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Radon Reduction Methods

EVALUATION OF SUB-SLAB VENTILATION FOR INDOOR RADON REDUCTION IN SLAB-ON-GRADE HOUSES

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ABSTRACT

Sub-slab ventilation (SSV) radon reduction systems were tested in nine slab-on-grade houses around Dayton, Ohio. The testing addressed the following house design/construction variables: slab size; foundation wall material of construction; presence or absence of sub-slab forced-air supply ducts; and presence of sunken living rooms as an obstruction and soil gas entry route in the slab interior. SSV design/operating variables addressed include: placement of the ventilation pipes inside or outside the house; location and number of vent pipes; SSV fan capacity; and operation of the SSV system in suction vs. in pressure. The results suggest that large slabs, block foundation walls, and sub-slab ducts can sometimes necessitate additional care in SSV design (number, location of vent points), but that, in general, radon levels can be reduced to 2 pCi/L or less with one or two points if there is a good aggregate layer under the slab. SSV from inside and outside the house give generally comparable performance, although in some cases interior might be preferable for large houses. Increasing the number of suction pipes from one to two, and increasing fan capacity from half to full speed, generally (but not always) appear to improve SSV performance. Only in the case of one large house with sub-slab ducts were two pipes required to reduce levels below 4 pCi/L. Low fan speed was generally sufficient to reduce levels below 4 pCi/L. Operation of SSV systems in pressure never gave better reductions than did operation in suction. Results from testing of slab-on-grade houses in Florida indicate that SSV systems generally require more suction pipes than were found necessary in Ohio, when the sub-slab material has poor permeability.

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

Much of the previous testing of residential radon reduction techniques has focused on houses having basements, including basements with adjoining slab-on-grade or crawl-space wings. Testing has been more limited in houses having solely a slab-on-grade substructure. Slab-on-grade houses offer various design and construction features which could impact the installation and performance of traditional sub-slab depressurization systems, and which, in some cases, might offer potential for application of alternative radon reduction techniques beyond sub-slab systems.

Previous reports (1,2) presented results from initial (Phase 1) testing of indoor radon reduction methods in four slab-on-grade houses in Dayton, Ohio. This paper expands those previous results to include further testing and data analysis for those four Phase 1 houses, plus testing on five additional slab-on-grade houses as part of a Phase 2 effort in the Dayton area. To provide additional perspective on this substructure type, recent results are also summarized from testing in 1 slab-on-grade house in Maryland, and in 14 slab-on-grade houses in Florida (3).

A number of house design and construction variables can impact the design and performance of radon reduction systems in slab-on-grade houses. The house design/construction variables addressed in the Ohio study include: slab size; nature of the foundation stem wall (hollow-block vs. poured concrete); presence or absence of forced air heating supply ducts underneath the slab; the presence or absence of interior slab openings/soil gas entry routes, such as plumbing openings under bathtubs; and sub-slab obstructions, such as sunken living rooms. Among other house variables that could be significant but that are not specifically addressed by the study in Ohio are: absence of aggregate underneath the slab (all of the Ohio houses had a good aggregate layer); nature of the interface between the floor slab and the foundation; sub-slab obstructions other than sunken living rooms (e.g., interior grade beams); and the impact if the forced-air ducts under the slab are return ducts (at negative pressure) rather than supply ducts (positive pressure). Some of these other variables are being addressed in testing underway or planned in slab-on-grade houses in Florida and New Mexico.

The characteristics of the native soil underlying the house can also be important, especially if there is no aggregate underneath the slab. All nine of the slab-on-grade houses in Ohio (and the one house in Maryland) were underlain by clay soil, with a layer of aggregate between the clay and the bottom of the slab. The Florida houses were on top of fine, moist sand with no aggregate, providing relatively poor sub-slab communication; as discussed later, these characteristics greatly influence the design of sub-slab ventilation (SSV) systems for the Florida houses. Future testing in New Mexico will address houses with no aggregate over expansive clays and coarse, dry sands.

SSV was the radon reduction method emphasized in the Ohio testing, and is the technique discussed in this paper. Mitigation design variables studied during this testing included: placement of the ventilation pipes vertically down through the slab from inside the house ("interior" SSV) vs. horizontally through

the foundation wall from outdoors ("exterior" SSV); location of the vent pipes; number of vent pipes; SSV fan capacity; and operation of the SSV system to draw suction on the sub-slab region vs. to pressurize the sub-slab. Other radon reduction approaches which were tested in addition to SSV -- but which were less effective and which are not covered in this paper -- were: continuous operation of the central furnace fan in houses having sub-slab forced-air supply ducts, in an effort to pressurize the sub-slab region; closure of the slab opening where the bathtub plumbing comes up through the slab; and "site ventilation." Site ventilation involves suction on a pipe embedded in the ground outside the house, in an effort to draw soil gas from the entire lot.

Table 1 lists the nine slab-on-grade study houses in Ohio, including the results of pre-mitigation alpha-track measurements in each house over a 3-month period during the winter. Various pertinent house variables are also summarized. 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 was measured using a Pylon Model AB-5 continuous radon monitor equipped with a 285 mL (17.4 in.^{3}) Lucas scintillation cell. The Pylons were programmed to measure radon hourly. Because of the significant day-to-day variability in indoor radon concentrations observed in the Ohio houses, the short-term radon measurements consisted of at least 48 hours (and commonly up to 96 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 the main living area under closed-house conditions. Essentially all of the monitoring was completed during the heating season (between December and March), except for a few of the Phase 1 measurements.

Diagnostic testing was generally limited primarily to measurements of suctions, flow rates, and radon concentrations in the piping of operating SSV systems. Sub-slab communication measurements were performed in some of the houses, but were generally not conducted in houses with sub-slab ducts. The ducts commonly radiated out from a centrally located furnace, effectively subdividing the sub-slab region into multiple zones. Initial sub-slab communication measurements in houses with ducts confirmed that suction did not extend between the sub-slab zones created by the ducts, presumably because of air leakage through the ducts; however, the suction field did extend well through the aggregate within a single zone.

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, alpha-track measurements will be repeated for at least 1 year with the systems operating. For quality assurance, these detectors are deployed in clusters of two or three; in addition, unexposed detectors, and detectors exposed to known radon levels in a chamber, are sent blind to the analytical laboratory.

SUB-SLAB SYSTEM DESIGN AND INSTALLATION

In houses having poured concrete foundation walls, an exterior suction point was created by coring a 4-in. (10-cm) diameter hole horizontally through the wall below slab level, to expose the sub-slab aggregate. A limited amount of aggregate in the immediate vicinity of the hole was removed; otherwise, no effort was made to excavate an opening under the slab. A fan was mounted on the foundation wall over the hole, exhausting horizontally away from the house at grade level. In the final installations, this fan was mounted on a piece of marine-grade plywood that was sealed onto the foundation wall over the hole. No piping extended from the fan through the hole into the sub-slab region. In houses having hollow-block foundation walls, exterior SSV points involved a 5-in. (13-cm) hole drilled through the foundation wall; a short segment of 4-in. PVC pipe was inserted through the hole, and expanding foam was injected into the annular gap between the pipe and the hole in the wall. This step was taken to reduce the amount of air drawn into the fan through the block cores (i.e., to reduce the block wall ventilation component of this system), since significant leakage of air through the block cores might be expected. The fan was then mounted on the outdoor end of the pipe segment, exhausting away from the house at grade.

For interior SSV systems, vertical PVC pipes penetrated the slab, generally in a furnace room, utility room, or bedroom closet. Again, aggregate immediately under the hole was removed, but no effort was made to excavate a pit under the slab. Each pipe extended up through the ceiling into the attic. If there were more than one suction pipe, the multiple pipes would be manifolded together in the attic, and connected to a single fan. The fan was mounted in the attic, and exhausted through the roof at a convenient location. In House 58, to determine whether interior SSV could be simulated from outside the house, a PVC pipe was inserted horizontally through the foundation wall from outdoors, for a distance of 6 to 7 ft (about 2 m) under the slab, simulating an interior pipe through the slab at that location.

Both the "exterior" and "interior" approaches were tested in four of the houses, to permit direct comparison of the two approaches in the same house. The interior systems in three of the houses included two suction pipes, located in different parts of the house, permitting testing of either pipe by itself, or both simultaneously. This multiple-pipe installation was to enable an assessment of the effect of the number and location of the vent pipes. The exterior system in the largest house (House 77) had two vent points, which could be operated one at a time, or both simultaneously (each with its own fan). In several houses where only exterior SSV was tested, the single fan was tested at two locations. In most houses, different fan speeds were tested.

In all cases, Kanalflakt T2 plastic-bodied fans were used, capable of drawing 270 cfm (127 L/s) at zero static pressure, and capable of 1.4 in. H_2O (350 Pa) suction at zero flow.

RESULTS

SSV SYSTEMS IN SUCTION

The best performance of sub-slab suction systems in each of the slab-on-grade houses is shown in Table 2. Where best performance was obtained during operation of two suction points simultaneously, these cases are marked in the table; in all other cases, only one suction pipe was operating. In houses where both exterior and interior SSV were tested, the results of the best installation of each are shown in the table for comparison. In houses where single exterior SSV suction points were tested at two locations, the performance is reported for each location (designated Site 1 and Site 2). In all cases, best performance was observed with the fan operating at high speed, although good performance was also attained at reduced fan speed. In general, these best results were obtained with the slab opening under the bathtub having been foamed closed. The pre- and post-mitigation radon levels presented here are short-term (48- to 96-hour) Pylon measurements, generally made immediately before and immediately after activation of the SSV fan, for back-to-back system on/off comparison. The first 5 hours of data taken immediately after the fan was turned on or off are excluded, in order to reduce the effect of the transient on the reported results.

Several conclusions are apparent from Table 2. Substantial reductions -- generally to a residual radon level of less than 1 to 2 pCi/L (37 to 74 Bq/m^3)* -- were achieved in all houses, with no more than two suction points (and generally only one). The generally good performance was probably aided by the very low air-flow resistance of the good layer of aggregate under the slab. As indicated in the table, the suctions in the SSV system piping were generally above 0.5 in. H_2O (125 Pa), and the flows were generally below 140 cfm (65 L/s), which is half fan capacity. These suctions/flows generally represent good SSV operation, and confirm that large amounts of air were not short-circuiting into the systems via sub-slab ducts or block foundation walls.

The apparent effects of the house variables and SSV system design/operating variables are discussed below.

Effect of Sub-Slab Forced-Air Supply Ducts--

The initial concern had been that houses with sub-slab heating ducts would not achieve high radon reductions with a reasonable number of SSV pipes, because the ducts would prevent effective distribution of the suction field underneath the slab. However, the results in Table 2 indicate that -- with the aggregate present under these houses -- any effect of the ducts is limited. The two houses without sub-slab heating ducts (Houses 70 and 72) did not consistently perform better than did comparable houses with ducts. On one hand, House 70 (large house, block foundation, no ducts) appeared to give better results with two-pipe interior SSV (0.2 pCi/L, 99% reduction) than did House 77, which was comparable in characteristics except that it had ducts (1.7 pCi/L, 89% reduction). But on

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* Radon in Bq/m^3 = 37 x value in pCi/L.

the other hand, House 72 (moderate size, block foundation, no ducts) did not seem to do as well with one-pipe interior SSV (1.6 pCi/L, 93% reduction) as did House 58, which was comparable but had ducts (0.8 pCi/L, 97% reduction). These radon levels are sufficiently low that -- given temporal and house-to-house variability, and measurement uncertainties -- it is not possible to quantify, from these data, any limited effect that the sub-slab ducts were having on SSV performance. The results from House 70 vs. House 77 are further compared later.

Effect of Interior vs. Exterior SSV--

From the standpoint of aesthetics, the choice between interior and exterior SSV for a given house will depend on the layout of the house and the preferences of the homeowner. It was desired to determine whether technical considerations might suggest one over the other under certain circumstances. For example, exterior SSV might be aiding in good performance in houses with radial sub-slab ducts, because the suction is drawn at the perimeter and thus might extend through the loose fill around the perimeter slab/foundation wall junction. In houses with block foundation walls below the slab, exterior SSV might be helpful or be a disadvantage, depending on the effects of the wall ventilation component that is likely to result. Large slabs with potential interior entry routes (in addition to the perimeter wall/floor joint) might be less effectively treated with exterior SSV.

In the four houses in Table 2 where both interior and exterior SSV were tested, the two SSV approaches appeared to perform about equally well in three of the houses (Houses 31, 58, and 77). These three houses cover the range from a small house with a poured foundation (31) to a large house with a block foundation (77); all had sub-slab ducts. In the fourth house, House 70, the interior SSV system appears distinctly superior; however, it must be noted that the interior SSV system utilized two suction pipes, while the exterior system drew on only one point. The large size of this house, and its block foundation, might also have contributed to this result. It should also be noted that in one of the houses where interior and exterior SSV appeared comparable (House 77), a two-point interior system connected to a single fan is being compared to a two-point exterior system where each exterior point has its own fan; it is not known whether the two-point exterior system would have performed as well as the interior system if both exterior points had been connected to a single fan.

Effect of Slab Size--

Regarding the effect of house size, the largest house (House 77, with a slab of 2,600 ft^2, or 240 m^2) required two suction pipes to reduce radon levels below 4 pCi/L; one pipe was insufficient. The other large house (House 70, with 2,350 ft^2, or 220 m^2) is also shown in Table 2 as having achieved its best performance with two interior suction pipes; however, operation of any one of the pipes was sufficient to reduce levels below 2 to 3 pCi/L. The likely reason for the better performance with one point in House 70 is that it did not have sub-slab ducts; in other respects, Houses 70 and 77 are similar (large houses, block foundations), although House 77 did have the added complexity of a sunken living room. For all of the other houses (ranging in size from 1,100 to 1,700 ft^2, or 90 to 160 m^2), one suction point was sufficient to reduce levels below

2 pCi/L. The effects of multiple suction points are discussed further later. As indicated previously, it appears that interior SSV might sometimes be preferred in houses with large slabs; but exterior and interior SSV appeared to perform equally well in houses with smaller slabs.

Effect of Block vs. Poured Concrete Foundation--

Regarding the effect of foundation material of construction, the houses having poured concrete foundations would appear to have most consistently achieved the best reductions. All four of the houses with poured foundations (Houses 15, 31, 47, and 58) were reduced to below 1 pCi/L (97 to 99% reduction) with each SSV approach (interior or exterior) tested in that house -- even though all of these houses had sub-slab ducts. By comparison, only one of the five houses with block foundations was reduced below 1 pCi/L, with a two-point interior SSV system (House 70, having no sub-slab ducts). The other block-foundation houses were reduced to levels of 1.6 to 3.7 pCi/L (81 to 93% reduction). In part, the poorer reductions in the block houses might be explained by the fact that the block houses were generally larger; except for House 85, all of the block houses were 1,700 ft^2 or larger, whereas all of the poured-foundation houses were 1,400 ft^2 or smaller. But size might not be the only explanation: House 85, with a block foundation, was only 1,100 ft^2, but it was not reduced below 1.6 - 2.5 pCi/L. Perhaps air leakage through the block foundation walls is reducing the effectiveness of suction distribution under the slab.

Effect of Number and Location of Suction Points--

In three of the houses, two-point SSV systems were tested. Table 3 compares the results obtained in these three houses when the system is operated with each of the suction points by themselves, and when the system is operated with both points. For Houses 70 and 77, the results reported previously in Table 2 reflected operation with both points. For all cases reported in Table 3, the mitigation fan is being operated at high speed.

Several observations can be made from Table 3. In House 31 -- a small house with a poured foundation and sub-slab ducts -- the best performance is achieved when only the one centrally located pipe in the furnace room is operated; connecting the second pipe, from the bath, causes a deterioration in performance compared to the furnace room pipe alone. And, not surprisingly, operation of the bath pipe by itself gives the poorest performance of all (although still reducing levels to below 3 pCi/L). The reason for this effect is not clear from the flow/suction measurements in the piping. The suction pipe in the bath maintains reasonable suction (0.4 to 0.8 in. H_2O, or 100 to 200 Pa) and reasonable flows (29 to 49 cfm, or 14 to 23 L/s), with the lower end of each range reflecting operation of this pipe in combination with the furnace room pipe, and the upper end reflecting operation of this pipe by itself. From these measurements, the bath pipe does not appear to be degrading performance by providing a short-circuit for air leakage into the system. The furnace room pipe appears to be best intercepting the radon source, and operation of this pipe by itself -- resulting in maximum suction (0.6 in. H_2O, or 150 Pa) and maximum flow (69 cfm, or 32 L/s) in this pipe -- appears clearly desirable. The apparent

conclusion is that more suction pipes are not always better.

In Houses 70 and 77, operation of two suction points is always better than operating only one. However, in House 70, operation of either point by itself is sufficient to reduce the house below 4 pCi/L. By comparison, in House 77, operation of any one point is only sufficient to reduce levels to between 6 and 8 pCi/L; operation of both points is required to achieve sufficiently low levels. Both of these houses are large with block foundations; the probable explanation for the better performance of single points in House 70 is that it does not have sub-slab heating ducts, and House 77 does have sub-slab ducts. The presence of a sunken living room in House 77 could also be contributing to the poorer performance of the single points in that house. It is noted that slightly better single-point performance with the interior SSV in House 70 was achieved with Point #2, which was located in the right front quadrant of the house, rather than with Point #1, which was centrally located. Thus, central location of a single suction pipe is not necessarily required, even in a large house, if there is good communication without obstructions such as sub-slab ducts. It is also noted that, in House 77, the individual exterior SSV suction points seemed to perform slightly better than did the individual interior pipes. This result could be suggesting that -- where there are insufficient suction points in houses having sub-slab ducts -- suction at the perimeter of the slab might be helpful because it "taps into" the permeable region where excavation for the footings had occurred during construction, a region which extends around the entire perimeter and which is less interrupted by the sub-slab ducts. With the block foundation in House 77, this result could also be suggesting that the wall ventilation component that might exist with exterior SSV systems could be important, especially when there is an insufficient number of points. (As noted previously, steps were taken in most of the block-foundation houses to reduce the wall ventilation component of exterior SSV systems.)

In the two houses where exterior SSV was tested at different locations, there appeared to be no effect of location in one (House 15), and some possible effect in the second (House 85). Both of these houses are small, and have sub-slab ducts; House 15 has a poured foundation, and House 85 a block foundation.

Effect of the Wall Ventilation Component in Block-Foundation Houses--

An effort was made in House 1 to investigate the significance of the wall ventilation component of exterior SSV in block-foundation houses. The original Phase 1 exterior SSV system in this house had consisted of a T2 fan mounted directly over the hole through the foundation wall; there was no pipe through the wall, nor were the block cores surrounding the hole mortared or foamed closed. Under these circumstances, it would be expected that there would be a significant wall ventilation component to this sub-slab-plus-block-wall ventilation system. As discussed in Reference 1, this Phase 1 installation resulted in indoor levels of 1.3 pCi/L (during mild weather), the highest residual radon level among the four Phase 1 slab-on-grade houses. The level increased to 10.6 pCi/L when the central furnace fan was operated continuously (to pressurize the sub-slab, counteracting the efforts of the SSV system to depressurize the sub-slab); continuous fan operation had not caused such a problem in the other three Phase 1 houses.

The first step taken at House 1, as part of the Phase 2 effort, was to remove the original fan, and to insert a 4-in. (10-cm) diameter pipe horizontally through the foundation wall into the sub-slab aggregate. The T2 fan was then re-mounted on this pipe. Expanding foam was injected to close the block voids around where the pipe penetrated the foundation. These steps should have greatly reduced the wall ventilation component of the system. Following these system modifications, radon levels in the house averaged 7.8 pCi/L over a 96-hour period in December, higher than had been observed with the original system. The pipe and foam were then removed, and the fan mounted on the foundation wall over the hole, as with the original installation. With this original configuration, the indoor levels averaged 2.8 pCi/L over 94 hours in January (somewhat higher than the 1.3 pCi/L reported earlier, perhaps because the earlier measurements had been made in April). The conclusion would appear to be that the wall ventilation component can be important in some cases. Taken together with the results from House 77, discussed above, it would appear that the wall ventilation component might be most important where the SSV system is marginal (e.g., in large houses having only one suction point). Since interior SSV performed well in the block-foundation houses (70, 72, and 77) when sufficient suction points were provided, it would appear that a major direct wall ventilation component is not required when the system is adequately designed.

Effect of Fan Capacity--

In many of the houses, the SSV system was operated with the Kanalflakt T2 fan both at maximum suction/flow and at about half suction, to investigate the effect of fan capacity. The performances at the two different fan capacities are compared in Table 4. The ability to achieve good performance at reduced fan capacity is important. Some percentage (probably between 30 and 70%) of the gas exhausted by the fan is air withdrawn from the house; thus, if fan capacity can be reduced without greatly reducing the radon reduction performance, the heating and cooling penalty of the SSV system will also be reduced.

As apparent from Table 4, operation of the fan at high capacity almost always resulted in lower indoor radon concentrations than did operation at reduced capacity. The exceptions are Houses 15, 31 (with interior pipe #1), and 85 (exterior site 1), where performance was the same at both capacities. In the majority of cases, operation at reduced capacity was sufficient to reduce the house below 4 pCi/L, although operation at high capacity reduced levels even further (generally below 2 pCi/L). The most dramatic improvements from operating at high capacity occur in those cases where high-capacity operation is not sufficient to reduce levels below about 2 pCi/L -- Houses 1, 31 (interior pipe #2), 70 (exterior, and interior pipe #1), and 77 (all single-suction-point cases). For these cases, the average radon level with the fan at high capacity was 4.0 pCi/L, while the average at reduced capacity was 9.2 pCi/L. For the other cases, where high-capacity operation achieved 2 pCi/L or less, reducing the fan to about half capacity increased radon levels from an average of 1.1 pCi/L (at high capacity) to an average of 2.1 pCi/L (at reduced capacity). Only in the case of House 77 (both interior points) did high-capacity operation achieve less than 2 pCi/L while reduced-capacity operation did not reduce levels below 4 pCi/L. In summary, it would appear that houses which are "easy" to treat

with SSV can be reduced below 4 pCi/L with fans of this size operating at reduced capacity; however, even with "easy" houses, there is usually (but not always) some marginal additional radon reduction that can be achieved by operating at high capacity.

The long-term objective defined by the Indoor Radon Abatement Act of 1988 is to reduce indoor radon concentrations to the levels which exist outdoors. To approach this objective, operation of the fans at high capacity in all cases would be preferred, since radon is generally reduced to lower levels at high capacity. Comparing the system flows indicated in Table 4, flows average about 35 cfm (16 L/s) less when the fan is at low capacity. Electrical consumption at low capacity is roughly one-third that at high capacity. Depending upon specific assumptions regarding the fraction of the 35 cfm which is withdrawn from the house, the local climate, and energy costs, the increased heating penalty and electricity cost resulting from operating the fan at high capacity rather than low capacity would be roughly $55 per year.

SSV SYSTEMS IN PRESSURE

In four of the Phase 2 slab-on-grade houses, the SSV fans were reversed so that the system was pressurizing the sub-slab region rather than drawing suction. In almost all cases, these sub-slab pressurization tests were conducted with the exterior SSV systems, since there is easy access to the external fans; only in House 70 was pressurization tested with an interior SSV system having the fan mounted in the attic. The results are shown in Table 5. Table 5 also presents the SSV pressurization results reported previously for the houses tested during Phase 1. In all cases, the suction vs. pressure comparisons shown in the table are with the suction and pressurization systems being operated at comparable conditions: the same ventilation points, and the same fan capacity.

These results, now with seven houses, confirm the earlier conclusions drawn from the three houses tested in the Phase 1 effort. In all cases, operation of the SSV system in suction gives greater radon reductions (88-99%) than does operation in pressure (43-90%). In several cases (Houses 31, 47, and 70), the difference between suction and pressure is dramatic.

For sub-slab pressurization to be effective, the system probably must create sufficient flows of fresh air under the slab to dilute the radon in the sub-slab gas. Because the sub-slab is under pressure, any radon in the sub-slab gas will be forced up into the house. Unlike sub-slab suction, where the system works by reversing the flows of sub-slab gas, establishing a pressure field under the slab may not be sufficient by itself with pressurization. With the geology present in Dayton, flows in the sub-slab systems were apparently not sufficiently great to provide the sub-slab dilution necessary to make pressurization work effectively.

