15 ft, diagonally away from the corner of the house. (Water treated.)	1.4	--

TABLE 4. PREDICTED INDOOR RADON CONCENTRATIONS BASED UPON PFT RESULTS, COMPARED WITH MEASURED RADON LEVELS

House No.	Exhaust Configuration[1]	Bsmt Tracer Ratio[2] ($x\ 10^{7}$)	Radon Release[3] (pCi/hr) ($x\ 10^{-7}$)	Expected Basement Radon Conc. from Re-Entrainment (Based Upon PFT Results)[4] (pCi/L)	Radon Measured in Bsmt[5] (pCi/L)
10	2. Horizontal at grade	0.4	45	18	2.1
22	2. Horizontal at grade	1.1	20	22	1.6
23	Vertical above eaves	0.9	32	29	0.9
24	1. Horizontal at grade	6.5	12	78	5.4
25	1. Horizontal at grade, parallel to house	1.5	27	40	4.6
34	1. Horizontal at grade, directed 90° away	1.3	39	51	2.4
	2. Horizontal at grade, extended to corner	1.9	39	74	3.5
	3. As in 2 above, extended 15 ft	1.0	39	39	1.4
38	Horizontal at grade	1.4	24	34	5.1

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[1] Configuration numbers shown here are identified in Table 3.

[2] The ratio of (Lime PFT concentration in basement, in PFT units/L):(Lime release rate in ASD exhaust, in PFT units/hr).

[3] The rate of radon release from the ASD exhaust, in pCi/hr, determined from the exhaust flow rates and radon concentrations.

[4] The predicted basement radon concentration, based upon PFT measurements, is calculated by multiplying the radon release rate times the PFT tracer ratio, (basement PFT concentration)/(PFT exhaust rate from ASD system).

[5] The measured basement radon concentration listed here is generally the average of the 4-day Pylon measurement made during, or just before, the PFT measurements.

TABLE 5. EFFECT OF WATER TREATMENT UNITS ON AIRBORNE RADON LEVELS

		Water	Airborne Radon (pCi/L)			
House No.	Story	Radon[1] (pCi/L)	Without Water Treatment	With Water Treatment	Reduction	Water Radon: Airborne Reduction[2]
Current Testing						
10	Upstairs	26,200	7.4	4.1	3.3	7,900:1
10	Basement[3]	26,200	10.1	7.1	3.0	8,700:1
20	Basement[3]	69,900	8.2	5.1	3.1	22,500:1
23	Basement[3]	11,500	1.7	0.8	0.9	12,800:1
34	Upstairs[3]	26,800	5.4	2.8	2.6	10,300:1
Prior Testing (Reference 1)[4]						
2	Basement[3]	53,200	2.8[5]	2.2	0.6	Questionable[5]
30	Basement[3]	206,000	29.1	5.2	23.9	8,600:1

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[1] For houses tested under current project, the water concentrations shown here are the averages of two pre-treatment measurements, made in December 1989 and January 1990. For the houses tested under the original project (Houses 2 and 30), the values shown are the average of the original 1985-86 analyses and of several analyses made during the period August 1986 through March 1987, since these were made closer to the time that the airborne radon measurements were made with the GAC on and off.

[2] The ratio of the water radon concentration to the reduction in airborne levels achieved by operating the GAC system, which should approximately equal the contribution of waterborne radon to the airborne levels. For comparison against the 10,000:1 rule of thumb.

[3] Washing machine is on this story.

[4] The measured effects of the GAC units on airborne radon are thought to be much less accurate in the prior testing, since the GAC on/off measurements were not made back-to-back in the earlier testing, and the measurements under "GAC on" and "GAC off" conditions were shorter than the 7 days used in the current project.

[5] Results from House 2 very uncertain because: Pylon measurement with GAC off far too short (only 20 hours in duration); possible basement ventilation by owner during measurement period makes results uncertain.

TABLE 6. APPARENT REASONS WHY STUDY HOUSES ARE STILL ABOVE 2 pCi/L

House No.	Mitigation System	Pre-Mitigation Radon (pCi/L)[1]	Post-Mitigation Radon (pCi/L)[2]	Reasons for Elevated Residual Radon
Houses greater than 4 pCi/L				
2	Wall press.	413	4.3	System limitations; water.
5	Wall press.	110	4.8	System limitations.
7	SSD	402	4.5	Re-entrainment.
9	Wall press.	533	11.5	System limitations; water.
10	DTD	626	11.5	Re-entrainment; water.
16	BWD	395	5.3	Inadequate sub-slab depressurization.
17	HRV	9	8.1	System limitations.
18	HRV	12	11.7	System limitations.
19	BWD	32	31.3	Inadequate sub-slab depressurization.
20	SSD+BWD +DTD	210	6.9	Water; perhaps re-entrainment; marginal sub-slab depress.
22	SSD	24	9.0	Re-entrainment.
24	SSD	66	4.1	Re-entrainment.
25	SSD	122	6.8	Re-entrainment.
27	DTD	21	4.5	Re-entrainment.
33	SSD	82	5.6	Unsealed entry route.
34	SSD	470	5.3	Re-entrainment; water.
38	SSD	309	7.8	Probably re-entrainment; water.
39	SSD	111	7.5	Inadequate sub-slab depressurization.
Houses between 2 and 4 pCi/L				
3	BWD+SSD	350	3.3	Inadequate sub-slab depressurization.
6	SSD	60	3.5	Probably re-entrainment; water.
8	BWD	183	3.4	Inadequate sub-slab depressurization.
12	DTD	11	2.5	Marginal sub-slab depressurization; probably re-entrainment; water.
13	SSD+DTD	64	2.5	Re-entrainment.
21	SSD	172	2.3	Probably re-entrainment.
23	SSD	98	2.5	Water; perhaps re-entrainment.
28	HRV	21	3.4	System limitations.
30	Water	17	3.6	System limitations.
31	SSD	485	2.3	Probably re-entrainment; water.

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[1] 1 pCi/L = 37 Bq/m^3

[2] Post-mitigation radon level is average of two or three winter-quarter ATD measurements in the basement.