COMPARISON WITH RESULTS FROM OTHER STUDIES

The one slab-on-grade house tested by Infiltec in an EPA-sponsored project in Maryland was a relatively large house (2,700 ft^2, or 250 m^2) with a block foundation stem wall and with forced-air supply ducts under the slab, similar

to House 77 in Ohio. The geology in Maryland was also similar to Ohio -- clay soil, with a good layer of aggregate underneath the slab. However, the results with interior SSV in the Maryland house were distinctly better than those observed in House 77. A single interior SSV pipe, located approximately in the middle of the slab and operating with a Kanalflakt T2 fan in suction, reduced radon concentrations in the Maryland house from a pre-mitigation level of 6 to 21 pCi/L, down to 0.7 pCi/L, a reduction 90% or greater. In House 77, a single interior pipe had been sufficient only to reduce levels from 16 to about 7 pCi/L (see Table 3). It is not clear why the performance is so different between these two houses.

Fourteen slab-on-grade houses tested in Florida (eight of which are reported in Reference 3) had no aggregate underneath the slabs. The slabs rested directly on fill material consisting of fine, compacted sand and clay which often had limited permeability to soil gas flow, especially when moist. The permeability of this fill may have been poorer than that of the native soil underlying the aggregate under the Ohio and Maryland houses, since the fill is specifically selected and compacted to support the elevated slabs characteristic of Florida slab-on-grade houses. The Florida houses varied in size between 1,500 and 2,570 ft^2 (140 and 240 m^2), had either block or poured concrete foundation walls, and did not have forced-air ducts underneath the slab. Several had sunken living rooms. Performance of interior and exterior SSV in these houses has been far less effective than it was in the Ohio and Maryland houses. In the Florida houses, two or three suction pipes have been necessary to reduce radon concentrations to post-mitigation levels of 3 to 9 pCi/L (generally 70 to 90+% reduction), compared to the 81 to 99% reduction achieved with only one or two pipes at the other sites. The two or three suction pipes were needed in Florida despite efforts to improve performance by excavating pits underneath the slabs where the pipes penetrated, and by using high-suction fans (capable of suctions up to 33 in. H_2O, or 8,100 Pa). In general, exterior SSV gave comparable reductions to interior SSV in Florida, although, in one house, exterior SSV was significantly less effective. These interior vs. exterior results appear generally comparable to those from Ohio (where the two approaches also generally compared well except in one house). However, in Florida, performance of exterior systems was reduced by high air leakage rates into the system, a problem far less pronounced in Ohio. In the Florida houses, the exterior suction pipes were often inserted horizontally some distance toward the interior of the slab in order to reduce leakage, making these exterior systems more similar to interior SSV.

It would appear that major obstructions such as sub-slab supply ducts (in the Ohio and Maryland houses) can fairly readily be handled by SSV systems, as long as there is a good aggregate layer. But where there is no aggregate and where the soil (or fill) under the slab is not reasonably permeable, design of the SSV system can be made more difficult, even when there are no apparent sub-slab obstructions, as indicated by the experience in Florida.

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TABLE 1. SUMMARY OF SLAB-ON-GRADE HOUSES TESTED DURING PHASES 1 AND 2 OF THE RADON REDUCTION FIELD PROJECT IN DAYTON, OHIO

House ID No.	Pre-mitigation Radon (pCi/L)[a]	Slab size (ft^2)	Foundation Material	Sub-slab Ducts?	Duct Config.	Sunken LR?
1[b]	17.5 (kitchen) 20.9 (bedroom)	1,700	Block	Yes	Radial	No
15[b]	16.3 (bedroom)	950	Poured	Yes	Radial	No
31[b]	12.6 (kitchen) 14.0 (bedroom)	950	Poured	Yes	Radial	No
47[b]	22.9 (kitchen) 24.1 (bedroom)	1,100	Poured	Yes	Radial	No
58	21.6 (liv. area)	1,400	Poured	Yes	Radial	No
70	15.4 (liv. area)	2,350	Block	No	--	No
72	17.9 (liv. area)	1,700	Block	No	--	No
77	16.0 (liv. area)	2,600	Block	Yes	Radial	Yes
85	10.3 (liv. area)	1,100	Block	Yes	Radial	No

[a] Pre-mitigation results are from alpha-track detectors exposed during the period December 1987 - March 1988 (Phase 1 houses) or November 1988 - January 1989 (Phase 2 houses), prior to completion of mitigation systems. Detectors exposed in clusters of two (Phase 2) or three (Phase 1); figures shown here are averages.

[b] Houses initially tested during Phase 1.

Conversion factors: Bq/m^3 = 37 x value in pCi/L. Area in m^2 = 0.093 x value in ft^2.

TABLE 2. BEST PERFORMANCE OF SUB-SLAB SUCTION IN SLAB-ON-GRADE HOUSES IN DAYTON

House No.	Interior/ Exterior SSV	Radon Concentrations (pCi/L) System Off Range	System Off Mean	System On Range	System On Mean	% Reduction in Mean	Suction (in. H_2O)	Flow (cfm)
1	Exterior	14-32	20.2	2- 6	2.8	86	N/A[e]	100
15[a]	Exterior (Site 1)[b]	6-42	17.9	0- 1	0.4	98	1.4	N/A
	Exterior (Site 2)	"	"	0- 1	0.5	97	1.2	43
31	Exterior[a]	7-27	14.7	0- 1	0.1	99	0.85	64
	Interior (#1)[c]	"	"	0- 1	0.3	98	0.6	69
47[a]	Exterior	20-39	29.6	0- 2	0.9	97	1.2	69
58	Exterior	19-43	27.5	0- 1	0.5	98	0.55	140
	Interior	"	"	0- 2	0.8	97	0.7	63
70	Exterior	12-44	23.5	2- 5	3.7	84	N/A	111
	Interior (#1 & 2)[d]	"	"	0-0.5	0.2	99	0.5-0.85	104
72	Interior	12-30	22.1	1- 3	1.6	93	1.2	12
77	Exterior (#1 & 2)[d]	9-23	15.7	1- 4	1.7	89	0.25-0.3	114
	Interior (#1 & 2)[d]	"	"	1- 3	1.7	89	0.65-0.8	148
85	Exterior (Site 1)	3-34	12.9	1- 5	2.5	81	1.2	45
	Exterior (Site 2)	"	"	0- 5	1.5	88	1.0	42

[a] Testing completed during Phase 1; these results have been reported in References 1 and 2.
[b] Sites 1 and 2 refer to different positions around the house where the one exterior suction point was located.
[c] #1 and #2 refer to individual suction points in homes having two-point systems installed.
[d] Two suction points operating simultaneously to achieve these best results. In all other cases, only one point is operating.
[e] N/A = not available.
Fan operating at high speed in all cases.

Conversion factors:
Bq/m^3 = 37 x value in pCi/L. Pa = 248 x value in in. H_2O. L/s = 0.47 x value in cfm.

TABLE 3. EFFECT OF ONE VS. TWO SUCTION POINTS IN SSV SYSTEMS IN SLAB-ON-GRADE HOUSES

House No.	Interior/ Exterior SSV	Mean pCi/L Before	Mean Performance After: Point #1 Only pCi/L	Point #1 Only % Red.	Point #2 Only pCi/L	Point #2 Only % Red.	Both Points pCi/L	Both Points % Red.
31	Interior	14.7	0.3	98	2.7	82	1.0	93
70	Interior	23.5	3.0	87	1.8	92	0.2	99
77	Interior	15.7	6.7	57	7.7	51	1.7	89
	Exterior	15.7	6.0	62	5.7	64	1.7	89

Locations of suction points:

House 31: #1 in furnace room (center of house); #2 in bath (center rear of house).

House 70: #1 in furnace room (center); #2 in bedroom closet (in right front quadrant).

House 77: interior - #1 in laundry room (center of left half of house); #2 in bedroom closet (center of right half).
exterior - #1 on rear wall, center of left half of house; #2 on rear wall, center of right half.

Fan at high speed in all cases reported here (best results). Both suction points connect to a single fan, except for exterior system in House 77, where each exterior point has its own fan.

Conversion factor: $Bq/m^3 = 37 \times$ value in pCi/L

TABLE 4. EFFECT OF FAN CAPACITY ON THE PERFORMANCE OF SSV SYTEMS (SLAB-ON-GRADE HOUSES)

House No.	Interior/ Exterior SSV	Suction Point Number	Mean pCi/L Before	Mean Performance After: High Capacity pCi/L	High Capacity % Red.	Low Capacity pCi/L	Low Capacity % Red.	Suction (in. H_2O) High[c]	Suction (in. H_2O) Low[c]	Flow (cfm) High[c]	Flow (cfm) Low[c]
1	Exterior	[b]	20.2	2.8	86	10.1	50	N/A	N/A[d]	100	37
15[a]	Exterior (Site 1)	[b]	17.9	0.4	98	0.2	99	1.4	0.8	N/A	N/A
31	Exterior[a]	[b]	14.7	0.1	99	1.4	90	0.85	0.5	64	N/A
	Interior	#1	"	0.3	98	0.3	98	0.6	0.3	69	33
	Interior	#2	"	2.7	82	13.7	7	0.8	0.1	49	14
	Interior	#1 & 2	"	1.0	93	--	--	0.4-0.55	--	80	--
47[a]	Exterior	[b]	29.6	0.9	97	2.9	90	1.2	0.45	69	25
58	Exterior	[b]	27.5	0.5	98	1.0	96	0.55	0.3	140	82
	Interior	[b]	"	0.8	97	2.2	92	0.7	N/A	63	23
70	Exterior	[b]	23.5	3.7	84	6.0	74	N/A	N/A	111	64
	Interior	#1	"	3.0	87	6.5	72	0.75	N/A	39	N/A
	Interior	#2	"	1.8	92	2.0	91	0.95	0.35	74	32
	Interior	#1 & 2	"	0.2	99	1.7	93	0.5-0.85	--	104	--
72	Interior	[b]	22.1	1.6	93	3.2	86	1.2	0.75	12	9
77	Exterior	#1	15.7	6.0	62	--	--	N/A	--	98	--
	Exterior	#2	"	5.7	64	--	--	N/A	--	125	--
	Exterior	#1 & 2	"	1.7	89	2.1	87	0.65-0.8	0.4-0.8	148	132
	Interior	#1	"	6.7	57	--	--	0.4	--	96	--
	Interior	#2	"	7.7	51	9.7	38	0.35	0.06	83	24
	Interior	#1 & 2	"	1.7	89	5.5	65	0.25-0.3	N/A	114	N/A
85	Exterior (Site 1)	[b]	12.9	2.5	81	2.5	81	1.2	0.35	45	16
	Exterior (Site 2)	[b]	"	1.5	88	2.8	78	1.0	0.5	42	27

[a] Testing completed during Phase 1; these results have been reported in References 1 and 2.
[b] Only one suction point was included in these systems.
[c] Suctions, flows in system piping shown for both high and low fan capacities.
[d] N/A = not available.

Conversion factors: Bq/m^3 = 37 x value in pCi/L. Pa = 248 x value in in. H_2O. L/s = 0.47 x value in cfm.

TABLE 5. EFFECT OF PRESSURIZATION VS. SUCTION IN SSV SYSTEMS (SLAB-ON-GRADE HOUSES)

House No.	Average Radon Concentration (pCi/L)			% Reduction	
	Pre-Mitigation	Post-Mitigation Suction	Post-Mitigation Pressure	Suction	Pressure
15[a]	17.9	0.4	1.8	98	90
31[a]	14.7	0.4	4.2	97	71
47[a]	29.6	2.9	16.0	90	46
58	27.5	0.5	5.7	98	79
70[b]	23.5	0.2	13.4	99	43
77[c]	15.7	1.7	3.1	89	80
85[d]	12.9	1.6	2.6	88	80

[a] Testing completed during Phase 1; these results reported in References 1 and 2.

[b] Performance shown is for a two-point interior SSV system. All other results reported here are for exterior SSV systems.

[c] Results obtained with the two-point exterior system.

[d] Results obtained with one-point exterior system, fan located at Site 2.

Conversion factor: Bq/m^3 = 37 x value in pCi/L.

RADON MITIGATION EXPERIENCE IN HOUSES WITH BASEMENTS AND ADJOINING CRAWL SPACES

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ABSTRACT

Active soil depressurization systems were installed in four basement houses with adjoining crawl spaces in Maryland. In addition, existing soil depressurization systems were modified in two additional basement-plus-crawl-space houses. These six houses were selected to include both good and poor communication beneath the basement slab, and different degrees of importance of the crawl space as a source of the indoor radon. The radon reduction effectiveness was compared for: depressurization only under the basement slab; depressurization only under a polyethylene liner over the unpaved crawl-space floor; and simultaneous depressurization under both the basement slab and the crawl-space liner. The objective of this testing was to identify under what conditions treatment of the basement alone might provide sufficient radon reductions in houses of this substructure, and what incremental benefits might be achieved by also treating the crawl space.

The results suggest that, when there is excellent communication beneath the basement slab, basement-plus-crawl-space houses can sometimes be treated by basement sub-slab depressurization (SSD) alone, even when radon levels in the crawl space indicate that the crawl space could be a source. With excellent communication, the incremental benefit of including sub-liner depressurization in the crawl space, in addition to basement SSD, can sometimes be limited (although the two in conjunction may still be needed if the goal is to achieve "ambient" levels indoors). However, when communication beneath the basement slab is poor, and if the crawl space is an important source, then sub-liner depressurization can provide potentially significant additional radon reductions compared to basement SSD alone.

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

Twelve existing houses in Maryland were selected to study cost-effective radon mitigation methods in three types of houses: five houses with basements and adjoining slabs on grade; six houses with basements and adjoining crawl spaces; and one house which was slab on grade with heating ducts beneath the slab. All of these houses had previously reported radon levels between 10 and 70 pCi/L (370 and 2600 Bq/m^3)*.

Active soil depressurization systems were installed in all of the houses. For the basement houses with adjoining wings, one sub-slab depressurization (SSD) pipe was installed beneath the basement slab, and a second suction pipe was installed either beneath the adjoining slab or through polyethylene sheeting placed over the floor of the adjoining crawl space. Radon concentrations were measured in the basement and on the first floor with: none of the suction pipes operating; SSD applied to the basement slab only; depressurization beneath the crawl-space liner or beneath the adjoining slab on grade only; and depressurization beneath both the lower slab and the crawl-space liner or upper slab. The objective of this testing was to identify under what conditions treatment of the basement alone might provide sufficient radon reductions in such basement-plus-adjoining-wing houses, and what additional reductions might be achieved by also treating the adjoining wing. Diagnostic testing (including sub-slab or sub-liner radon concentrations, and sub-slab suction field extensions and air flows) was conducted to help understand the conditions influencing the performance of these systems.

This paper addresses the testing on the six basement-plus-crawl-space houses. These six houses included four which had had no prior radon mitigation system, and two which had existing systems which were not fully effective.

MEASUREMENT METHODS

INDOOR RADON MEASUREMENTS

For short-term measurements of radon mitigation system performance, radon gas was measured using a Pylon Model AB-5 continuous radon monitor equipped with either a 17.4 in.^{3} (285 mL) Lucas scintillation cell or a PRD-1 passive radon detector. The Pylons were programmed to measure radon hourly. One Pylon was placed in the basement, and one in the living area above the crawl space, generally for about 2 weeks; during this time, the mitigation system would be cycled through its range of operating conditions (system off, basement treatment only, crawl-space treatment only, treatment of both wings), with the system being left at a given condition for at least 48 hours.

For a long-term measurement of SSD performance, 3-month alpha-track detector measurements are being repeated for at least 1 year with the systems operating. These long-term results are not covered in this paper.

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* Radon in Bq/m^3 = 37 x value in pCi/L.

DIAGNOSTIC TESTING

In selecting houses for this study, it was desired to cover a range of the key variables, including the communication under the basement slab, and the relative importance of the basement vs. the crawl space as a radon source. Knowledge of these parameters is also important for understanding the conditions under which basement-only treatment is sufficient, and what additional benefit can be derived by also treating the crawl space.

Sub-slab Pressure and Flow Measurements

To characterize communication under the basement slab, sub-slab pressure and flow measurements were taken with a "Blower Floor," consisting of a high-suction vacuum cleaner, a calibrated flow meter, and a digital micromanometer.

Where a sump existed, the sump cover was removed (if feasible) and a plate with a 1.5-in. (4-cm) opening was secured over the sump with duct tape. The vacuum cleaner nozzle was sealed into the 1.5-in. opening to depressurize the sump. Measurements of induced air flow in the vacuum were taken as the suction in the sump was measured using the micromanometer. The suction underneath the basement slab was also measured through several 0.25-in. (0.6-cm) test holes drilled through the slab at selected locations, usually in the basement corners.

In houses with no sump, a 0.5-in. (1.25-cm) suction hole was drilled through the slab (at a location which appeared promising for the ultimate SSD suction point). Suction was drawn on the sub-slab through this hole with the vacuum cleaner. Flow in the vacuum cleaner was measured, as was the differential pressure across the slab through the 0.25-in. (0.6-cm) test holes. One test hole was located 4 in. (10 cm) from the suction hole, and several test holes were usually located in the basement corners.

Radon Measurements Under Basement Slab

To assess the source strength under the basement, sub-slab radon measurements were taken through 0.25-in. (0.6 cm) holes drilled in each corner of the basement slab area. Sub-slab gas was pumped through a 17.4 in.^{3} (285 mL) Lucas cell at approximately 0.03 cfm (1 L/min), and photomultiplier counts were recorded at 1-minute intervals. Although this "sniffing" technique does not allow the radon to reach equilibrium with its decay products, the sensitivity of this non-equilibrium measurement system was determined experimentally to be about 1.4 times the sensitivity of an equilibrium situation; this sensitivity was used to estimate sub-slab values.

Radon Measurements in Crawl-Space Soil

As a rough estimate of the source strength in the crawl space, radon measurements were made near the surface of the crawl-space soil. Where the crawl-space floor was covered with a preexisting vapor barrier, a 0.25-in. (0.6 cm) hole was made through the vapor barrier (generally within arm's reach of the access door to the crawl space), and sub-barrier samples were taken with the sniffing technique described above. Where there was no existing vapor barrier

in the crawl space, the air sampling tube was inserted approximately 6 in. into the soil, or into the aggregate on top of the soil, to collect the soil gas sample. Generally, no measurements were taken of radon levels in the breathable area of the crawl space.

Post-Mitigation Diagnostics

To define the operation of the SSD system after installation, measurements were made of the suction and flows in the system piping, and the extension of the suction field created under the basement slab by the system.

DESCRIPTION OF STUDY HOUSES

The six houses included in this testing are summarized in Table 1. In addition to certain house construction characteristics and the pre-mitigation radon concentrations, the table summarizes results from the pre-mitigation diagnostic testing.

In all cases, the crawl-space floor consisted of bare soil (often with an existing vapor barrier) or of aggregate on top of soil (with no vapor barrier). Only one house (House 208) was a split level, with a half-depth basement adjoining a relatively low crawl space; the remainder of the houses were ranches. The basements were somewhat larger in floor area than were the crawl spaces, by factors ranging from 1.05 to 2.2.

Two of the houses (Houses 208 and 277) already had operating mitigation systems which had reduced radon levels to the range of 4 - 10 pCi/L at the time this work began. House 208 had a one-pipe basement SSD system. House 277 had a one-pipe basement SSD system tied into a sub-liner depressurization system in the crawl space, connected to a single fan.

House 208 is a split level house. The lower half is approximately 4 ft below grade in the rear. The upper level is above a crawl space which is at the same level as the basement slab. The crawl space and upper level are separated from the lower level by the block foundation wall and an access door. There is no sump. The total floor area of the basement slab and the crawl space (the "house footprint") is 1375 ft^2 (130 m^2), with a basement/crawl area ratio of 1.05.

House 277 is a ranch-style house built over an L-shaped basement and an interlocking L-shaped crawl space. The basement is unfinished and has no sump. The crawl space is at the same grade as the basement floor. The crawl-space floor is uneven and has been covered (as part of the earlier mitigation effort) with a sealed plastic barrier. The foundation walls are hollow block.

No data are available on pre-mitigation sub-slab radon levels in these two houses. As indicated in Table 1, both had poor airflow beneath the basement slab. As part of this project, additional basement SSD pipes were installed; these pipes improved the distribution of the suction field beneath the basement

slab and resulted in effective mitigation, as discussed later, greatly improving the performance of the original installations.

House 582 has a basement which is divided into two parts: a finished family room; and an unfinished utility room with washer/dryer, furnace, and sump. The crawl space is open to both parts of the basement. The house has a garage on grade which is adjacent to the crawl space, and there are living spaces over the basement and crawl space, but not over the garage. This house has excellent sub-slab air flow. Of particular interest, higher radon concentrations were measured in the crawl-space soil than were found beneath the basement slab, as shown in Table 1, suggesting that the crawl space might be a major contributor to the indoor radon. The total footprint is 825 ft^2 (77 m^2), and the basement/crawl area ratio is 1.8.

Houses 1165 and 1248 were both characterized by relatively high sub-slab radon levels for this area (>1,000 pCi/L) and excellent sub-slab flow. By comparison, radon levels in the crawl-space soil were only moderate, suggesting that the basement may be the primary source. House 1165 has a basement, of which approximately 80% is finished living space and the remainder is a utility/work room. There is no sump. There is also a large crawl space open to the basement, and a garage on grade adjacent to the crawl space. There are living areas above both the basement and the crawl space, although there is no living space above the garage. There are both duct and plumbing penetrations between the crawl space and the living area above it, and there is a full bath in the basement. The footprint is 1375 ft^2 (130 m^2), and the area ratio 1.7.

House 1248 has a relatively small basement with poured concrete walls and an adjoining crawl space which is open to the basement. There are living spaces above both the crawl space and the basement, with forced air ducts in both the basement and the crawl space. The basement is a deep basement (rather than a walkout), and there is a sump on the side of the basement opposite the crawl space. There are no adjacent slabs on grade. With a footprint of 900 ft^2 (84 m^2) and an area ratio of 1.8, House 1248 is approximately 65% of the size of House 1165 (both in the area of the basement slab and in the area of the crawl space surface).

House 1357 is a brick and block colonial, with a garage on grade, a deep basement, and a crawl space between the garage and the basement. The foundation walls are hollow cinder block. The crawl space has an uneven surface of packed soil and is open to the basement; there is no sump. There is forced air heat, and there are several plumbing penetrations through the basement slab (for a washing machine and sink). House 1357 was characterized by high radon levels under the basement slab, and poor sub-slab airflow; in this instance, there was no measurable sub-slab airflow. Radon levels in the crawl-space soil were not as high as at most of the other houses; however, concentrations in the crawl-space air were once measured at 25 pCi/L at a time when the levels in the basement were only 5 pCi/L, suggesting that the crawl space could still be a contributor. The house footprint is 875 ft^2 (81 m^2), and the area ratio is 2.2.

DESCRIPTION OF REMEDIATION SYSTEMS

In the four houses not having sumps, one or more SSD pipes were installed through the basement slab. Houses 1165 and 1357 each received one-pipe systems; House 208 received an additional pipe and fan to supplement the previous system, thus winding up with a two-pipe system, each pipe having its own fan; House 277 received an additional two pipes tied into the previous system, to create a three-pipe system. Typically, about 0.5 ft^3 (15 L) of aggregate was excavated from under the slab where the pipes penetrated. In the two houses which had sumps (Houses 582 and 1248), the sump was fitted with a permanent radon sump cover and a suction pipe. In all houses, the suction pipe was thin-walled 4-in. (10-cm) PVC pipe. Except for House 208 (which had two independent SSD pipe/stack/fan systems and no crawl-space sub-liner system), the SSD pipe(s) were T'd together with the sub-liner suction pipe from the crawl space, and connected to a single in-line fan mounted outside the house or in the garage attic, with the exhaust released above the roof in all houses. The fans had a rated capacity of 180 cfm (85 L/s) at 0.5 in. H_2O (125 Pa). All basement cracks were caulked along accessible floor/wall joints (i.e., not behind finished walls or other inaccessible locations).

Sub-liner depressurization systems were installed in each house except House 208. Except in House 277, the liner material was 8-mil (0.2-mm) high-durability polyethylene sheeting, laid to form a barrier over the entire crawl-space floor. In the final installations, the liner was sealed by overlapping the individual sheets (by 6 to 12 in., or 0.15 to 0.3 m), and sealing these seams with urethane caulk; the junctions of the sheeting with the perimeter foundation wall and with interior piers were sealed in the same manner. A single 4-in. (10-cm) PVC suction pipe was inserted through the plastic liner at one location, with a plywood "flange" around the pipe underneath the liner to support the pipe and to lift the polyethylene off the soil at that location to aid in distribution of the suction field. Wherever possible, the measurements of mitigation system performance included measurements with and without the sheeting sealed around the perimeter wall, to evaluate the benefits of this sometimes-difficult installation step.

In House 277, where the sub-liner system had been installed by an earlier mitigator as part of the original mitigation effort, the liner was 20-mil (0.5-mm) plastic, and a loop of perforated piping was located around the perimeter of the crawl space under the plastic. Suction was drawn on this loop. The plastic was already sealed at seams and around the perimeter, so that testing without perimeter sealing was not possible during this project.

RESULTS

The radon reduction results from the testing in the six houses are summarized in Table 2. These results represent at least 48 hours of measurements at each test condition, using the continuous Pylon monitors.

EFFECTS OF TREATING THE BASEMENT SLAB ONLY

Applying a vacuum beneath only the basement slab reduced the radon levels both in the basement and in the living area above the crawl space in all of the houses except House 1357. With the exception of that house, reductions in the basement were consistently high (82 to 98%), reducing concentrations to below 1 pCi/L in these short-term measurements. The one house having less than 90% reduction in the basement (House 582) had the relatively low percentage reduction of 82%, at least in part because the pre-mitigation value was below 4 pCi/L. (In all of the houses, pre-mitigation values at the time of these Pylon measurements were much lower than they had been when the earlier, cold-weather charcoal detector measurements had been made, even though the Pylon measurements were largely completed during the month of February.) In the houses other than 1357 for which Pylon measurements were successfully completed in the living area above the crawl space, radon reductions were about 80% in the living area with basement-only treatment, reducing concentrations to 1.2 pCi/L and less.

In House 582 -- where the crawl space appears to be an important radon source but where sub-slab communication is excellent, as discussed earlier -- basement-only treatment did about as well in reducing levels upstairs as it did in House 1165, where the communication is also excellent but where the crawl space seems less of a source. Basement-only treatment in House 582 appeared only slightly poorer in reducing levels in the basement, compared to Houses 1165 and 1248 (also good communication, crawl space less of a source). Based upon these fairly good results in House 582, it would appear that -- when communication is very good -- basement-only treatment may be sufficient even when the crawl space is an important radon source.

In House 1357, SSD under the basement slab reduced basement levels about 40%, much less than in the other houses. Concentrations in the living space above the crawl actually appeared to increase from 2.5 to 3.5 pCi/L when basement SSD was applied (although, given the variability of radon measurements, this 1 pCi/L differential is so small that it is not certain that any real change had occurred at all). This relatively poor performance in House 1357 with basement SSD only might intuitively be attributed to the very poor sub-slab communication (and possibly the relative importance of the crawl space as a radon source, as suggested by the 25 pCi/L once measured in the crawl-space air). House 208 also had poor sub-slab communication (although not as poor as House 1357, which gave <u>no</u> airflow during the pre-mitigation diagnostic testing); House 208 had still had elevated radon levels with its original one-pipe SSD system, and achieved the high removals shown in Table 2 only because of the additional suction pipe and fan added as part of this project.

EFFECTS OF TREATING CRAWL SPACE ONLY

<u>Sub-Liner Depressurization with the Liner Sealed</u>

As shown in Table 2, sub-liner depressurization in the crawl spaces, without any treatment of the basement, effectively reduced radon levels in both the basements and the living areas of all five test houses in which this approach was tested. (House 208 did not receive crawl-space treatment; House 277 was not

tested in the crawl-space-only mode.) The results shown in the table are for the case where the liner was sealed at seams and around the perimeter. Reductions ranged from 38 to 73% in the basement, and from 15 to 88% in the living area above the crawl space. Except for House 1357, reductions in the basement from crawl-space-only treatment were not as great as the reductions achieved by basement-only treatment, as might be expected. For the two houses other than 1357 where measurements were successfully completed in the living area with both mitigation approaches, crawl-space-only treatment gave living-area radon reductions which were comparable to basement-only treatment in one house (House 582, 88 vs. 84%), and substantially poorer in the other house (House 1165, 15 vs. 82%). The fact that crawl-space-only treatment is so much poorer than basement-only treatment in House 1165 suggests that, in this house, either: a) most of the radon in the living area was probably flowing upstairs from the basement; or b) the basement SSD pipe was being very effective in achieving "site ventilation" (i.e., in extending its suction field underneath the crawl-space soil).

Crawl-space-only treatment in House 1357 gave significantly greater radon reductions in the basement than did basement-only treatment (73 vs. 41%). This result would appear to be consistent with the expectations that the crawl space is an important source of the radon in the house, and that poor sub-slab communication would reduce the effectiveness of a one-point SSD system in the basement. The levels in the living area above the crawl space were reduced to 1.3 pCi/L with the crawl-space-only system, a 48% reduction from the pre-mitigation level of 2.5 pCi/L; the basement-only system had given no apparent reduction in the living area.

Sub-Liner Depressurization without Sealing the Liner

The results discussed above are for the final sub-liner depressurization installation in each house, which involved sealing the liner at seams and around the perimeter. Prior to that complete sealing, the sub-liner depressurization system was tested without the liner's being sealed around the perimeter (although it was still sealed between the sheets of polyethylene). Testing without the liner sealed was conducted only for the crawl-space-only case, not in conjunction with basement SSD. Comparison of the radon reductions achieved with the crawl-space-only systems before and after liner sealing indicates that sealing improved reductions in all four houses where before/after measurements could be made, both in the basement and upstairs. Basement reductions increased from a pre-sealing range of 0 to 60%, to the post-sealing range of 38 to 73%; upstairs reductions increased from 0 - 56% to 15 - 88%.

It is emphasized that -- although the differences in the percentage reductions may appear significant -- these differences often represent only a few pCi/L. Given the variability in indoor radon levels with time, it is not clear if the apparent differences reflect a real effect of liner sealing.

EFFECTS OF TREATING BOTH THE BASEMENT AND THE CRAWL SPACE

As shown in Table 2, simultaneous SSD in the basement and sub-liner depressurization in the crawl space was clearly superior to basement-only

treatment in House 1357. Radon reductions both in the basement and in the living area above the crawl space are significantly higher with the combined treatment compared to basement-only treatment (90 vs. 41% in the basement, 84 vs. 0% upstairs). Again, this result is consistent with the diagnostic results indicating that sub-slab communication is poor, and suggesting that the crawl space might be an important source in that house. In one other house (House 582), which had excellent sub-slab communication, simultaneous treatment appears somewhat superior to basement-only treatment (92 vs. 82% in the basement, 96 vs. 84% above the crawl space). However, the differential between the radon levels for simultaneous vs. basement-only treatment is so small in House 582 (fractions of a pCi/L), that measurement uncertainty and temporal variation in radon levels could easily explain the differences; thus, it is not clear that there is truly a significant difference in the performance of the two approaches in this house. In the other two houses for which complete data are available (Houses 1165 and 1248) -- both of which had excellent communication -- basement-only treatment appears at least as effective as simultaneous treatment in reducing the radon levels both in the basement and upstairs.

In summary, in the one house where sub-slab communication is poor and the crawl space might be an important source, treatment of both wings appears necessary. (Additional suction pipes in the basement might also have improved the performance of the basement-only system; post-mitigation suction field extension measurements in this house confirm that the suction was not extending underneath the entire slab.) In the three houses having excellent sub-slab communication, treatment of the crawl space appears either unnecessary, or of reduced incremental value.

Simultaneous treatment of the basement and the crawl space was always superior to crawl-space-only treatment, providing greater reductions both in the basement and upstairs. Reductions of 38 to 73% in the basement with crawl-space-only treatment increased to 90 to 96% with simultaneous treatment; reductions of 15 to 88% in the living area above the crawl space increased to 84 to 96%. Therefore -- although crawl-space-only treatment was sufficient to reduce levels in these houses below 4 pCi/L on both floors, due to the low pre-mitigation values -- it appears always beneficial to supplement a sub-liner depressurization with SSD in the basement, regardless of the sub-slab communication or the importance of the crawl space as a source.

In House 277 -- which has poor communication -- the three-pipe basement SSD system, combined with the sub-liner depressurization system having a perforated piping loop under the liner, is the most extensive of the systems tested under this project. Yet this system gave the lowest percentage reductions (82% in the basement, 84% upstairs) and the highest residual radon levels (1.7 pCi/L in the basement, 0.7 pCi/L upstairs) of any of the basement-plus-crawl-space systems. Even though the residual levels are less than 2 pCi/L, these results suggest that, with poor-communication houses, more extensive systems (e.g., multi-pipe basement SSD installations, crawl-space sub-liner systems with perforated piping under the liner) will sometimes be needed. The system at House 277 was not tested in the basement-only or the crawl-space-only mode, so that it is not possible to assess the relative contributions of the basement and crawl-space components of the system.

CONCLUSIONS

The four conclusions listed below are based on the results from the six basement-plus-crawl-space houses tested in this study. These conclusions must be qualified, recognizing that: the number of houses tested was limited, considering the range of house variables to be tested (e.g., communication, importance of crawl space as a source); and the pre-mitigation radon concentrations existing at the time of testing (February 1989 in most cases) were low, so that changes in the radon concentrations caused by the mitigation systems were small (in terms of pCi/L) and within the background variability created by temporal radon variations and measurement uncertainty.

1) When communication under the basement slab is excellent (as defined in Table 1), and when the crawl space is not a primary contributor to the indoor radon levels: basement-plus-crawl-space houses can sometimes be treated by basement SSD alone. Under these circumstances, the incremental benefit of including sub-liner depressurization in the crawl space, in addition to basement SSD, may sometimes be limited. This result can be true even where diagnostic measurements indicate radon levels in the crawl space several times higher than those in the living areas of the house. However, even in houses with excellent communication, basement SSD may have to be supplemented with sub-liner treatment in order to achieve "ambient" radon concentrations indoors (i.e., a fraction of a pCi/L).

2) When communication under the basement slab is poor (as defined in Table 1), and when the crawl space might be a primary contributor to indoor radon: sub-liner depressurization in the crawl space, in conjunction with basement SSD, can provide potentially significant additional radon reductions compared to basement SSD alone. This study did not definitively address the potential for achieving these increased radon reductions through an improved design of the basement SSD system (e.g., an increased number of suction pipes), rather than by adding sub-liner depressurization.

3) Combined treatment of the basement and the crawl space always provided greater radon reductions in this study than did crawl-space treatment alone. Thus, it would not usually be desirable to install a sub-liner depressurization system in the crawl space without also tying in basement SSD pipes. In most cases, crawl-space treatment alone is not as effective as is basement treatment alone; only in one house, which had poor sub-slab communication in the basement and high radon concentrations in the crawl space, did sub-liner depressurization in the crawl space prove more effective in reducing indoor radon levels than did SSD applied to the basement slab.

4) When applying sub-liner depressurization in a crawl space, with a single suction pipe penetrating the liner at a central location, sealing the polyethylene sheeting to the crawl space perimeter walls (as well as at seams between sheets) appeared to provide roughly a 10 to 40 percentage point improvement over the reductions achieved with the liner sealed only at seams between sheets.

If these conclusions from the six study houses can be extrapolated to the general housing population, they are relevant to several different aspects of commercial radon remediation. First, they clearly suggest that simple sub-slab vacuums applied to the lowest levels of basement houses with adjoining crawl space are likely to reduce the radon levels substantially, especially in houses with good sub-slab flow beneath the basement slab. Therefore -- where the goal of remediation is to reduce radon levels below 4 pCi/L or to achieve the most cost-effective remediation (as has commonly been the case) -- then SSD beneath the basement slab is likely to be an appropriate approach.

However, where the goal of remediation is to achieve ambient levels (a fraction of a pCi/L) indoors, these findings suggest that, even under the best of conditions, it may sometimes be necessary to supplement SSD systems with sub-liner depressurization of exposed crawl space soil. Since installation of sub-liner systems is generally difficult and labor intensive, adding crawl-space treatment to a basement SSD system may be expected to increase the cost of remediation by more than 100% in many instances.

It is important to note that the experience with House 1357 clearly illustrates that, in some instances, the crawl space may be a primary source of indoor radon. In such cases -- and when, in addition, communication under the basement slab is poor -- the likelihood is increased that a sub-slab vacuum beneath the basement slab will have to be supplemented by sub-liner depressurization, even to achieve 4 pCi/L.

For the professional diagnostician and mitigator, therefore, it is important to utilize appropriate diagnostic tests to assess when basement SSD by itself will potentially not be sufficient. The diagnostic tests used in this study suggest that sub-slab flow beneath the basement slab, together with radon measurements in the crawl space air or soil gas, may be useful predictors of when crawl-space treatment will also be desirable.

It is re-emphasized that additional testing -- on a larger number of basement-plus-crawl-space houses, with more adjustments to the mitigation system design/operating variables, and with higher pre-mitigation radon levels -- would be necessary to confirm these conclusions.

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TABLE 1. SUMMARY OF BASEMENT-PLUS-CRAWL-SPACE HOUSES TESTED IN MARYLAND

House No.	Foundation	Pre-mit. Indoor Rn (pCi/L)*	Source Concentration (pCi/L) Sub-slab (Basement)	Soil (Crawl)	Basement Sub-slab Airflow**
208	Block	10.2-23.2	117- 225	N/A	Poor
277	Block	7.6-27.8	N/A	N/A	Poor
582	Poured	9.8-17.3	138- 305	888	Excellent
1165	Block	13.2-13.8	193-1570	144	Excellent
1248	Poured	25.3-41.8	1725-3674	374	Excellent
1357	Block	15.1-18.4	600-1800	67	Poor

* Pre-mitigation indoor radon levels as determined by charcoal detector measurements in the basement during cold weather. Measurements made by homeowner prior to EPA study, and by EPA during house selection process.

** "Poor" airflow is defined here as less than 30 cfm (14 L/s) drawn by the diagnostic vacuum cleaner through a 0.5-in. (1.25-cm) suction hole when 1.5 in. H_2O (370 Pa) suction is being maintained under the slab at a test hole 4 in. (10 cm) away (when no sump present). "Excellent" airflow is defined as greater than 50 cfm (24 L/s) under the same conditions. When sump is present, suction is drawn through a 1.5-in. (4-cm) hole through sump cover, ~0.1 in. H_2O in sump; sumps connecting to drain tiles usually result in excellent flow.

TABLE 2. SUMMARY OF RADON REDUCTIONS ACHIEVED (PYLON MEASUREMENTS)

House No.	System Off* Avg. pCi/L** Bsmt	L.A.	Bsmt SSD Only Avg. pCi/L Bsmt	L.A.	Crawl Sub-Liner Only Avg. pCi/L Bsmt	L.A.	Bsmt + Crawl Avg. pCi/L Bsmt	L.A.
208	8.9	N/A	0.5	1.2	***	***	***	***
277	9.7	4.4	N/A	N/A	N/A	N/A	1.7	0.7
582	3.8	2.5	0.7	0.4	1.4	0.3	0.3	0.1
1165	4.8	3.4	0.1	0.6	3.0	2.9	0.2	0.4
1248	5.1	N/A	0.4	N/A	2.8	N/A	0.5	N/A
1357	10.5	2.5	6.2	3.5	2.8	1.3	1.1	0.4

* "System-off" values are Pylon measurements made back-to-back with the various system-on tests reported in the table. These Pylon values differ from the pre-mitigation charcoal detector levels reported in Table 1 probably due to temporal effects.

** Radon levels are the average generally of at least 48 hours of hourly Pylon measurements in the basement ("Bsmt") and in the living area ("L.A.") above the crawl space. Upstairs Pylon malfunctioned in House 1248.

***House 208 did not include sub-liner suction in crawl space.

N/A - Not available.

Conversion factors: Bq/m^3 = 37 x value in pCi/L; cm = 2.54 x value in in.; L/s = 0.47 x value in cfm; Pa = 248 x value in in. H_2O.

ENGINEERING DESIGN CRITERIA FOR SUB-SLAB DEPRESSURIZATION SYSTEMS IN LOW PERMEABILITY SOILS

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ABSTRACT

Radon mitigation by sub-slab depressurization (SSD) in houses built over soils with low permeability (less than 10^{-5} cm^2) requires different techniques than the more common case of slabs laid over permeable gravel beds. Over the past 2 years 14 slab-on-grade houses in South Central Florida with compacted soil fills and initial indoor radon concentrations between 400 and 4000 Bq/m^3 (10-100 pCi/L) were mitigated using SSD systems. Studies of these installations indicate that the completion and analysis of certain diagnostic tests can yield parameters useful to the mitigator for the design and installation of successful mitigation systems. Results from the study houses have been combined into tables and graphs that can be used to help determine recommended numbers and placement criteria of the suction holes. Fan and pipe size selection is assisted by other tabulated or derived information. Installation techniques are suggested to enhance the system operation and effectiveness.

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

INTRODUCTION

Sub-slab depressurization (SSD) is generally the most common and most effective radon mitigation strategy employed in basement and slab-on-grade houses. In many areas of the country, the standard building practice is to place a layer of coarse gravel directly beneath a vapor barrier before pouring the slab. When this has been done, an SSD system is usually quite effective

because of the good permeability and communication afforded by the gravel layer. However, many older houses were built before using gravel became a common practice and in some areas of the country gravel is not readily available. In these houses the slabs are poured over either the native soil or a fill soil that has been compacted to some degree to prevent settling away from the slab once the concrete has hardened. Most of the time such a soil fill has much lower permeability to air flow (usually less than 10^{-5} cm^2). In such instances an SSD system will not operate as effectively as it would over a coarse aggregate bed. Since much of the literature (1-4) about SSD systems addresses slabs poured over gravel, guidance in the installation of SSD systems over low permeability soils has generally been lacking. Ericson et al. (5) in Sweden and other researchers (6) have reported cases of low permeability beneath the slabs and either have made some generic observations about the average slab area affected by given suction holes or have offered unique remedies found to work in specific houses. However, no uniform guidance uniquely addressing design and installation strategies for solving this problem seems to exist.

The South Central Florida (Polk County) area is one area in the U.S. where coarse gravel is not readily available. The customary building practice is to prepare a base of fill soil, overlay it with a vapor barrier, and then pour the slab. This practice usually produces somewhat low, but fairly uniform, communication in sub-slab gas flow. From December 1987 to September 1989, 14 single-story slab-on-grade houses with living areas of about 120-240 m^2 (1300-2600 ft^2) and initial indoor radon concentrations of 400-4,000 Bq/m^3 (10-100 pCi/L) have been mitigated with (SSD) systems. The systems have ranged from central- and perimeter-located single suction hole systems to up to four central and/or five perimeter suction holes, with a variety of combinations. Suction pits ranged from no pits to up to 0.05-0.06 m^3 (12-15 gal) in size. Different sizes of fans and pipes have been installed. Suction holes were drilled through the slab and through stem walls under the slab. Fans have been located in attics and outside the houses.

There is continuing research being conducted relevant to design criteria for similar sub-slab mitigation systems in the same and other areas of Florida, across the U.S., and in other parts of the world. The University of Florida, in particular, is contributing much complementary research to houses in a different part of the state. The purpose of this report is to outline some aids in design and installation of SSD radon mitigation systems for use by mitigators working on houses where slabs are laid over uniform low-permeability soils.

BACKGROUND INFORMATION

PROBLEM ASSESSMENT

Before a mitigator or homeowner starts to design a radon mitigation system, it should of course be established that there is an indoor radon problem. It is reasonable and ethical for a mitigator to communicate to the homeowner that EPA has published guidance (7) for making reproducible measurements of radon concentrations in residences, including recommendations

for using the results to make well-informed decisions about the need for additional measurements or remedial action. Other complimentary publications that give more detail and updated information on the specific use of measurement techniques are also available (8,9).

Once it is determined that the house in fact does have elevated radon concentrations, before any other action is taken, certain basic house information needs to be obtained. Some of the most crucial elements to note include the area of the slab(s), the sub-slab media or aggregate, the floor and ceiling covering, the existence and characteristics of any interior load-bearing walls, and the existence of interior footings. Any information that can be determined about the slab/wall interface is important, as is the existence of any slab cracks and utility penetrations including plumbing lines. The type of heating and air conditioning and the location of the duct work and returns are also helpful to know. Some of this information can be obtained from the homeowner, from either existing knowledge or plans, documents, or pictures taken during construction or renovation. The rest may be visually noted or measured during a visit to the house.

A visit and visual inspection provides an excellent opportunity to check for potential radon entry points into the building shell. The cracks and utility penetrations noted above are likely candidates. One technique for detecting radon gas almost instantaneously is called the radon "sniff." It consists of pulling the gas sample through a scintillation cell while counting the alpha disintegrations detected each minute. This type of investigation is strictly a diagnostic tool and has no set EPA protocol. Such a device and procedure tests the candidate entry points for higher radon concentrations than the ambient room air.

SUB-SLAB COMMUNICATION AND PERMEABILITY

All of the information described above in the problem assessment process is useful regardless of the type of mitigation plan to be employed. Before attempting to design an SSD system, one other diagnostic test needs to be run. The diagnostic sub-slab communications and permeability measurement involves drilling at least one 30-40 mm (1.25-1.5 in.) hole just penetrating the slab in the corner of some closet or other space designated by the homeowner near the center of the slab and drilling several 10-13 mm (0.375-0.5 in.) pressure and velocity sample holes (6-10) at various distances (1-5 m or 3-15 ft) in several directions from the suction hole. A variable speed/suction vacuum cleaner is used to depressurize the volume beneath the slab at the suction hole. Instruments capable of measuring pressures in the 500-5000 Pa (2-20 in. wc) range and low flows (0.5-20 L/s or 1-40 cfm) are needed to make the sub-slab permeability measurements, and measurements down to 0.2 Pa (0.001 in. wc) are needed for the pressure field extension (communication) test. Figure 1 is a floor plan of a house in which one suction hole was drilled in a back bedroom closet and nine test holes were drilled in available corners of rooms and closets. The resulting approximate pressure contours have been drawn.

SUCTION HOLE DETERMINATION

DETERMINING THE NUMBER OF SUCTION HOLES

Once the decision has been made to install an SSD system for radon mitigation purposes, the most critical questions to answer are how many suction holes will be needed to remedy the problem and where to put them. If the house has more than one slab then, for determining the number of suction holes, each slab is treated separately. The single most useful diagnostic tool to use as input in this determination is the sub-slab pressure field extension measurement. From it, the mitigator should have a reasonable feel for what types of communications are present under the slab. The recommended procedure calls for a small test hole to be placed about 300 mm (12 in.) from the vacuum cleaner suction hole. With the vacuum cleaner set to produce about a 375-500 Pa (1.5-2 in. wc) pressure differential at that test hole, which is about what a standard mitigation fan would produce, the pressure field measurements should be taken at the various pressure and velocity sample holes. At most of the nearby holes some differential pressure may be measured, but at some of the more remote ones, more than likely no consistent reading will be possible. It is important to remember that in low-permeability soils sufficient time must be allowed for the pressure field to be established (3-5 minutes for nearby holes and successively longer times for the more remote ones). The greatest distance from the suction hole at which a definite pressure is recorded before the first zero pressure is read should be taken as the effective radius of extension, r, of the pressure field from a suction hole in that location. The analysis to follow assumes that the sub-slab medium is fairly uniform. If there seems to be reason to doubt the validity of this assumption, an additional suction hole(s) may be recommended.

Once the effective radius of extension from the suction hole is determined, the next input required is the approximate area of the slab being considered. Figure 2 is a graph in which the effective radius of extension is plotted on the x-axis (from right to left) and the area of the slab is plotted on the y-axis. The diagonal lines divide the regions of the effective coverage area of the indicated number of suction holes. Find the effective radius, of extension r, that was determined, go straight up parallel with the y-axis until you find the area of the slab. The region between the diagonals where the radius and area intersect indicates the approximate minimum number of suction holes required by that slab. This number may need to be increased if features such as interior footings, sunken slab areas, sub-slab obstructions, or geometrical shapes of the slab, seem to limit sub-slab communication. Erratic or discontinuous results of the communication test will indicate the possibility of such a condition. If the diagnostic test was made when the sub-slab soil was unusually dry, then the soil permeability and the pressure field extension determined will most probably be greater than those that would have been measured during a wetter season. Generally in low-permeability soils, there is little likelihood in producing too great a flow for the depressurizing fan, so when in doubt, an extra hole is a better option than not having enough.

DETERMINING THE SUCTION HOLE PLACEMENT

If the mitigation system is being installed in an unfinished space such as a basement where there are no restrictions on the placement of the suction holes, then the mitigator has a great amount of flexibility in making his decision. A floor plan drawn to scale, perhaps one on which the sub-slab communication is plotted, is very useful at this point. Sketching in the effective areas of pressure field extension from various suction hole placements will give an idea of the optimum configuration to ensure the best coverage of the slab. Geometry suggests that holes located about 1 effective radius, r, from the nearest exterior wall(s) will give the widest coverage. However, in practice, sometimes the soil near the edge of a slab has not been compacted as well as that near the center, producing either a possible settling space between the top of the soil and the bottom of the slab or else just a more permeable trench near the perimeter of the slab. If the diagnostic communication test indicated that a greater pressure field extension resulted from a near-perimeter suction hole than from a central suction hole without a much larger flow, then the placement of the suction holes nearer the perimeter is recommended. If, however, the communication test showed much greater flows from perimeter holes without much greater pressure field extension, then slab cracks or other leakage is probably limiting the pressure field extension, and perimeter suction holes should be avoided.

When the slab being mitigated is predominantly under finished space, such as a finished basement or a slab-on-grade house, practical locations are usually far more restricted. In such a circumstance a floor or house plan is very helpful. The finished basement scenario is probably the more difficult system to design. Usually the best locations from the homeowners' viewpoint are corners of closets because there the installations will be less noticeable and obtrusive. However, quite often closets will not be spaced to give full or adequate pressure field coverage. If that is the case, one may consider placing the suction hole in the corner of a room and then perhaps "boxing off" that corner if the homeowner does not want the pipe to show. Boxing off can be used for more central locations as well. The added difficulty with finished basement installations involves finding a place or places for the pipes to penetrate the basement ceiling which will line up with an acceptable first story floor penetration.

Slab-on-grade houses usually also have most, if not all, of the area to be mitigated as finished space. Closets may be spaced more advantageously than are often found in finished basements. Moreover, there may be a pantry or other location where a suction hole may be concealed. There may still be large areas that cannot be affected by near-closet suction holes. These are most typically open living room/dining room/kitchen/den areas. Quite likely there would be more resistance from the homeowner to placing any interior piping, even concealed, in such spaces. One possibility to pursue in such a occurrence would be an exterior suction hole penetrating horizontally through a stem wall beneath the slab rather than vertically through the slab in an interior space. What is required for such an exterior penetration to succeed is that the stem wall must be accessible from outside the house (no porches, patios, or concrete or paving directly adjacent to the outside wall where the penetration is

proposed) and that the penetration can be installed without losing the pressure field to slab cracks and stem wall leakage as was mentioned earlier with near-perimeter placement in slab-on-grade houses. If the footing is on expansive soils or there seem to be foundation or structural weaknesses near the stem wall in question, a suction hole should not be placed there.

One other possible suction point location in some slab-on-grade houses is through an attached garage area. Some garages actually have a portion of the house slab exposed at one end of the space. Even if not, other garages are a few steps down from the house floor level. In such an instance, the house stem wall may form the lower course or two of the interior wall of the garage. Then a horizontal penetration through the stem wall beneath the slab could be a good suction point. Even if the garage is just a small step down from the house slab, it may be possible to penetrate the garage slab and extend the system depressurization under the house. A potential problem with using a garage penetration is that often the garage slab has settled and/or cracked, leaving possible by-passes where garage air may be drawn into the system, reducing the effective suction head and limiting the effectiveness of the system.

FAN SELECTION

COMPARING SUB-SLAB FLOW CURVES WITH VARIOUS CURVES

While the pressure field extension measurements of the sub-slab communication diagnostic give a good approximation of an effective depressurization radius, the pressure and flow measurements are indicators of the sub-slab permeability. Specifically, recommended procedures call for the simultaneous measurement of the suction at the scaling baseline hole and flow from the 30-40 mm (1.25-1.5 in.) suction hole at suctions of at least 0.5, 2.0, and 5.0 kPa (2, 8, and 20 in. wc) produced by a vacuum cleaner. When these measured values are plotted on an x-y axis, such as in Figure 3 for the highest permeability (10^{-5} cm^2) and one of the more typical (10^{-7} cm^2) encountered in the Polk County, Florida, study houses, one obtains a flow curve for the sub-slab fill material.

Also plotted in figure 3 are fan performance curves taken from the EPA Training Course Manual (10) and from other published fan company figures. The RDS and R-150/K-6 are inline centrifugal fans designed with radon mitigation in mind. The radial and vortex blowers are higher suction instruments that may be adapted for use in mitigation systems. On such a simultaneous plotting, the intersections of the soil curves with the fan curves indicate about where the system will operate. Figure 3 suggests that, for both soils, but especially the one with the lower permeability, the system will tend to operate near the high suction/low flow end of the fan curve for the RDS, R-150/K6, or the radial blower. The fan curve data for the vortex blower did not extend further than the 1.5 kPa (6 in. wc) suction in the plot, but it obviously intersects both soil curves at higher suctions and higher flows.

FAN CHOICE CONSIDERING OTHER FACTORS

Because the mitigation field experience in low-permeability soils is still in an early phase, it is not clear what the durability of a fan will be when it

is operated at low flows and relatively high suctions. Some indications suggest that fan failure may occur sooner in such an operating environment. The fans are often placed in attics which will be quite hot during the cooling season. High heat with low flows through the fans may lower the durability of the fans. Research is currently underway to determine if the system deteriorates with time or if it is maintained fairly constant until some type of failure occurs abruptly. Harrje et al. (11) at Princeton University have developed a diagnostic which investigates the durability of the fan as well as the mitigation system as a whole.

The inline centrifugal fans, since they have been designed for radon mitigation situations, have been kept fairly lightweight and affordable. The blowers that produce the higher suctions are generally built for industrial applications and therefore are somewhat heavier and more costly. The power requirements to operate these various fans may differ quite widely. The lightweight inline fans are designed to perform in the 100-200 W power range. The heavier, higher suction blowers will sometimes have several times this power requirement. Therefore, the operating costs may vary greatly with the choice of mitigating fan. Since research data have not been collected for a long enough time in this area, it is not clear how to predict the long-term costs of these various systems. If the inline fans have too short a lifetime, replacement costs may make this system more expensive. If their durability is long enough, then their lower initial cost and operating costs may make them the more cost-effective system.

The inline centrifugal fans are designed to run very quietly (less than 6 sones) and, according to most reports, receive very little, if any, criticism from homeowners in this regard. However, the larger, more powerful blowers, especially if designed for industrial applications, characteristically produce quite a bit more noise, often a steady, high-pitched whine. This noise factor usually is dealt with by installing the fan as far from the living space as possible and including soundproofing when the system is first installed. Both of these options may increase the initial installation costs, and a remote fan placement will require longer piping runs which may reduce the system effectiveness. Even with the additional precautions to limit the noise output, some people sensitive to noise may still object to the larger fans.

Decisions on interior versus exterior suction holes and piping definitely have a bearing on fan selection. If the exhaust pipe from suction holes in a basement is routed through a rim joist to the outdoors, or if a suction hole in a slab-on-grade house is through an exterior stem wall, then the fan will probably be placed somewhere outside the house. Such a fan must be rated for exterior applications. In some model lines these fans are more expensive than interior fans. The ease of handling and weight of the units with the supports required are other factors to consider in the fan selection process.

PIPE SELECTION

Generally most mitigators use PVC pipe when installing SSD systems. It is lightweight, easy to cut and handle, convenient for fittings and accessories, strong in its glueing characteristics, noncorrosive, and smooth so as to offer

low resistance to air movement. For permeable sub-slab environments conducive to high volumes of airflow, 100 mm (4-in.) or larger PVC pipes are generally used. For the low flows resulting from the low permeability soils addressed in this document, 100 mm (4-in.) or smaller PVC pipes are usually adequate. The smaller piping has the added advantages of being lighter and easier to handle, less obtrusive to the homeowner, easier to conceal if desired, and usually less expensive for the pipe, fittings, and accessories. Therefore, an important determination is what size of pipe is the best to use for the given mitigation project.

AIRFLOW VERSUS APPLIED SUCTION

The choice of pipe size is most directly governed by the volume rate of flow (or velocity) expected to move through the pipe. The larger the volume moving, the greater the resistance if the cross sectional area is kept constant. However, increasing the pipe size will lower the frictional loss for a given volume rate of movement. Therefore, the best inputs for estimating the optimum pipe size for a mitigation system again come from the sub-slab communication diagnostic pressure/flow measurements. If the fan has been selected that is expected to be used in the mitigation system, then the point of intersection of the fan curve with the sub-slab flow curve will give a good approximation of the airflow that can be expected in the system.

From the airflow estimate, one may use a chart such as Figure 4 to estimate the friction loss in various sizes of pipes or ducts. This chart, like most of the available documentation on airflow through pipes or duct work (12), is calculated for "average" pipe, which is usually some type of iron pipe with a given smoothness and joints estimated to be present at some regular frequency. PVC pipe is quite a bit less resistive to air movement because of its greater smoothness. Therefore, these approximations usually overestimate the friction loss that would actually be found in PVC pipes. If the fan selected is one in which the sub-slab flow curve intersection with the fan curve is in the 375-500 Pa (1.5-2 in. wc) range, then one would probably want to keep the friction loss to 0.8-1.5 Pa/m of pipe. If the fan curve intersects the sub-slab curve at something greater than 1 kPa (4 in. wc), then a friction loss of 3-5 Pa/m of pipe could be tolerated.

To use a chart such as Figure 4, find on the y (vertical) axis the airflow determined from the sub-slab/fan curve intersection. Go across horizontally until you are in the friction loss range (x-axis) you determined as above. The closest pipe size diagonal (those rising from left to right) would be approximately the best pipe size to achieve your goal. It is advantageous from the perspective of friction loss to go with the larger pipe, but if other factors such as expense, ease of handling, or homeowner preference indicate otherwise, the smaller pipe would probably still be a safe choice, especially in light of the lower friction of PVC pipe discussed previously.

The friction loss in straight pipes is only part of the loss of suction head that is experienced in a system. Usually the next most significant features contributing to friction loss are the bends or tees in the system. A

90° elbow or tee in a pipe usually contributes the greatest pressure drop potential of any of these features. A 45° elbow has slightly over half the friction loss of a 90° elbow, and a 30° elbow has less than half that of a 90° one. Table 1 lists the approximate length of pipe that produces the same friction loss as each of several of the more commonly used connectors.

TABLE 1. APPROXIMATE FRICTION EQUIVALENCIES FOR VARIOUS FITTINGS

	Equivalent Run of Pipe (m)			
	Pipe Diameter (mm)			
Type of Fitting	37.5	50	75	100
Tee	0.5	0.6	1	1.5
90° Elbow	0.3	0.5	0.6	1
45° Elbow	0.25	0.3	0.5	0.6
30° Elbow	0.15	0.25	0.3	0.5

To determine the friction loss in Pascals (Pa) for a system, determine the total length of pipe and the number and kinds of fittings for each pipe size. Multiply the number of fittings for a pipe size by the equivalency from Table 1 for that fitting and pipe. Add the total equivalent meters so determined to the actual length of pipe to be used to get the adjusted total length of pipe. Then use the friction loss factor determined from Figure 4 to multiply by that adjusted total. Repeat the calculation for each pipe size and add the total together for the whole system.

APPLICABILITY AND AVAILABILITY

If the above calculation indicates a larger pipe size than is feasible or desired by the homeowner, then perhaps a fan that can draw a larger suction at lower flows is called for. If, however, a certain pipe and fitting size is determined that is acceptable, then local supply stores should be investigated to ensure that enough pipe, fittings, and accessories are easily available. PVC pipe comes in a variety of thicknesses (sometimes called schedules). The thicker walls are for high-pressure applications; consequently that PVC is heavier and more expensive. The applications described here require no extra thickening, so the thinnest-walled PVC pipe is usually adequate and preferred for its weight, ease of cutting, and cost. However, some of the fittings and couplings for one schedule will not fit properly or tightly on the same size pipe of a different schedule. So a crucial part of the pipe selection process is that there be an adequate supply of fittings and accessories for the size and schedule of the PVC selected. Other couplings, reducers, bushings, etc., should be investigated at this phase of the process to ensure complete compatibility and availability for the system. These are used chiefly at the various interfaces--pipe to slab, pipe to fan, and fan to exhaust.

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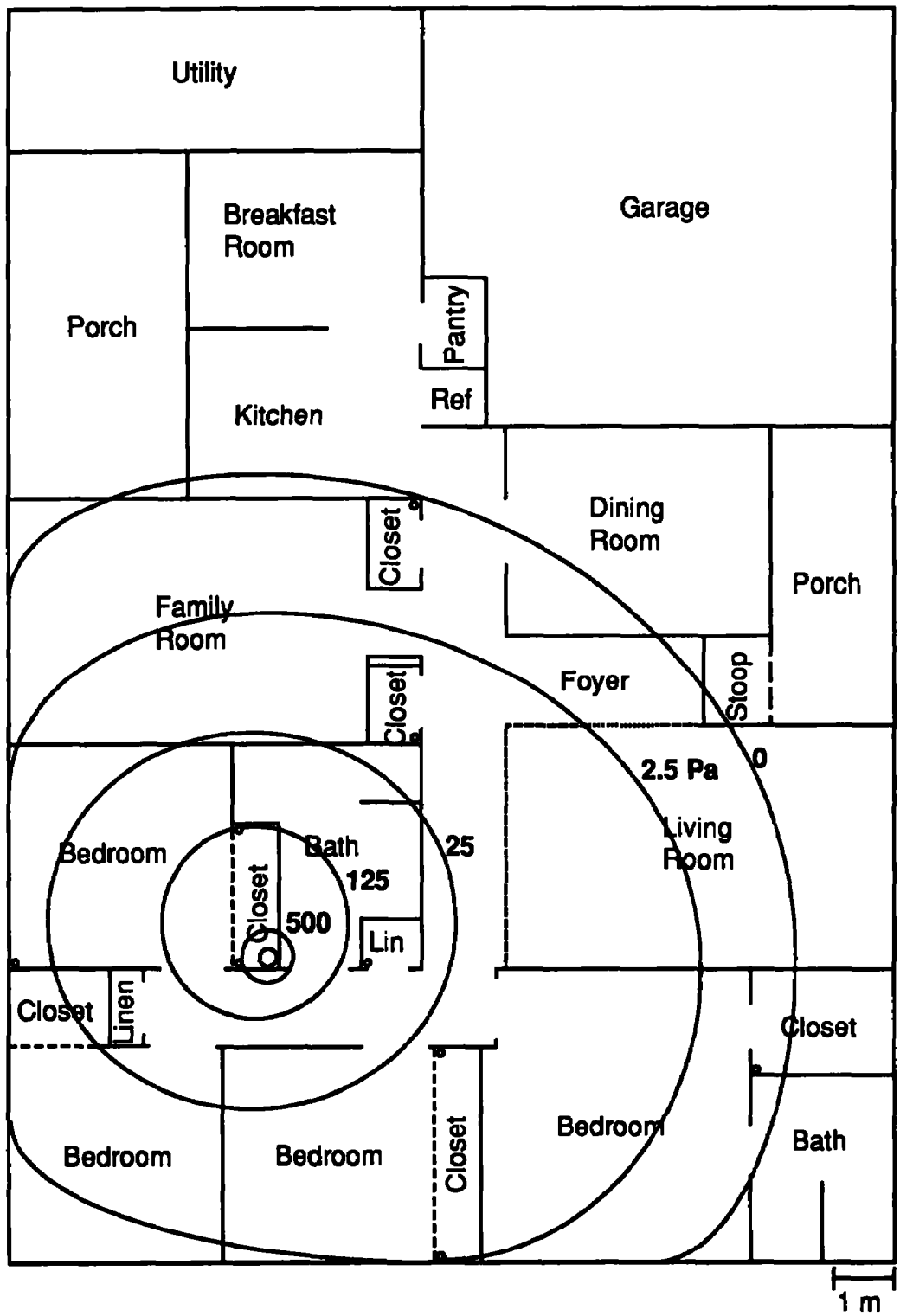

Figure 1. Approximate pressure contours from a suction hole in a representative house plan (5 kPa suction at suction hole).

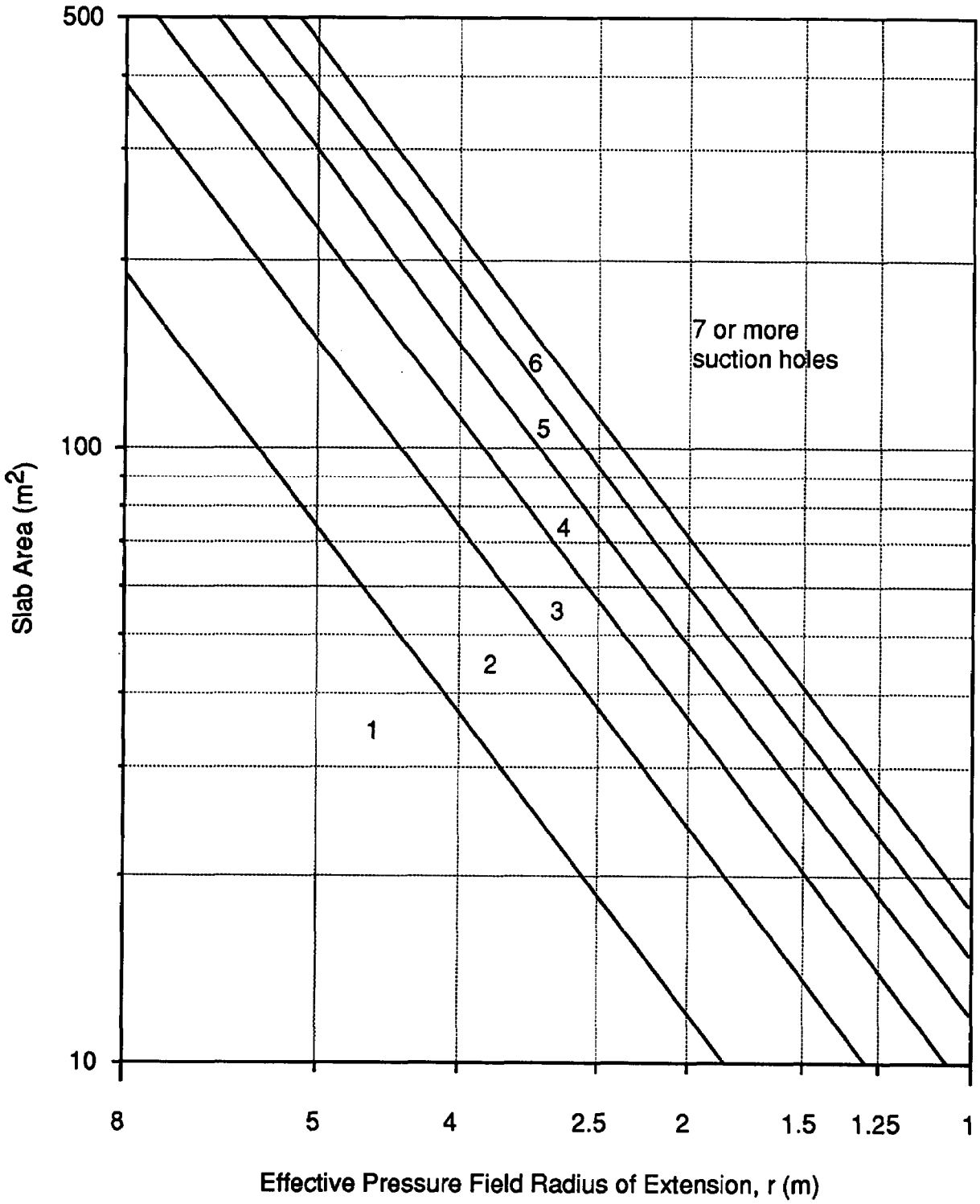

Figure 2. Minimum number of suction holes based on effective radius of extension, r, and area of slab.

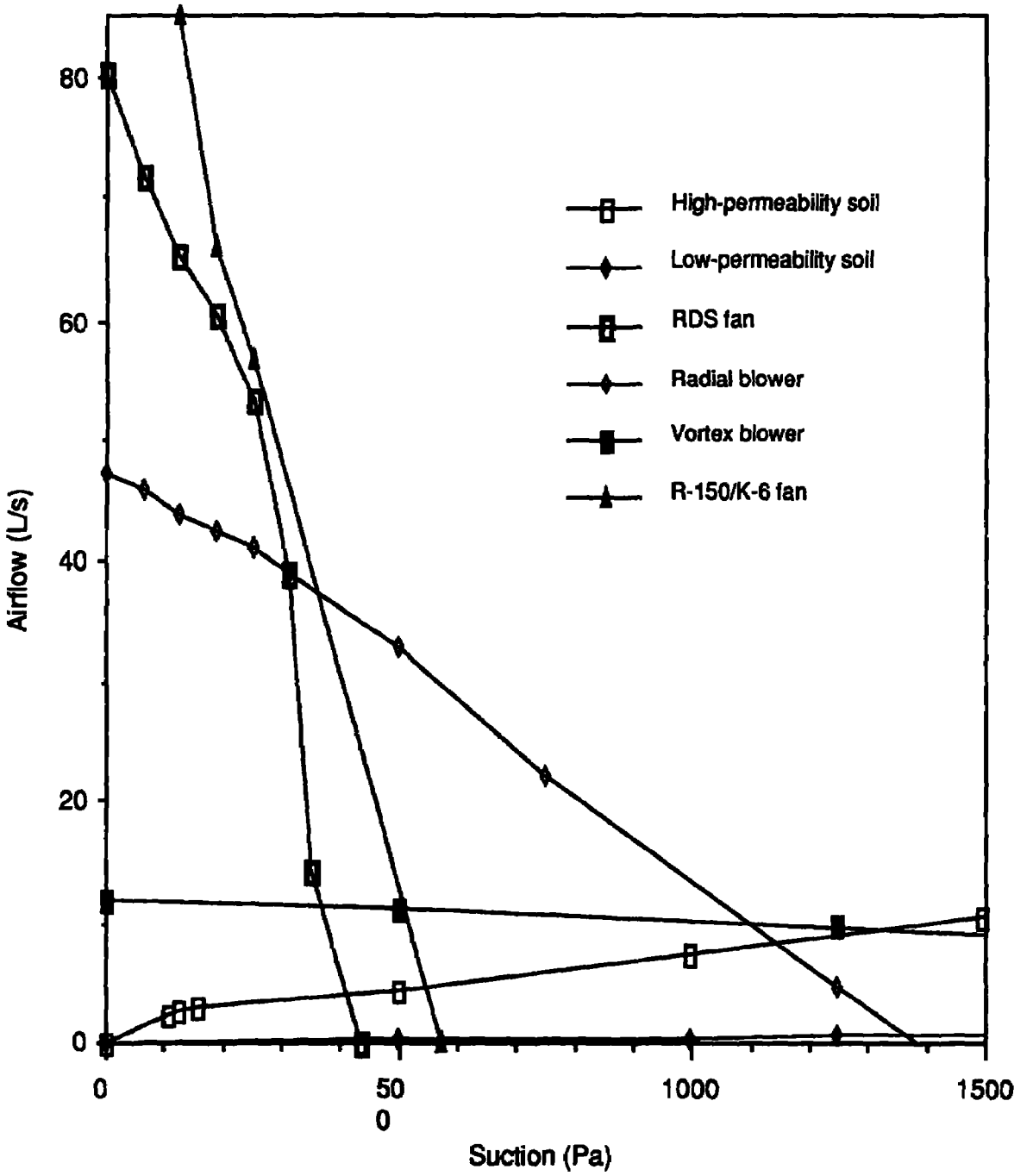

Figure 3. Sub-slab curves for two permeabilities plotted with fan curves for four different kinds of fans.

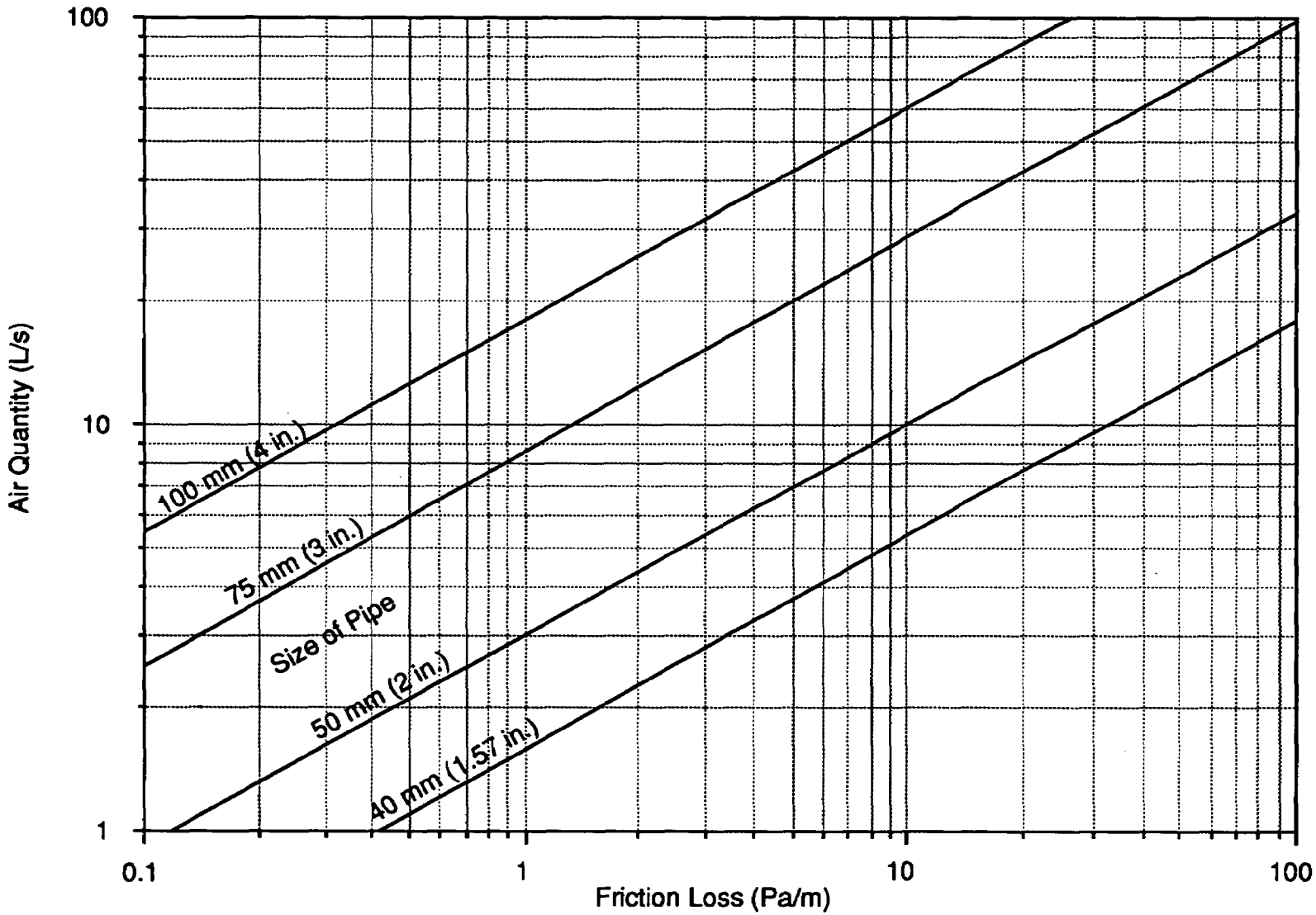

Figure 4. Friction chart for average pipes.

RADON MITIGATION TECHNIQUES FOR BASEMENT HOUSES WITH POOR SUB-SLAB COMMUNICATION

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ABSTRACT

While the sub-slab depressurization (SSD) technique is widely used to mitigate radon levels in basement houses, there are instances for which this method is not a viable option. For example, in some houses the slab is poured directly on the soil resulting in poor-to-nonexistent communication under the slab. To apply SSD methods requires elaborate plumbing and multiple suction holes in the slab. In an effort to develop viable alternatives, EPA has funded research to explore other radon mitigation options. Case studies will be presented that include: basement pressurization with and without heat extraction, and filtration using charcoal. In the first, air from the upper portion of the house was forced into the basement producing a pressure barrier at the slab/soil interface. In one case heat was extracted from the upstairs air using a heat pump to supply hot water for the occupants. The air filtration method used a bed of charcoal to remove the radon gas. The charcoal bed was flushed with outdoor air to extract the radon before it decayed completely to radon daughters.

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

INTRODUCTION

Phase I of this EPA Radon Mitigation Demonstration, in Nashville, Tennessee, identified many basement houses which had poor sub-slab communication. In attempting to implement a sub-slab depressurization (SSD) system in houses such as these, special attention had to be taken to ensure an adequate means to prevent radon entry into the basement. In an effort to determine if less expensive techniques were available that might have a higher probability of success, the mitigation methods described below were investigated. These techniques may be applicable in other areas such as Central Florida where the lack of communication under the slab increases the complexity of SSD systems.

DESCRIPTION OF HOUSES

Nine houses were selected for the Phase II demonstration in Nashville, TN. Of these, six are basement houses and three are crawl space houses. Of the six basement houses only four have been mitigated as of the date of this paper. A brief description of these four houses follows. A final EPA report describing all of the mitigation efforts in Nashville should be available by the summer of 1990.

DW 01 is a one story frame house with brick veneer upstairs. The basement is a daylight walkout at the back of the house with walls of concrete block. The basement area is approximately 70% finished with a bedroom and den in the front (below-grade) part of the basement and an unfinished laundry room and workshop at the rear. The heating system for the house includes a central heat pump which is seldom used and two wood stoves, one upstairs and one in the finished basement. There are no other combustion appliances in the house. Charcoal measurements made in the winter of 1987-88 in the basement by the homeowner showed the radon level to be 21.4 pCi/L. Results of blower door infiltration measurements at 4 Pa showed 2 ACH (air changes per hour) for the basement and 1.4 ACH for the whole house.

DW 35 is a two story frame house with brick veneer on the exterior. The basement is almost totally below grade with walls of cut stone. The basement is semi-finished but unused because of water problems. A central gas fired furnace in the basement has numerous leaky joints around attempted seals with asbestos tape. Also located in the basement are a gas fired clothes dryer and water heater. Visual inspection showed numerous thermal bypasses from the basement to upstairs. A seldom-to-never used fireplace is located in one room of the basement. The flue has been closed loosely with sheet metal but still shows air exfiltration. A previous radon measurement in the basement was 18 pCi/L. Infiltration measurements at 4 Pa showed that the basement was very leaky: 6.3 ACH for the basement, and 4.4 ACH for the whole house.

DW 38 is a one story brick veneer house with a walk-out daylight basement. The walls of the basement are concrete block with three of the walls about half below-grade by about 3-4 ft (0.92 - 1.22 m). The basement is 50% finished with a den in one part and a laundry room and work shop in the other. The heating and air-conditioning (HAC) system is a central unit in the basement (heat pump) with very leaky ductwork (both supply and return). There were no combustion appliances in the basement. Previous measurements in this house were 11.1 pCi/L in the basement. Infiltration measurements at 4 Pa resulted in values of 2.8 ACH for the basement and 1.6 ACH for the whole house.

DW 47 is a single story frame/brick veneer house with a walk-out basement. The homeowner was in the process of finishing the basement when mitigation was undertaken. The walls of the basement are concrete block with three sides below grade. The house is totally electric with the air handler located upstairs. The basement contained a roughed-out opening for a fireplace with a large amount of bypass area to the upstairs flue box. Also located in the basement is a heat pump water heater using basement heat. Previous radon measurements by the homeowner were 13.1 and 16.9 pCi/L upstairs and 21.1 pCi/L in the basement. Infiltration measurements at 4 Pa gave values of 2.4 ACH for the basement and 1.3 ACH for the whole house.

MITIGATION SYSTEMS

In three of the houses (DW 01, DW 38, and DW 47), radon levels were mitigated by pressurizing the basement with air withdrawn from upstairs. This was done in two of the houses (DW 01 and DW 38) by using an in-line blower with maximum flow capability of approximately 400 cfm at 0 in. H_2O (11.35 m^3/min at 0 Pa) (T3A Turbo 8, R.B. Kanalflakt, Inc., Sarasota, FL). In DW 01 the air inlet was located in the central hallway of the house and in DW 38 it was located in the floor of the kitchen.

In the third house (DW 47) a heat pump water heater (HPV-80, Therma-Vent™, Therma-Stor Products Group, DEC International, Inc., Madison, WI) was used to withdraw air from the upstairs area, down through the heat pump, and then exhaust the air into the basement. The heat extracted from the air was used to provide hot water for the homeowner. In DW 47 the air inlet was located in the central hallway.

Several parameters of each of these three houses were monitored and recorded using a datalogging device. The parameters were: air temperatures upstairs, in the basement, and outdoors; air pressure differentials between the basement and upstairs, between the basement and outdoors, and between the basement and the sub-slab region; wind speed and direction; rainfall amounts; HAC operation; and continuous radon levels both in the basement and on the first floor. The monitoring period was quite long, ranging from several weeks to months in duration. Due to space limitations, the bulk of this monitoring data cannot be listed and explained in this paper.

A major point considered for this type of mitigation system was the amount of sealing required in the basement to achieve sufficient

overpressurization while keeping the airflow rate down to less than 300-400 cfm (8.51 - 11.35 m^3/min). Also considered were the effects of such a system on the air infiltration of the house. Air infiltration was measured to determine how much of an energy penalty the system imposes on the house. Results of these studies will be included in the EPA final report.

In the remaining basement house (DW 35) an off-the-shelf activated charcoal air cleaning unit (Radsorb-222, RAd Systems, Inc., Westborough, MA) was used to remove the radon gas from the basement air. In this device the radon gas adsorbed by the charcoal is removed by reverse flushing to the outdoors before the radon completely decays to its daughter products and remains trapped in the charcoal bed. The radon levels in both the basement and the first floor were continuously monitored over a period of several months.

HOUSE MITIGATION RESULTS

These houses were mitigated during 1989. Because of the length of monitoring time, the mitigations extended from January through November of 1989. Prior to mitigation, long term alpha track detectors (ATDs) were installed in the houses. ATDs were obtained from Tech-Ops Landauer, Inc. (Glenwood, IL). The results of these pre-mitigation measurements are shown in Table 1. The radon levels in the basements ranged from 9.4 to 24.4 pCi/L and the levels on the first floor ranged from 4.9 to 10.4 pCi/L. Short term (3 day), closed house, charcoal canister (CC) measurements were carried out just prior to mitigation. Charcoal canisters were provided and analyzed by Scientific Analysis, Inc. (Montgomery, AL). These results are shown in Table 2. The agreements between the ATD results and the CC values are not as good as might be expected. The differences are attributed to differences in the time of year and to weather. The average levels in the basement and on the first floor for both the CC and the ATD measurements are summarized in Figure 1.

House DW 47

The first house to be mitigated was DW 47 using the HPV-80 device. The radon levels in the basement and on the first floor along with the house parameters were continuously monitored beginning on 1/31/89. The continuous radon monitor (CRM) values during the pre-mitigation period averaged 13.1 pCi/L in the living room and 18.1 pCi/L in the basement. The HPV-80 system was installed on 3/15/89, and the openings between the basement and upstairs were sealed the following day. The major openings that were closed were the bypass to the chimney flue, the water and sewer pipe penetrations, and an opening in the sub-floor below the HAC. Since the basement was largely unfinished, sealing these openings was simple and effective. The HPV-80 fan was turned on at 6:40 pm on 3/15/89. The radon levels began to decline within 6 hours, and within 12 hours the levels were less than 2 pCi/L in both the basement and on the first floor. The CRMs remained in the house until 4/13/89. Over this post-mitigation period the average radon levels were 1.8 pCi/L in the basement and 1.7 pCi/L on the first floor.

Prior to turning on the HPV system, the basement pressure was averaging about 2.5 Pa below ambient outdoor pressure. With the system on,

the basement pressure was approximately 2.5 Pa above ambient outdoor pressure. The HPV system flowrate was 141 cfm (4.00 m^3/min) measured at the exhaust outlet in the basement. On 4/4/89 the HPV system was shut down for approximately 48 hours and then was turned back on. The pressure changes over this period are shown in Figure 2, and the changes in the radon levels are shown in Figure 3. During the time the HPV system was on, the sub-slab pressure was averaging about 2 Pa below the basement pressure, and the basement was about 2.5 Pa above the outdoor pressure. With the HPV system off, the sub-slab pressure increased to 1 Pa or less (below the basement pressure) and the basement pressure decreased to about -3 Pa relative to the outdoors. The radon levels in both the basement and on the first floor increased by factors of 5 or more. When the system was turned back on, the levels decreased sharply as seen in Figure 3. Overall the reduction in radon levels was approximately 92% in the basement and 83% on the first floor.

House DW 38

The second house to be mitigated using basement pressurization was DW 38. In this house an in-line duct fan was used to pull air from the kitchen upstairs. The air was then distributed in the basement in two zones, the finished den and the unfinished workshop. The mitigation system was installed and energized on 4/25/89. Prior to mitigation, the radon levels and house parameters were monitored beginning on 4/13/89. The average pre-mitigation radon levels measured with the CRMs were 10.6 pCi/L on the first floor and 14.6 pCi/L in the basement. Also over this period, the average basement pressure was approximately 1 to 2 Pa below the outdoor ambient pressure, and the sub-slab area pressure was approximately 2 Pa more positive than the basement. During the initial mitigation a small fan [158 cfm at 0 in. H_2O (4.48 m^3/min at 0 Pa), model R125, Fantech, Inc., Sarasota, FL] was used. It was soon apparent that the fan could not supply sufficient airflow to overcome the leaks to the upstairs and to the outdoors. A larger fan was installed [410 cfm at 0 in. H_2O (11.63 m^3/min at 0 Pa), model T3A Turbo 8, R.B. Kanalflakt, Inc., Sarasota, FL] to pressurize the basement.

Sealing this house was difficult because of limited access to the overhead from the basement. The finished basement ceiling had acoustic tile attached directly to the floor joists. Also, the homeowner had made several changes in the electrical and plumbing systems over the years and consequently left many openings. The HAC system located in the unfinished part of the basement not only had many leaks in the cold air return but also had a return vent in the finished area of the basement that had to be sealed off. To prevent the pressurization air from leaking back upstairs through the return duct, a back-draft damper was constructed at the return opening upstairs. Also, to prevent back-flow through the supply vents in the basement, back-draft flaps of vinyl were attached to the outside of the supply grills. Also, a direct path to the attic in the basement stairwell required sealing. In summary, this house was extremely difficult to seal. The basement and the upstairs were never completely isolated.

Following installation of the larger pressurization fan and sealing of as many of the openings as possible, the pressure difference between the basement and the sub-slab region was on the average reduced to zero. The

basement was never pressurized above the outdoor ambient conditions. However, by achieving a neutral pressure difference relative to the sub-slab, radon gas flow into the basement was significantly reduced. No condensation problems were observed with the kitchen air pulled down into the basement. The radon levels in the basement, as measured with the CRM, averaged 1.3 pCi/L. These levels were confirmed with CC measurements carried out on 8/22-24/89. The CC results, shown in Table 2, were 1.2 pCi/L in the basement and 0.9 pCi/L on the first floor.

House DW 01

Radon in this house was mitigated over the period from 10/2/89 to 10/6/89. Prior to mitigation the datalogging system was installed on 9/13/89 and remained until 11/6/89. The pre-mitigation radon levels in this house were 19.5 pCi/L in the basement and 9.8 pCi/L on the first floor as measured with CCs and shown in Table 2. The average radon levels recorded with the CRMs (model R210F radon monitor, Femto-Tech, Inc., Carlisle, OH) were 22.5 pCi/L in the basement and 8.5 pCi/L on the first floor. The basement pressurization mitigation system was installed and turned on at approximately 4:00 p.m. on 10/3/89. Sealing of the basement openings to the upstairs and to the outdoors was delayed until 10/5/89. With only the pressurization fan installed and no additional sealing, the radon levels dropped within 6 hours to 2.8 pCi/L upstairs and 4.2 pCi/L in the basement. This is shown in Figure 4. The average pressure in the basement relative to: the outdoors changed from -0.4 to -0.2 Pa, the upstairs from +0.03 to +2.30 Pa, and relative to the sub-slab area from -0.1 Pa to zero. With a limited amount of sealing the radon levels dropped further to 1.6 pCi/L upstairs and 1.9 pCi/L in the basement. The average pressures in the basement increased to +1.1 Pa relative to the outdoors, +2.4 Pa above the upstairs, and +0.14 Pa above that under the slab.

On one occasion, the homeowner inadvertently left the door between the upstairs and basement open for most of a day. During this time the pressurization was lost in the basement and the radon levels in both the basement and the first floor increased sharply. These results are shown in Figures 5 and 6, respectively.

The radon levels and the house parameters were monitored until 11/6/89. The radon levels in the basement averaged 1.2 pCi/L and on the first floor 1.1 pCi/L. These levels were confirmed with CC measurements carried out over the period 11/6-8/89. These tests gave the results (shown in Table 2) of 0.2 pCi/L in the basement and upstairs.

House DW 35

This house was mitigated with the charcoal adsorption unit (Radsorb-222). The unit was installed on 5/30/89. Continuous radon monitors (model R210F radon monitor, Femto-Tech, Inc., Carlisle, OH) were installed prior to installation on 5/18/89. Pre-mitigation radon levels averaged 11.2 pCi/L in the basement and 5.4 pCi/L on the first floor. The charcoal

adsorption unit was operated more-or-less continually for the next 6 months. Monitoring of the radon levels in the basement and upstairs continued throughout most of this period. Monitoring was interrupted on several occasions by failure of the CRM devices. The failures were due to excessive moisture levels in the basement. Over the last period for which data were available for this paper, the average levels measured by CRMs (model AB5 with PRD1 passive cells, Pylon Electronics Development Co., Inc., Ottawa, Canada) were 5.5 pCi/L in the basement and 4.2 pCi/L upstairs. The CRMs also indicate that during heavy rains the levels can increase drastically. During one such rain storm on 10/17/89 the levels increased to about 54 pCi/L in the basement and 25 pCi/L upstairs. Following the rain storm, the charcoal device reduced the levels to 6.4 pCi/L in the basement and 3.5 pCi/L upstairs within 24 hours. The radon levels in both the basement and the living area over this period are shown in Figure 7.

Post-mitigation CC measurements were carried out over the period 11/6-8/89 as shown in Table 2. These levels are higher than those measured with the CRMs over a much longer period. However, the CC measurements were begun shortly (about 6 hours) after a storm dropped approximately 1.2 in. (3.05 cm) of rain in the area. CRMs will be used to monitor this house for some additional period of time. Also, long term ATDs have been installed both in the basement and upstairs.

CONCLUSIONS

The basement pressurization technique has been applied to three houses of differing age and construction type. In one house heat was extracted from the upstairs air before pressurizing the basement. The degree of success in reducing the radon levels with this method is determined by how tight the basement can be made to air leaks to the outdoors and to the upstairs. Changes in house tightness are currently being quantified. For houses in which the HAC system incorporates continuous ductwork in good condition, the sealing is not too difficult. For houses in which the floor joists are used as the sides of cold air return ducts, sealing can be very difficult and time consuming. Each house has to be evaluated on its own. Use of diagnostic tests such as blower door measurements can aid in the evaluation prior to mitigation system design. The charcoal adsorption technique is currently under test in one house. The device is capable of reducing moderate levels (10 to 15 pCi/L) of radon to levels that approach 4 pCi/L. However, the device cannot control rapidly increasing levels as produced during water capping of the surrounding soils. The long-term effectiveness of the device is currently under study.

TABLE 1. ALPHA TRACK DETECTOR MEASUREMENTS FOR NASHVILLE PHASE II BASEMENT HOUSES

Location Code	Date Installed	Date Removed	Days Exposed	Radon Level (pCi/L)	Comments
DW 01-B*	09/22/88	09/14/89	357	12.6	Pre-Mitigation
DW 01-B	09/22/88	09/14/89	357	16.2	Pre-Mitigation
DW 01-L*	09/22/88	09/14/89	357	5.4	Pre-Mitigation
DW 01-L	09/22/88	09/14/89	357	5.0	Pre-Mitigation
DW 35-B	09/20/88	05/30/89	252	9.4	Pre-Mitigation
DW 35-B	09/20/88	05/30/89	252	9.6	Pre-Mitigation
DW 35-L	09/20/88	05/30/89	252	5.4	Pre-Mitigation
DW 35-L	09/20/88	05/30/89	252	4.9	Pre-Mitigation
DW 38-B	09/21/88	05/04/89	225	11.1	Pre-Mitigation
DW 38-B	09/21/88	05/04/89	225	11.2	Pre-Mitigation
DW 38-L	09/21/88	05/04/89	225	9.9	Pre-Mitigation
DW 38-L	09/21/88	05/04/89	225	9.3	Pre-Mitigation
DW 47-B	09/21/88	03/16/89	176	12.5	Pre-Mitigation
DW 47-B	09/21/88	03/16/89	176	24.4	Pre-Mitigation
DW 47-L	09/21/88	03/16/89	176	8.1	Pre-Mitigation
DW 47-L	09/21/88	03/16/89	176	10.4	Pre-Mitigation
DW 47-B	04/13/89	10/03/89	173	1.6	Post-Mitigation
DW 47-B	04/13/89	10/03/89	173	1.5	Post-Mitigation
DW 47-L	04/13/89	10/03/89	173	1.7	Post-Mitigation
DW 47-L	04/13/89	10/03/89	173	1.5	Post-Mitigation

* B - Basement, L - 1st Habitable Level Above Basement

TABLE 2. CHARCOAL CANISTER MEASUREMENTS FOR NASHVILLE PHASE II BASEMENT HOUSES

House ID	Date Started	Date Stopped	Radon Level (pCi/L) Basement Test 1	Basement Test 2	1st Habitable Level Test 1	1st Habitable Level Test 2	Comments
DW 01	9/13/89	9/15/89	19.0	20.0	9.6	9.9	Pre-Mitigation
DW 01	11/6/89	11/8/89	0.3	0.1	0.1	0.2	Post-Mitigation
DW 35*	11/6/89	11/8/89	9.6	9.2	6.3	6.1	Post-Mitigation
DW 38	4/4/89	4/6/89	17.5	17.8	13.6	13.6	Pre-Mitigation
DW 38	8/22/89	8/24/89	1.3	1.1	1.0	0.8	Post-Mitigation
DW 47**	3/14/89	3/16/89	4.6	4.7	1.8	1.9	Pre-Mitigation

* Time constraints did not permit pre-mitigation charcoal measurements
** Post-mitigation charcoal measurements could not be made due to homeowner's constraints

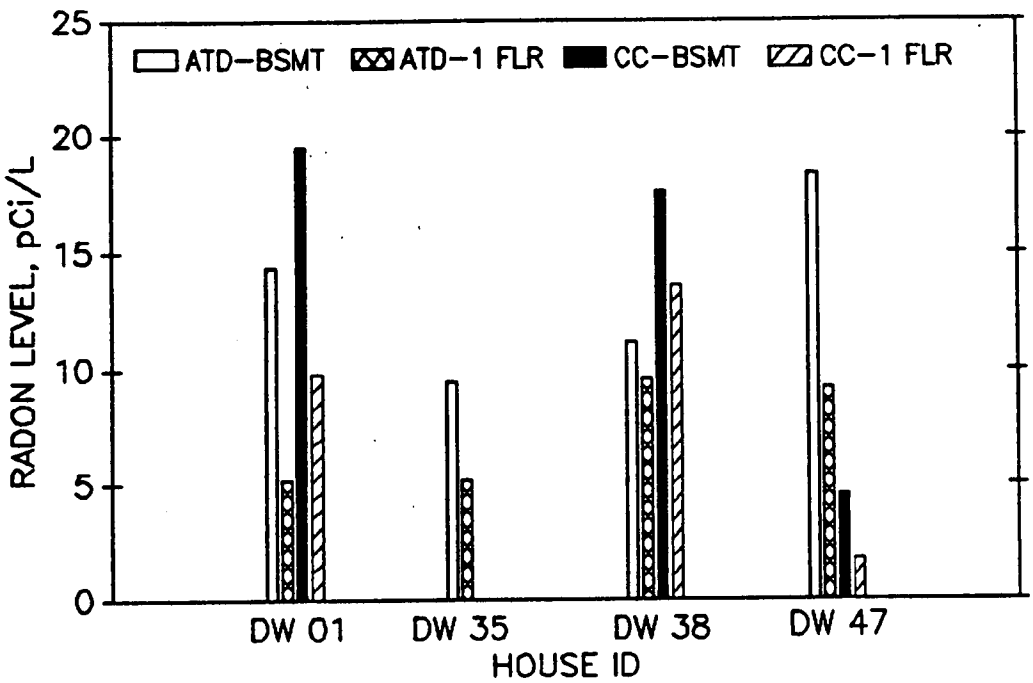

Figure 1. Pre-mitigation ATD and CC results (no CCs at DW 35).

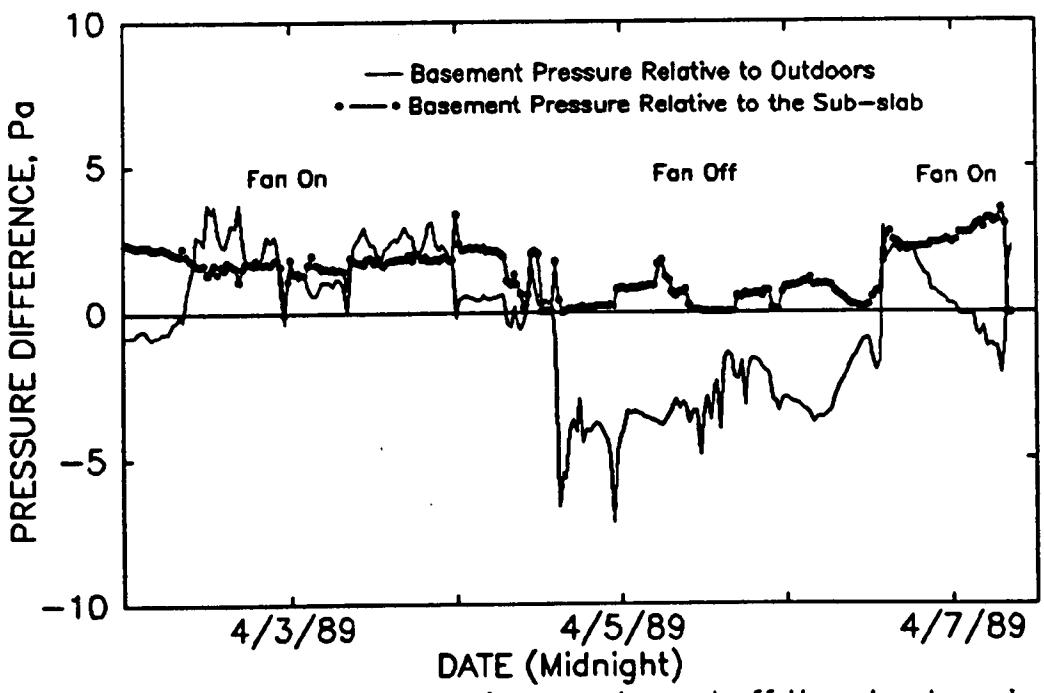

Figure 2. ΔP changes as the fan was turned off then back on in DW 47.

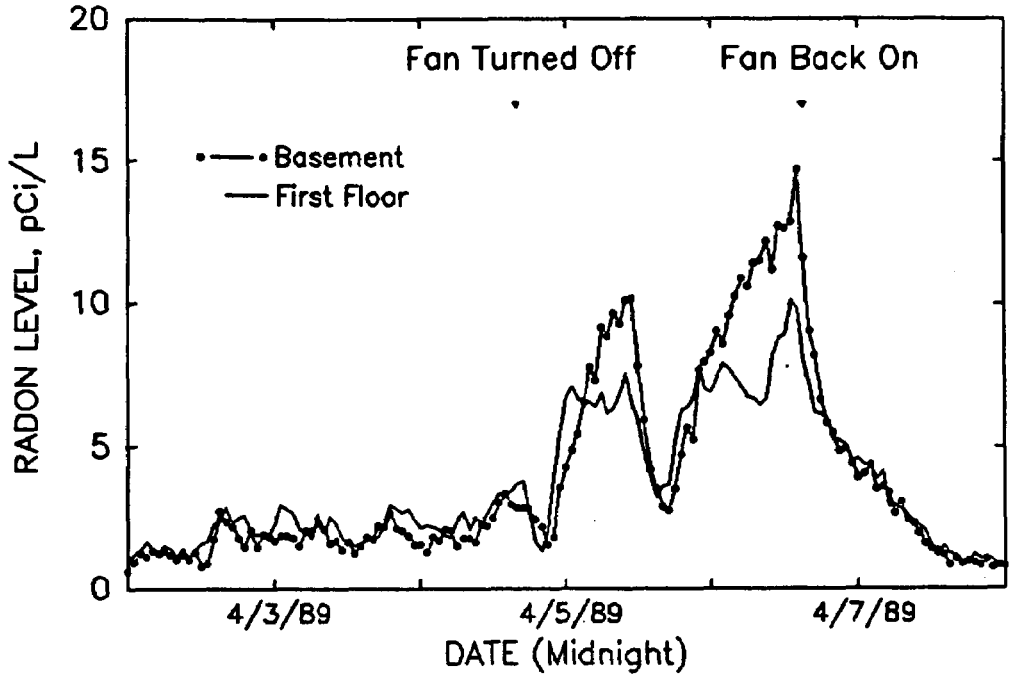

Figure 3. Radon level changes as the fan was turned off then back on in DW 47.

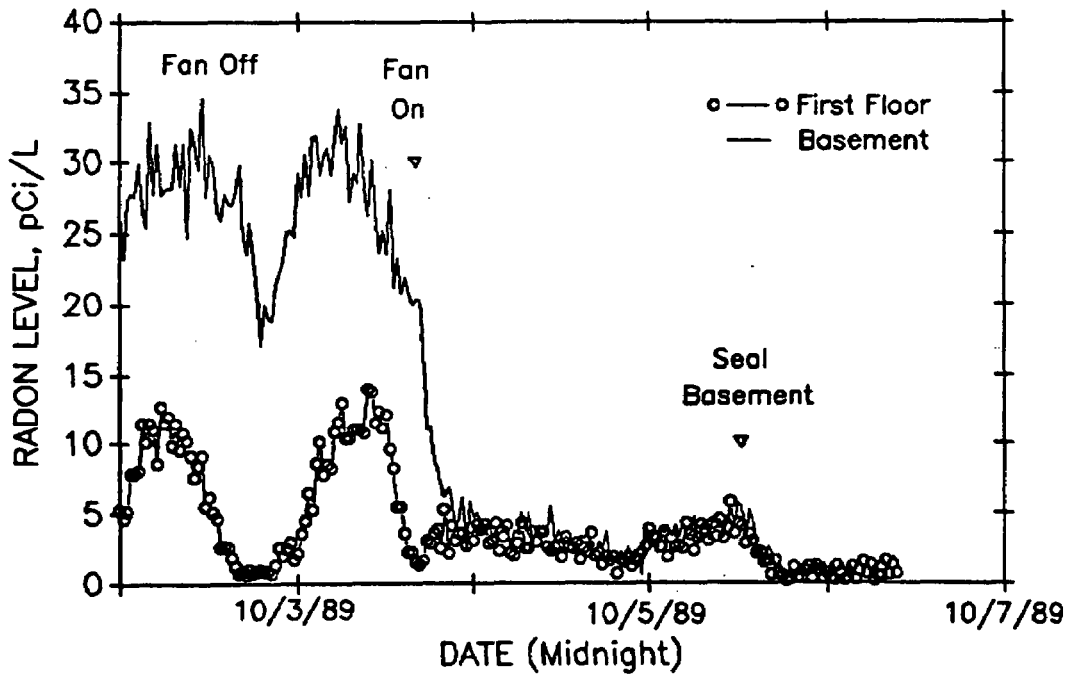

Figure 4. Changes in radon levels as the fan was turned on and as the basement was sealed in DW 01.

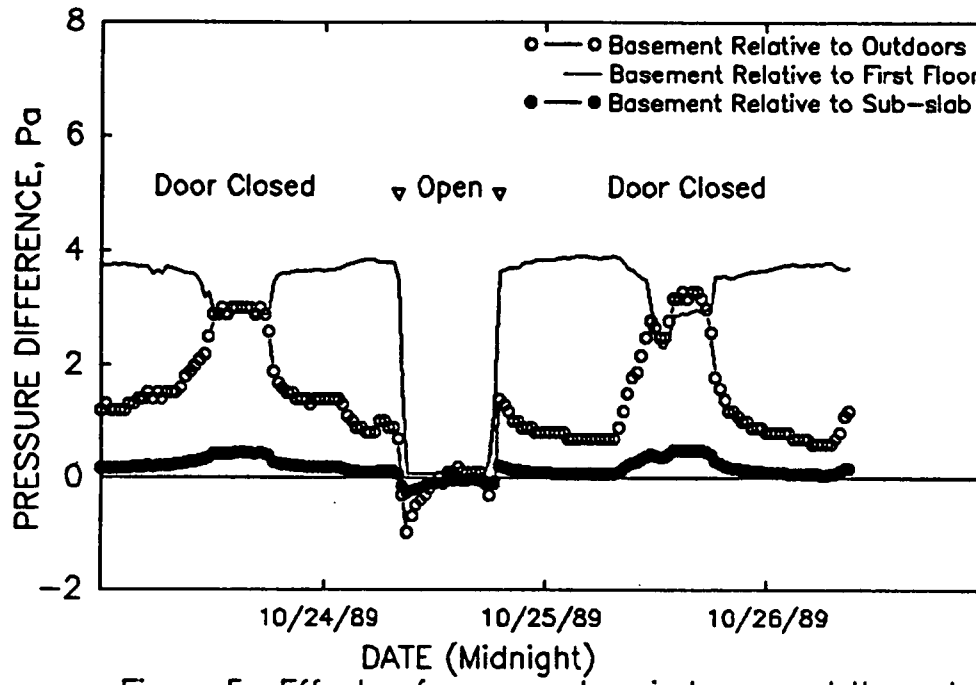

Figure 5. Effects of pressure loss in basement through door left open in DW 01.

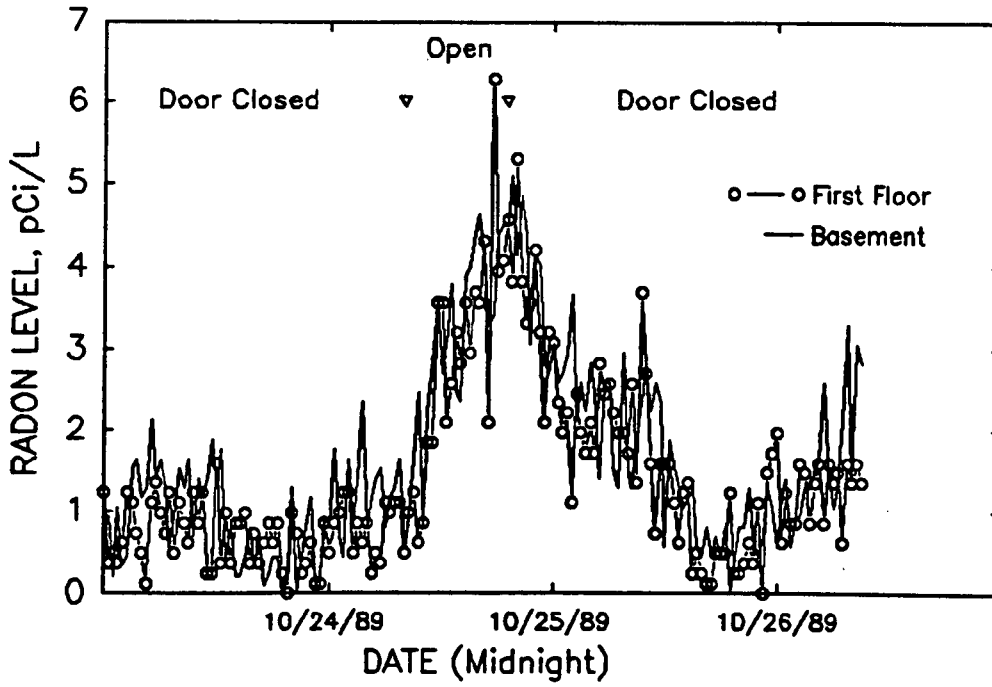

Figure 6. Effects of pressure loss on radon levels in DW 01.

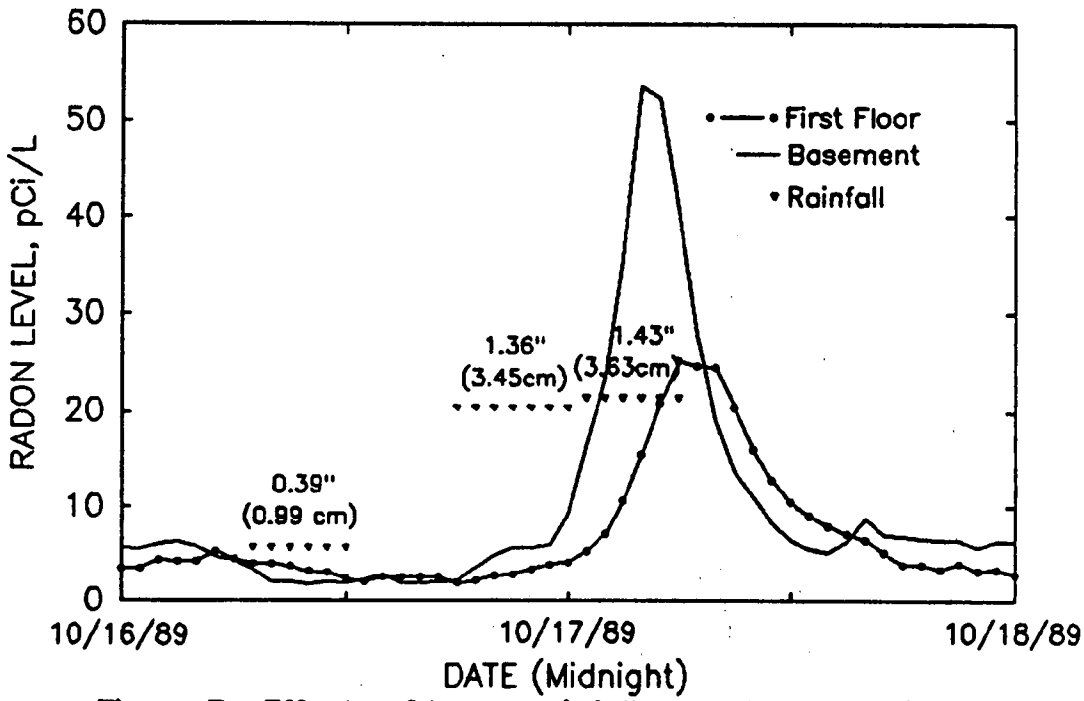

Figure 7. Effects of heavy rainfall on radon levels in house DW 35 mitigated with charcoal adsorption device.

ONE-YEAR FOLLOW-UP STUDY OF PERFORMANCE OF RADON MITIGATION SYSTEMS INSTALLED IN TENNESSEE VALLEY HOUSES

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ABSTRACT

Subbarrier depressurization systems were installed for radon mitigation in two basement ranchers in Oak Ridge, TN, and in two ranchers with partial basements in Huntsville, AL. System performance parameters, including pressure field extension, subslab permeability, and indoor radon concentrations, were followed in each house for a year or longer. In general, these performance factors were stable over the year. In one house built on a slab without underlying aggregate, the subslab permeability has increased in two of four suction pits. In another house, the extension of the field of depressurization is markedly anisotropic. In three out of the four houses, mitigation measures that do not consume electrical power seem to have provided 30 to 60% reductions in indoor radon concentrations.

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

INTRODUCTION

Radon is widely perceived as one of the most significant health risks present in indoor air (1). According to recent state surveys, radon levels in excess of the Environmental Protection Agency (EPA) guideline of 150 Bq m^{-3} are widely distributed throughout the U.S. (2). As a result, research programs have been supported on a regional basis to more quickly develop mitigation technologies required for variant macro-geologic and house-construction characteristics. A radon research program in the Tennessee Valley has been sponsored by multiple agencies to:

1. better understand the physical basis of factors underlying radon entry and its control,

2. refine diagnostic methods for implementation of effective radon control methods, and

3. improve radon control technologies while systematically reducing radon levels in study houses.

In addition, a study of performance of radon mitigation systems for one year following installation was made in two houses in Tennessee and two houses in Alabama.

Several research groups have evaluated mitigation system performance over extended periods of time. The principal means of evaluation to date have included post-mitigation radon monitoring with alpha track devices and follow-up visits to inspect the system for operational integrity. Nitschke (3) discovered numerous design flaws in early subsurface depressurization systems installed in New York houses. Prill (4) discovered in six houses in Washington and Idaho that performance of subsurface pressurization systems declined due to flow obstruction at the outlet and due to occupant interference with vents and fans.

Because of the substantial seasonal variation of indoor radon concentrations that we have seen in the Huntsville study houses (5), the pressure and flow characteristics of the systems were followed closely to monitor system performance. In each of 4 houses with basements, 12 or more sampling holes were installed in the concrete slab and repeated measurements of radon concentration and air pressure were taken at these sites. In addition, flow and subslab permeability in the system were followed. This paper will discuss what changes were seen in the pressure field and indoor radon concentrations during the first year of operation.

DESCRIPTION OF STUDY HOUSES

The study houses were selected based on: (1) the above research goals, (2) indoor radon survey data, (3) the availability of tightly clustered houses with similar construction characteristics, and (4) predicted homeowner cooperation with a 1-2 year, highly instrumented, research program. The Oak Ridge/Knoxville area of eastern Tennessee, and the Huntsville area of Madison County, AL, were selected because of their comparatively high indoor radon levels in state surveys (6), different underlying geologies, and similar housing stock. A data base of prospective houses was generated in both locales from radon surveys of approximately 500 houses using charcoal monitors, and door-to-door screening using continuous radon monitors.

For the larger study of radon entry and control, four basement ranchers in Oak Ridge, TN, and four crawlspace houses in the Garth Mountain area of Huntsville, AL, were selected. All eight study houses had substructural (i.e., crawlspace and/or basement) and superstructural levels of equal floor area to minimize variability in radon entry, transport, and exhaust properties. The Huntsville houses (HU11-HU14) and Oak

Ridge houses (OR15-OR18) were clustered within a 0.4 and 1.2 km radius, respectively, to minimize the variability in underlying geology and the time dependence of meteorologic events. The four houses included in this study were:

House HU13 This is a single-story house, built around 1957 and rebuilt after a fire in 1978. The house has a substructure composed of crawlspace and walkout basement areas below the living area. There was no vapor barrier in the crawlspace and a continuous wall between crawlspace and basement areas with two doors. There are two single garage doors opening into the basement area. There is an attached parking area with slab-on-grade construction. An electric furnace with forced-air distribution system is located in the basement. An electric central air conditioning unit is located beside the rear wall. The occupants routinely use a wood stove in the upstairs living area for heat during the winter months. The house is built on flat land with few trees in the backyard. There are three adult occupants, one of whom was home most of the time.

House HU14: This is a single-story house, built around 1962, with a split foyer entrance and a substructure composed of crawlspace and walkout basement areas below the living area. There was no vapor barrier in the crawlspace. There is a continuous wall, with a door, between the crawlspace and basement areas. There a double garage door that opens into the basement and is opened twice per day for brief periods. An electric heat pump with forced-air distribution system is located in the crawlspace. An electric central air conditioning unit is located beside the rear wall. The occupant routinely uses an upstairs wood-burning fireplace in the wintertime. The house is built on sloping land with many trees in the backyard. There is one adult occupant who was home evenings and weekends.

House OR15: This is a single-story house, built in 1963, with a full walkout basement below the living area. Three-quarters of the basement area is finished with panelled walls and tiled floors. There is an attached carport with slab-on-grade construction. Beneath the carport slab is a fallout shelter that can be entered from the basement. An electric furnace with forced-air distribution system is located in the basement. An electric central air conditioning unit is located beside the side wall. The house is built on sloping land with few trees in the backyard. There are two adult occupants, one of whom was home most of the time.

House OR16: This is a single-story house, built in 1963, with a full walkout basement below the living area. Three-quarters of the basement area is finished with panelled walls and tiled floors. There is an attached carport with slab-on-grade construction. An electric furnace with forced-air distribution system is located in the basement. An electric central air conditioning unit is located beside the rear wall. The house is built on sloping land with many trees in the backyard. There are two adult occupants, both of whom were home during evenings and weekends.

DESCRIPTION OF MITIGATION MEASURES

WEATHERIZATION, HAC SEALING, AND SLAB SEALING

The first stage of radon mitigation performed in the Huntsville houses was simple weatherization measures and sealing of the heating and air conditioning (HAC) system. All houses were weatherized to a similar degree, consistent with standard Tennessee Valley Authority (TVA) recommendations and practice.

In both Huntsville houses the return-side ductwork extended into all substructural compartments. Prior to house weatherization, inspection of the HAC systems revealed leaky ductwork. For the return duct,

leak testing was performed by two methods, physical inspection (i.e., for large holes or gaps) and by utilizing a smoke pencil. For small leaks, latex caulk, fingertip caulk, and duct tape were applied to seal the leaks. In cases where joint leakage was due to nonsupport of the duct, sheet metal support bands were added. In more severe cases (i.e. large holes or missing connections), heavy gauge sheet metal form connectors, support cuffs,or cover plates were fabricated and permanently attached with sheet metal screws. These joints were sealed with latex caulk as well. In both houses, the pan-type return ducts were renailed to the floor joist and the edges sealed with latex caulk. In addition, all other accessible metal to metal joints in the return ducting were sealed with latex caulk. Confirmation of sealing was made by using a smoke pencil.

In both Huntsville houses, the central HAC unit was located in the crawlspace. Smoke pencil testing of the units revealed that the units were very leaky and drew crawlspace air into the HAC system. Since 100% sealing of the units was impossible, user-removable service panels were sealed with a combination of modeling clay, fingertip caulk, and duct tape. Similar seals were fashioned for all inter-panel joints and gaps between the chassis and user-removable panels. Other non-removable panels or non-serviceable areas were permanently sealed with latex or silicon caulk. Effectiveness of the sealing effort was judged by smoke stick testing. After all direct surface seals were completed, the entire cold-air return duct system was permanently covered with a vapor-seal/fiberglass duct-jacketing.

In all of these houses, the slabs were in reasonably good condition with most deficiencies being small "hair line" cracks. However, in HU14 there were some large (0.5 cm) cracks. For houses OR15 and OR16 access to the slab was limited since most of the basement area was finished. All stress cracks in the slabs were expanded to a V-shaped channel, 0.5 to 1.5 cm in width and 1.5 cm in depth using a percussion-type bit and filled with flowable urethane sealant. If needed, an application of latex caulk or liquid adhesive was used to fill large gaps to prevent bleed-through of the flowable sealant. After the first application of the flowable sealant had aged for 3 days, an additional layer was applied to fill any depressions or gaps which had occurred during the curing process. Cracks and perforations in the block walls were sealed with latex caulk or expansion foam. Wall outlets were sealed with a combination of latex and fingertip caulk. Slab-wall expansion joints were filled with backer rod followed by flowable urethane caulk. In House OR15, the fallout shelter was isolated from the basement with a removable, weather stripped plywood door.

SUBSLAB VENTILATION SYSTEMS

All pits for subslab ventilation were square in design, approximately 60 x 60 cm in size, and with a depth chosen according to permeability test results. Excavation depths of each pit depended upon the subslab permeability and the depth permeability profile data. Standard 10 cm (4") or 15 cm (6") schedule 40 PVC pipe was inserted within the pit to a depth of 30 cm beneath the bottom of the slab and filled with gravel (1 to 2 cm). A 60 x 60 cm cardboard shield was then inserted around the pipe and concrete was poured and finished. The pit pipe was then attached to the main 10 cm (4") PVC pipe trunk equipped with a Kanalflakt pipe fan. Exhaust locations for HU13 and HU14 were through the side of the house and OR15 and OR16 were through the roof. A detailed description of the system installed at each house is given below.

House HU13 The substructure consists of a basement/crawlspace combination with a hollow block wall separating the two compartments. The basement construction consists of hollow concrete block walls with interior walls built over the slab. A thick 15 cm layer of aggregate was found under the slab, and excellent communication and permeability (140 to 190 x 10^{-7} cm^2) were observed between diagnostic holes and slab suction points within the basement. Subslab to wall communication was not detected in the basement during subslab diagnostic tests. Due to the excellent communication and permeability found under the slab, only one 50 cm deep mitigation pit was installed near the center of the basement slab.

House HU14 The substructure consists of a basement/crawlspace combination with a hollow block wall separating the two compartments. The basement construction consists of hollow concrete block walls with interior walls built over the slab. Some (~8 cm) aggregate was found under the slab. Subslab permeability was reasonable ranging from 88 to 128 x 10^{-7} cm^2 between diagnostic holes and slab suction points in the basement. Subslab to wall communication was not detected in the basement during the subslab diagnostics experiments. Due to the relatively good communication among test holes in the slab, only one 65 cm deep subslab mitigation pit was installed in the basement.

House OR15 The substructure consists of a mostly finished basement with hollow block wall construction. All interior walls are built over the slab. Varying layers of aggregate were found under the slab (0 to 15 cm) with permeability ranging from 4 to 123 x 10^{-7} cm^2 at different sites under the slab. Subslab to wall communication was not detected in the basement during subslab diagnostic experiments. Due to the varying depths of gravel found under the slab and wide ranges of permeability, two mitigation pits were installed. Pit 1 was 40 cm deep and Pit 2 was 120 cm deep. Post mitigation radon measurements indicated that the structure had not been sufficiently mitigated although diagnostic tests revealed an excellent pressure field extending over 90% of the slab area. Based on collected grab sample data, an additional source of radon within the structure was determined to be the attached fallout shelter (in excess of 3700 Bq m^{-3}). Attempts were made to isolate the shelter from the structure by the sealing of the basement/shelter wall and the entrance door. When these measures failed, an 8 cm (3") PVC pipe was connected from the air exhaust of the shelter to the subslab mitigation system to depressurize the shelter. A control valve was installed in the 3" line to allow the room to be maintained at a constant -10 Pa. This action reduced the radon levels within the occupied structure to less than 100 Bq m^{-3}.

House OR16 The substructure consists of a mostly finished basement with hollow block wall construction. All interior walls are built over the footing with a poured concrete floor. Varying layers of aggregate were found under the slab (0 to 5 cm) with permeability ranging from 0.1 to 1.7 x 10^{7} cm^2 throughout the slab. Subslab to wall communication was not detected in the basement during subslab diagnostic experiments. Due to the varying depths of gravel found under the slab and the overall poor permeability, a total of four mitigation pits of 120 cm in depth were installed.

CRAWLSPACE VENTILATION AND MODIFICATIONS

Passive ventilation of the crawlspace areas in HU13 and HU14 was attempted by the installation of standard 20 cm (8") x 40 cm (16") vents. The addition or replacement of the vents did require some modifications to the substructures. Where below grade vents were required, gravel lined brick-walled wells were installed. Three below grade crawlspace vents were added on the side of the crawlspace opposite the basement in House HU13. Two additional above grade crawlspace vents were added to the front of the house. Three below grade crawlspace vents on the side of the crawlspace opposite the basement and one below grade vent on the north, rear corner of the house were added in House HU14. Two additional above grade vents were added to the front of House HU14.

Vapor barriers and active subbarrier ventilation systems were installed in the crawlspaces of the houses. The crawlspace walls were prepared for the adhesion of the barriers by scraping and then painting the inner walls and upper floor supports with gloss or semi-gloss masonry enamel. A straight length of 8 cm (3") schedule 40 PVC pipe was laid roughly along the center length of the crawlspace floor with a 8 cm (3") T placed approximately in the middle of the pipe. The ends of the main 8 cm (3") trunk were

then capped and 2.5 cm (1") horizontal holes were drilled in the side of the trunk at staggered 2 to 3 m intervals. Perforated 2.5 cm (1") PVC pipe (0.6 cm hole per 20 cm of pipe) was then inserted into the trunk and cemented in place with epoxy and PVC cement. The barriers were then placed over the piping system with 90 cm overlaps. Care was taken to custom trim the barrier to conform to the various supports and obstacles in the crawlspace. Sealing of vapor barrier material to itself and to the painted portions of the walls was accomplished with double sided tape. From the central trunk T, a series of adaptations were made to connect the 8 cm (3") trunk to the 15 cm (6") pipe fan. Flexible ducting was then attached to the exhaust side of the fan and run to an existing vent to exhaust outdoors. The flexible duct was hung from the ceiling using permanent galvanized band-strapping.

EXPERIMENTAL METHODS

The study design included a variety of radiological, environmental, and house dynamic measurements with near-continuous and episodic data acquisition schedules. Continuous measurements of radon, temperature, and relative humidity were performed in substructural (i.e., crawlspace and basement) and superstructural (i.e., upstairs) zones. Differential pressures were monitored between: (1) substructural and superstructural zones, (2) substructural and outdoor zones, and (3) basement and subslab zones. These monitors were also used on an episodic basis to evaluate the impact of clothes dryers and HAC systems on differential pressures across various building membranes. Meteorologic measurements of wind speed, wind direction, and rainfall were made in two locations per housing group; barometric pressure was measured in one location. Episodic measurements included subslab radon concentration and permeability, and pressure difference across the slab. These techniques have been described by Dudney et al. (7).

Subslab permeability was determined by applying a 10-fold or greater range of pressures to a hole in the slab and measuring the resultant flow of exhausted air (8). In premitigation studies, suction was applied with a variable speed shop vacuum to a 3.8 cm ID hole in the slab. Airflow was measured with a hotwire anemometer inserted into a 2.6 cm ID PVC exhaust pipe. In several houses, the permeabilities of the subslab soil and soil/gravel mixtures were investigated as a function of depth by coring the 2.6 cm ID holes to depths of approximately 10, 40, 80 and 120 cm. In post-mitigation studies, suction was applied with a variable speed mitigation blower through 10.2 and 15.2 cm holes in the slab. These holes connected directly to 50 x 50 cm gravel-filled pits having typically 40 and 150 cm depths for houses with and without subslab gravel layers, respectively. Airflow was monitored with a hotwire anemometer inserted into a 13.9 or 15.2 cm ID exhaust pipe. Induced differential pressure was monitored at the point of entry into the slab with an electronic vacuum gauge.

The extension of the subslab pressure field was determine by applying controlled pressures to pre-mitigation holes or post-mitigation pits and monitoring the induced pressure through 1 cm ID holes in the slab at several remote locations. In the pre-mitigation diagnostic phase, negative pressures of 0.5, 2.0, and 5.0 kPa were used whenever possible to enhance comparisons between different houses and time periods (e.g., pre- and post-mitigation phases). After mitigation, pressures were limited to about 0.35 kPa due to the blower capacity.

Figure 1 shows scale drawings of the basements and crawlspaces of the four houses described above. The locations of pits for the subsurface depressurization systems and of all sampling holes are indicated.

RESULTS

In a manner similar to Fowler (9), we monitored pressure field extension for nearly a year in these houses. Figure 2 shows the results from the houses. There was no discernible change over time in the induced pressure fields when the mitigation systems were operated normally. What is most noteworthy is the clear difference in pressure field extension under different sectors of the slab. In House HU13, the

sampling sites closest to the driveway (1, 2, 7, and 17) showed a gradual drop in pressure with increasing distance from the pit. The sampling sites on the crawlspace side of the pit (3, 9, 10, 13, 15, 16 and 18) showed a much steeper decline. At a distance of 7 m, there was measurable pressure on the driveway side but not on the crawlspace side. Because of the lack of a close sampling site on the crawlspace side of the slab at House HU14, it is unclear whether the pressure field extension varies significantly with direction. Because multiple pits were installed at the Oak Ridge houses, only sampling sites at the ends of the houses were included in analysis of pressure field extension. Distances were computed from the nearest pit. For House OR16, distances were computed from Pits 2 and 3, which are those on the uphill side of the house. At House OR15, the pressure field is easily measurable at a distance of 5 m. It is clear from the data that there is an enhancement of pressure extension on the side of the house where the fallout shelter is located. Since a -10 Pa depressurization was applied to the shelter, the enhanced extension may result from communication between shelter and subslab zones. In House OR16, the pressure field falls off rapidly on the end by Pit 3 but not so rapidly on the end by Pit 2.

For both Huntsville houses (HU13 and HU14), data from sampling sites closest to pit showed a decline in induced pressure during the first several months of operation (see Table 1). This effect was only seen in the holes where the induced pressure was largest and easiest to measure. This decline in pressure following initial start-up may reflect the removal of fine particulate material from the flow paths and the consequent absence of some flow restrictions and pressure drops near the point of applied depressurization.

Using the techniques described by Matthews (8), permeability was monitored at all suction pits on a recurring basis. Detailed analysis has not been completed on all available data, but there is no clear evidence of change in subslab permeability except at House OR16 (see Table 2). The slab at this house was poured directly onto packed clay. We suspect that severe drought conditions during 1988 may have contributed to shifting of the soil beneath the slab, resulting in the opening of channels leading to the suction pits. Continued monitoring during 1989 (data not shown) has revealed continued increase in the permeability in Pits 1 and 4. The 1989 results and results from tracer gas experiments will be reported separately.

Radon reduction efficiency was quite good in these houses following initial installation and adjustment of the systems (see Table 3). Reductions ranged from 89 to 97% in 1988. During 1989, there was an extended period during which the electric power to the systems was cycled on for a week followed by a week without power. In Figure 3, the data from the period around Julian Dates 80 to 160 (1989) include most of the period during which the power was cycled on and off. The comparison of power-off radon concentration to *a priori* radon concentrations suggests that, except for House HU13, from 40 to 80% of the reduction may be due to the passive effects of modifications that were made to the houses. The reader should note that this comparison is suspect due to strong seasonal variations that can occur in this area. This effect is easily seen (see Figure 3) in the changes in indoor radon that occurred in House HU14 during the first 50 days of monitoring.

In summary, this study has shown that there is generally very good stability in the performance of radon mitigation systems that depressurize the soil beneath concrete slabs in three of these existing houses. One house built on a slab without aggregate (OR16) was a notable exception. There was evidence of domains beneath the slab of House HU13 with distinctly different extensions of the field of depressurization. There is evidence present that in three of these houses passive measures, such as slab sealing, can yield considerable radon reduction.

ACKNOWLEDGEMENTS

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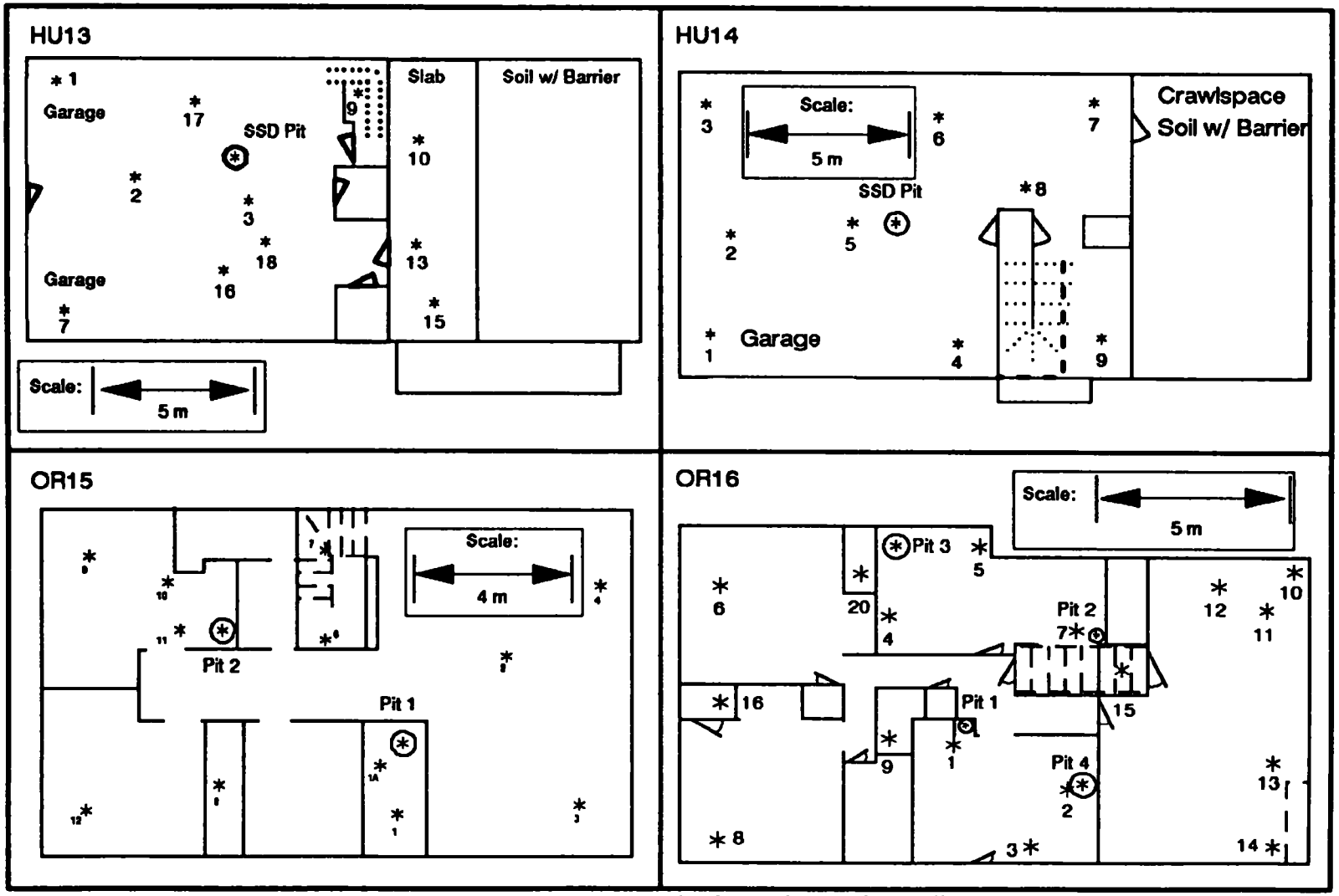

Figure 1. Schematic of substructures indicating depressurization points and sampling locations.

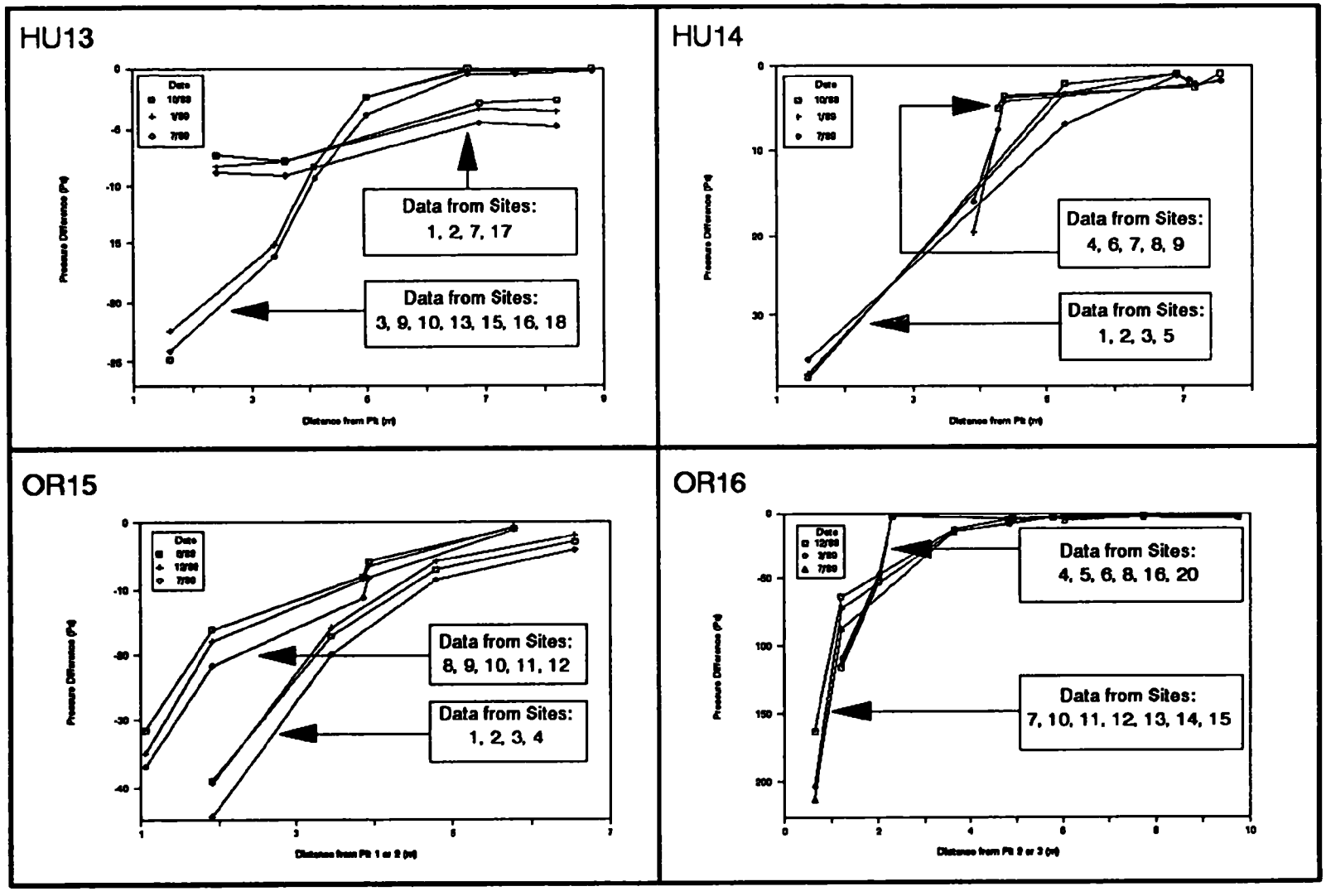

Figure 2. Variation of pressure with distance under slab for four houses.

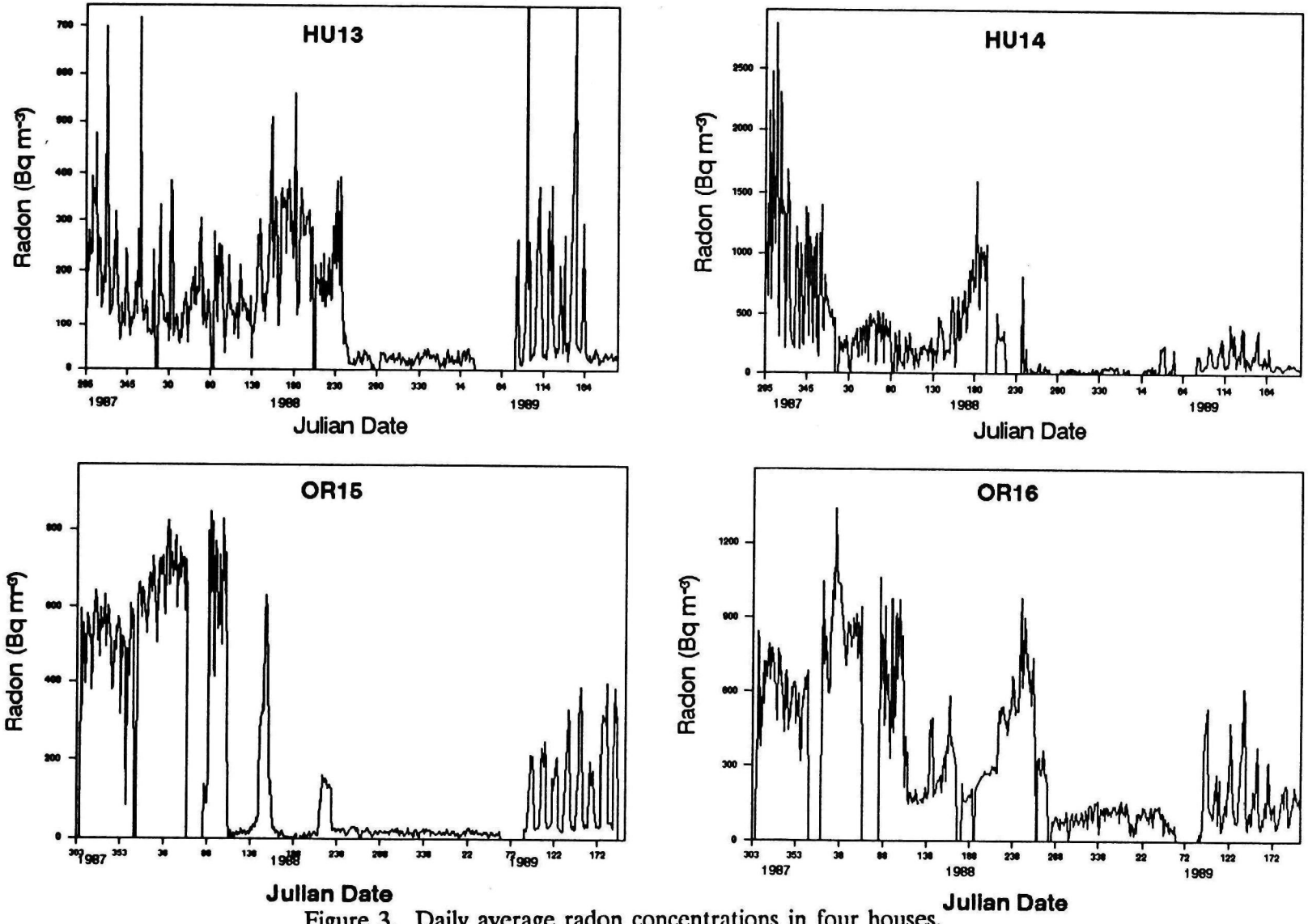

Figure 3. Daily average radon concentrations in four houses.

Table 1. DIFFERENTIAL PRESSURE (Pa) AFTER INSTALLATION.

Date	House/Sampling Site 13/3	14/5
8/88	-28 (113%*)	-43 (118%)
10/88	-25 (103%)	-39 (106%)
11/88	-23 (96%)	-35 (97%)
12/88	-22 (89%)	-36 (98%)
1/89	-23 (93%)	-38 (105%)
2/89	-22 (89%)	-35 (97%)
7/89	-24 (100%)	-37 (100%)

* Fraction of 7/89 value, expressed as a percentage.

Table 2. VARIATIONS IN SUBSLAB PERMEABILITY (x 10^{-7} cm^{-2}) AT OR16 IN 1988.

Date	Pit 1	Pit 2	Pit 3	Pit 4
5/88	4.0 ± 0.5	7.4 ± 1.8	5.1 ± 1.3	----
6/88	----	----	----	10.3 ± 1.2
11/88	16.7 ± 1.0	5.5 ± 0.5	5.1 ± 1.3	20.0 ± 1.1
12/88	14.6 ± 0.9	5.2 ± 0.5	5.1 ± 0.8	18.8 ± 2.0

Table 3. RADON REDUCTION EFFICIENCY: 1988 AND 1989.

House	1988 Pre-Mitigation	1988 Post-Mitigation	1989 System Off	1989 System On
HU13	191 Bq m^{-3}	21	235	32
HU14	958	30	220	63
OR15	585	26	218	35
OR16	724	78	315	100

A COST-EFFECTIVENESS COMPARISON OF PRIVATE-SECTOR RADON REMEDIATION WITH TRADITIONAL RADIATION PROTECTION ACTIVITIES

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ABSTRACT

Private-sector radon remediation can be well over 100 times more cost-effective than the minimum expenditure of $1000 to avert a whole-body person-rem mandated by the U.S. Nuclear Regulatory Commission for marginal control of exposures to radiation due to effluents from nuclear power plants (10 CFR 50 Appendix I). Using data from the Pennsylvania Department of Environmental Resources (DER) and from Radon Detection & Control (RDC; a commercial radon remediation firm) spanning more than two years, we relate differences in radon concentrations measured before and after remedial action to capital and operating costs. Simple demographic assumptions and concentration-to-collective dose equivalent conversions lead to a quantitative demonstration of the dramatic imbalance in society's valuation of radiation protection by nuclear utilities when compared to that in the home. The DER data show that an effective person-rem can be averted for $3.01 in high-radon houses (104 houses; average, 189 pCi/L; median 112 pCi/L; GSD 2.75), while the RDC data show that an effective person-rem can be averted for $9.41 in more typical houses (201 houses; average 28 pCi/L; median 19; GSD 2.31).

INTRODUCTION

A basic tenet of public health activities is that limited resources should be used in a way that is most beneficial to the most people. Studies on the value of a human life have demonstrated the great incongruities in how money is spent for increments of health and safety (1, 2). In this paper, we demonstrate that radon remediation activities can be 100 to 300 times more cost effective than radiation protection activities at nuclear power plants required by U.S. Federal regulations (3).

In the case of nuclear power, the risk is perceived as dread, unknown, uncontrollable, imposed, and manageable with someone else's money. In the case of radon exposure in the home, the risk is perceived as less dread, better known, more controllable, voluntarily accepted, and manageable only with one's own money. The traditional perception of the home as a "safe haven" from the ills of the outside world runs counter to the acceptance of a serious radiological risk that may exist from natural (or, rather, technologically-enhanced natural) causes. The public health perspective, however, dictates that society's resources should be refocused on indoor radon, rather than on tiny increments of safety achieved at tremendous cost in controlling effluents from nuclear power plants.

DATA

Two sets of data are used in this study. The first is from the Pennsylvania Department of Environmental Resources (DER) report summarizing the Pennsylvania Radon Research and Demonstration Project (4). This report lists radon concentration data from 104 houses for which measurements before and after remediation were available. The DER data arose from research and development work, and the houses to be remediated had *very* high radon concentrations (many over 200 pCi/L). These data are not a random sample of houses, and remediations were done in the mid-1980s when the technology was in its infancy. Concentration measurements were made using grab or continuous flow-through alpha scintillation measurements. There is no evidence that measurements were made using integrating detectors such as charcoal, diffusion barrier charcoal, or alpha track.

The second set of data are from Radon Detection & Control (RDC). These data included 201 houses remediated between 1987 and 1989, mostly in the Allegheny and Beaver County areas of western Pennsylvania. The RDC data represent a more typical set of radon remediations in that they were done for real estate transactions, for relocation companies, or for health concerns of the occupants. The RDC radon measurements were made using activated charcoal screening detectors[1] exposed for two to four days and processed commercially. In some cases, the concentrations are averages of two or more measurements. The radon concentrations were measured at the same location before and after remediation.

ANALYSIS AND DISCUSSION

The DER data are summarized in Table 1a, while the RDC data are summarized in Table 1b. From left to right, the columns are the initial or "Before" remediation radon

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[1]Key Technology, Inc., P.O. Box 562, Jonestown, PA 17038; or Air Chek, Inc., P.O. Box 2000, Arden, NC 28704.

concentration; the final or "After" remediation concentration; the remediation cost; the percent reduction of radon concentration; the percent reduction in radon concentration per $1000 spent on remediation; the change in concentration; the change in concentration per $1000 spent on remediation; the ratio of the "Before" to the "After" concentrations; and the ratio reduction achieved per $1000 spent on remediation. Note that minimum and maximum entries in different columns may be from different houses; these values were the minima and maxima in the entire data set.

Table 1a. Summaries of the Pennsylvania D.E.R. data (Weston & Simon 1988).

	Radon Conc. Before (pCi/L)	Radon Conc. After (pCi/L)	Remed-iation Cost ($)	% Re-duction	% Re-duction per 1000$ %/k$	Conc. Change (pCi/L)	Conc. Change per 1000$ (pCi/L)/k$	Reduct. Factor	Reduct. Factor per 1000$ (/k$)
No. of houses	104	104	104	104	104	104	104	104	104
Minimum	11.6	0.3	1301	-53.2	-13.0	-62.1	-15.1	0.65	0.16
Maximum	1653.2	178.8	16185	99.9	73.7	1576.2	312.3	893.0	222.9
Mean	189.1	10.6	3729	90.4	29.6	178.5	47.4	112.4	33.3
Std.Dev.	240.2	27.7	2156	23.2	14.2	231.3	49.7	145.0	40.7
Geo. Mean	112.3	2.5	3324	92.7	27.8	107.4	32.3	44.8	13.5
G.S.D.	2.75	4.43	1.57	1.21	1.59	2.91	2.61	4.96	4.98
r^2 (lognorm.)	0.992	0.930	0.966					0.972	

Table 1b. Summaries of Radon Detection & Control data, 1987-89.

	Radon Conc. Before (pCi/L)	Radon Conc. After (pCi/L)	Remed-iation Cost ($)	% Re-duction	% Re-duction per 1000$ %/k$	Conc. Change (pCi/L)	Conc. Change per 1000$ (pCi/L)/k$	Reduct. Factor	Reduct. Factor per 1000$ (/k$)
No. of houses	201	201	201	201	201	201	201	199	201
Minimum	4.2	0.0	150	-2.7	-1.4	-0.3	-0.2	1.0	0.0
Maximum	156.0	18.3	2905	100.0	634.4	155.6	380.7	390.0	421.1
Mean	28.1	2.0	1030	87.3	99.0	26.1	27.7	29.3	30.3
Std.Dev.	29.0	2.4	325	15.8	63.4	28.4	37.3	46.8	52.9
Geo. Mean	19.2	1.3	957	86.1	90.3	16.6	17.4	14.5	15.4
G.S.D.	2.31	2.53	1.55	1.24	1.47	2.59	2.50	3.21	2.97
r^2 (lognorm.)	0.969	0.993	0.862					0.997	

Under each column are the number of houses used in that column; the minimum, maximum, arithmetic mean, and standard deviations of each quantity; and the geometric mean and geometric standard deviations (GSD; dimensionless) of the quantities. For the DER data, the geometric means and GSDs for the difference, % reduction, concentration change per $1000, and percent per $1000 were calculated from 101 data pairs, omitting the 3 negative values. For the RDC data, geometric means and GSDs were calculated from 197 to 199 non-negative values

for those columns with negative entries, or, in the case of the ratio, with zero final concentration.

The DER houses had larger average initial ("Before" remediation) concentrations than did the RDC houses, with arithmetic means of 189 ± 240 and 28 ± 29 pCi/L, respectively. This is due to the different selection processes, and to the fact that many of the DER houses were in the Reading Prong area of southeastern Pennsylvania, a region with exceptionally high indoor radon levels. Both data sets showed lognormal distributions, as seen in Figures 1 and 2, with geometric means of 112 $\times\div$ 2.75 (r^2 = 0.992) and 19 $\times\div$ 2.31 (r^2 = 0.969). Lognormal fits were done by the LPROBIT code using Finney's weighting method (5).

The maximum in the DER data set, 1653 pCi/L, was more than ten times higher than the maximum in the RDC data set, 156 pCi/L. The minimum "Before" value (i.e., 4.2 pCi/L) in the RDC data may indicate the force that the real estate and relocation companies have on radon remediation decisions.

Final ("After" remediation) concentrations averaged 10.6 and 2.0, respectively, for the DER and RDC data. The lower final concentration for RDC is understandable in light of the fact that they usually guarantee a concentration below 4 pCi/L, and usually continue to remediate until the concentration is below this level. Again, both data sets showed lognormal distributions, with geometric means of 2.5 $\times\div$ 4.43 (r^2 = 0.930) and 1.3 $\times\div$ 2.53 (r^2 = 0.993). The wide GSD, 4.43, for the DER data, along with its moderate deviation from lognormality may reflect the varying conditions applied to remediation during the DER's research and development process.

The DER data show significantly higher average remediation costs than the RDC data: \$3729 ± \$2156 vs. \$1030 ± \$325. The geometric means were \$3324 $\times\div$ 1.57 (r^2 = 0.97) vs. \$957 $\times\div$ 1.55 (r^2 = 0.86). These numbers are understandable in light of the differing nature of the two endeavors: the DER project was a research and development activity, done to develop technologies; the RDC work is done commercially in a competitive atmosphere, and benefits from well-established practices in remediation.

We chose three ways of looking at the data: *percent reduction, concentration change*, and the *reduction factor*. The percentage reduction is the difference in radon concentrations divided by the "Before" concentration, expressed as a percent; the concentration change is simply the difference between "Before" and "After" concentrations; and the reduction factor is the ratio of the "Before" to "After" concentrations. All three methods are somewhat flawed because no concurrent long-term background concentration measurements were available. Since indoor radon levels cannot be reduced below ambient outdoor levels using any of the remediation methods employed for DER or by RDC, both percent reduction and reduction factor have values limited by background concentration. The limits are unimportant for high initial concentrations, but can restrict measures of success when starting from lower concentrations.

The *percentage reduction* summaries are given for each data set in Table 1. The means are 90.4% for the DER data, and 87.3% for the RDC data. The mean percentage reduction is a somewhat misleading statistic, since its maximum value is 100, with many houses very near this value. The mean *percentage reduction per \$1000* spent on remediation is 29.6%/\$1000 for DER vs. 99.0%/\$1000 for RDC, which primarily reflects the different average remediation costs.

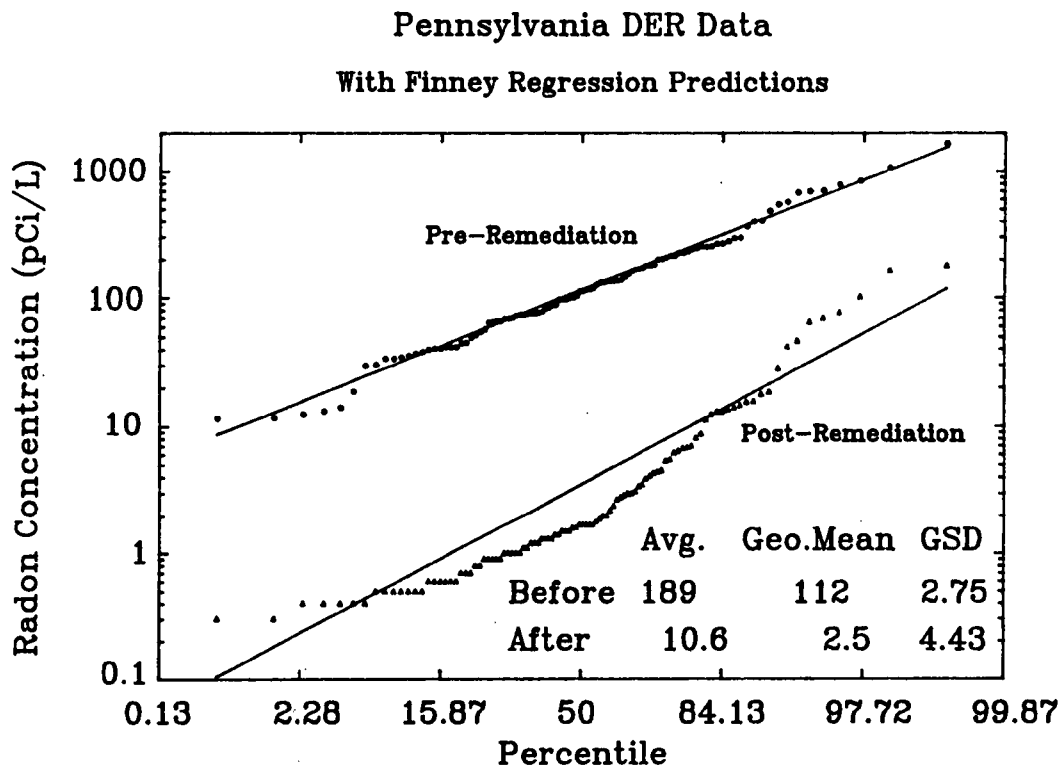

Figure 1. Log-probability plot of "Before" and "After" radon concentrations in 201 houses remediated by Radon Detection & Control, with Finney-weighted regression lines.

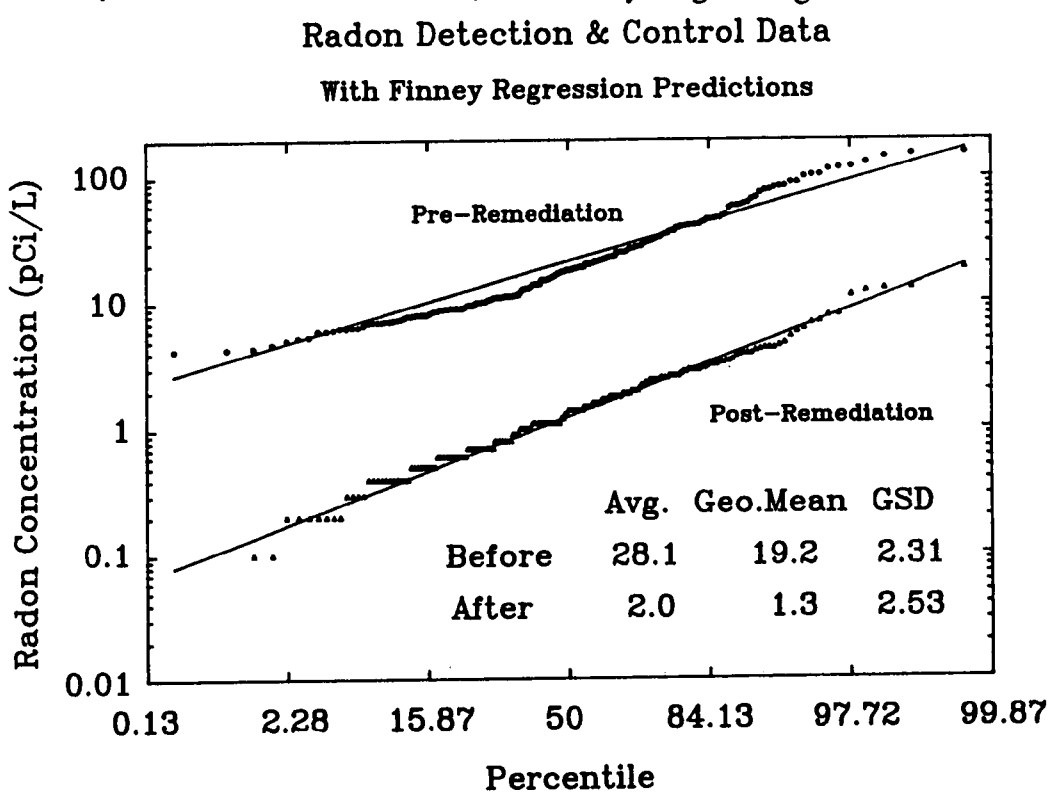

Figure 2. Log-probability plot of "Before" and "After" radon concentrations in 201 houses remediated by Radon Detection & Control, with Finney-weighted regression lines.

The *concentration change* summaries show arithmetic means of 179 ± 231.3 pCi/L for the DER data and 26.1 ± 28.4 pCi/L for the RDC data, the difference largely reflecting the fact that the DER houses had higher concentrations to begin with. The geometric means were 107 pCi/L $\times\div$ 2.91 and 16.6 pCi/L $\times\div$ 2.59, respectively. The mean *concentration change per $1000* was 47 ± 49 [pCi/L]/k$ and 28 ± 37 [pCi/L]/k$ for the DER and RDC data, respectively, indicating that, while the concentration changes in the DER work averaged nearly 7 times greater than the RDC work, the remediation cost per unit concentration change averaged only 1.7 times greater for the DER work. Note that this analysis does not include operating and maintenance costs.

Perhaps more interesting than the percentage reduction is the *reduction factor*. Reduction factors as great as 893 were achieved in the DER program, and 390 in the RDC work. Average reduction factors were 112 and 29, respectively, with geometric means of 45 $\times\div$ 4.96 (r^2 = 0.972) and 29 $\times\div$ 3.21 (r^2 = 0.997), indicating both more vigorous remediation efforts in the DER demonstrations and the limiting effects of ambient radon concentrations when remediating houses with initially low radon levels. Of great interest are the mean *reduction factors per $1000* spent on remediation: these were 33/$1000 and 30/$1000 for DER and RDC, respectively, with geometric means of 13.5/$1000 and 15.4/$1000, indicating that the work was quite comparable in terms of cost-effectiveness when expressed in terms of reduction factors!

The dose equivalent averted through remediation is directly proportional to the concentration change. To evaluate the overall cost-effectiveness of the two remediation projects, we summed the "Before" and "After" concentrations, as well as the costs, as shown in Table 2. These concentration sums can be considered as "Collective Concentration" by analogy with "Collective Dose" and "Collective Dose Rate" as defined by the International Commission on Radiological Protection (6).

Table 2. Sums of concentrations and costs, with analysis statistics for PA D.E.R. and RD&C data.

	Sum of Radon Conc. Before (pCi/L)	Sum of Radon Conc. After (pCi/L)	Sum of Remed-iation Costs ($)	Overall % Re-duction	Overall % Re-duction per 1000$ %/k$	Overall Conc. Change (pCi/L)	Overall Conc. Change per 1000$ (pCi/L)/k$	Overall Reduct. Factor	Overall Reduct. Factor per 1000$ (/k$)
PA D.E.R.	19664	1102	387797	94.4	25.3	18562	47.9	17.8	4.8
R.D.&C.	5649	402	206936	92.9	90.2	5248	25.4	14.1	13.7

The columns in Table 2 that begin with the word "Overall" differ from the mean or geometric mean values presented in Table 1 because they are computed only from the sums given in Table 2, rather than from the actual distributions. The overall percent reduction in each data set (94.4% and 92.9%, respectively, for DER and RDC) is *greater* than the mean because greater reductions were achieved in high initial concentration houses than in low concentration houses. The percent/$1000 values (25% and 90%) are based on the mean remediation costs in Table 1, and are *lower* than the means in that table.

The collective dose equivalent averted by remediation is proportional to the overall concentration change, which was 18562 pCi/L for the DER work and 5248 pCi/L for the RDC remediations. While the DER overall concentration change is 3.5 times higher than the RDC change, the cost-effectiveness value for DER is only 1.9 times that for RDC (47.9 vs. 25.4 [pCi/L]/$1000) based on average remediation costs from Table 1.

The overall reduction factors were 17.8 and 14.1, respectively, for DER and RDC, while the reduction factor per $1000 values were 4.8/$1000 and 13.7/$1000, indicating an almost three-fold better investment with the later work when viewed in these terms.

Rather than dealing with risk, as the DER report does, we compute the effective dose equivalent averted by remedial actions, and compare the cost per unit effective dose equivalent averted by remedial actions. The many assumptions needed to do this are summarized in Table 3. We calculate 1.93 lung-rems (to an adult) from a 1-year exposure to a concentration of 1 pCi/L of radon from the product (1 WL/[200 pCi/L])(8766 hours/environmental year)(1 occupational month/170 hours)(0.75 fraction of time spent at home)(0.5 rad/WLM)(20 rems/rad = Quality Factor for alpha radiation). *Effective* dose equivalent rate per unit concentration (0.23 effective rems/([pCi/L]-year) is obtained by multiplying by the ICRP weighting factor for the lung (6), i.e., $w_{lung} = 0.12$.

Table 3. Assumptions used in calculating the expenditure per person-rem.

200	[pCi/L]/WL, i.e., 50% equilibrium
0.5	rad/WLM (ref. 7)
20	Q (rem/rad; ref. 6)
0.12	w_{lung}, i.e., effective rem per lung rem (ref. 6)
0.75	fraction of time spent at home
8766	hours/environmental year
170	hours/occupational month
4	persons per house
10	years life expectancy for radon control system
125	$/year energy penalty (ref. 11, modified)
29	Watt fan[a]
0.10	$/kWhr[b]
1.93	lung rems/([pCi/L]-year)
0.23	effective rems/([pCi/L]-year)
62.7	effective microsieverts/([Bq/m^3]-year)
25.42	$/year, fan operation cost

[a] Dayton Electric Mfg. Co., 5959 W. Howard St., Chicago IL 60648; Model 4C720.
[b] Duquesne Light Co., Pittsburgh, PA; 1989

The value of 0.5 rad/WLM is taken from Harley and Cohen (7), and is probably an underestimate of the conversion for children (8, 9), for which estimates as high as 1.2 rad/WLM are available (8). Additionally, the value of 0.75 of one's time in the house is somewhat higher

than the values of 0.64 to 0.73 used by some at the EPA (10); however, the EPA work is based on data which dramatically under-represent infants, small children, and the elderly.

Additionally, we assume that there are 4 persons per house, and a ten-year life expectancy for the remediation system. We further assume $125/year for operating costs and the cost of loss of conditioned air. Due to the use of a 29 W fan by RDC, rather than the more common 90 W fan, we have lowered our estimate of annual costs below the $150 estimated by Henschel (11). It is important to point out that the annual cost is not well known, and is limited at the lower end by the fan operation cost ($25.42), but may be much greater than our estimate in some cases.

A critical assumption in our calculations is that the change in radon concentrations are representative of the air that house occupants actually breathe. We do not know the proportion of houses for which this is the case. In some cases, the radon measurements are simply screening values measured in the lowest livable area of a house; in other cases, they are representative measurements of air that the occupants breathe. If a ratio for basement concentration to first floor concentration of 2.5 is used (12), then our calculated average cost per (unit collective effective dose equivalent [CEDE] averted) could be multiplied by no more than this factor.

The average cost per unit CEDE averted is tabulated in Table 4. The remediation cost plus the operation and maintenance costs are added to yield totals of $4979 for the DER work and $2280 for the RDC remediations. Average concentration changes are multiplied by 0.23 effective rem per ([pCi/L]-year) and multiplied by 4 persons and 10 years to get the 10-year CEDE averted values of 1657 person-rems per house for the DER houses and 242 person-rems for the RDC houses. These values, divided by the total 10-year cost, give the average cost per unit CEDE averted, in dollars per person-rem. The values for the DER and RDC houses are $3.01/person-rem and $9.41/person-rem, respectively.

Table 4. Average cost per unit collective effective dose equivalent averted in radon remediation and as required of the nuclear power industry.

	Cost of 10-year Energy Penalty	Capital Outlay	Total	Average Rn Conc. Change (pCi/L)	10-year CEDE[a] Averted (person-rems /house)	Average Cost per unit CEDE[a] Averted ($/person-rem)
PA D.E.R.	$1250	$3729	$4979	178.5	1657	$3.01
This Study	$1250	$1030	$2280	26.1	242	$9.41
10 CFR 50[b]						$1000.00
10 CFR 50[c]						$33333.33

[a] Collective Effective Dose Equivalent
[b] (App.I Sec.II.D.; whole body)
[c] (App.I Sec.II.D.; thyroid)

The U.S. Nuclear Regulatory Commission has set values of $1000 per whole body rem and $1000 per thyroid rem as the *minimum* amounts that must be expended to limit offsite

releases of radioactivity by nuclear power plants (3). The latter value can be converted to effective dose equivalent by dividing by the ICRP risk-based weighting factor for the thyroid, i.e., 0.03, giving $33,333.33. The NRC cost per unit CEDE averted values are roughly 300 and 10,000 times greater than the DER values, and 100 to 3,000 times the more realistic RDC values. Clearly, these numbers are inconsistent.

If a cancer fatality rate of 2×10^{-4} per person-rem is assumed, dollar values to save a human life can be computed. These are $15,000 and $47,000 for the DER and RDC remediations, and $5,000,000 and $167,000,000 for the NRC release limits. The radon remediation costs are in line with other common societal expenditures for life saving (1,2), but the NRC values are not.

CONCLUSIONS

By analyzing two sets of radon remediation data, we have shown that remediation can be a cost-effective activity when compared to other life-saving measures in our society. Expenditures in other areas of radiation protection, such as those required of nuclear power plants by the U.S. Nuclear Regulatory Commission, can be hundreds or even thousands of times less cost-effective.

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THE EFFECTIVENESS OF RADON REDUCTION IN NEW JERSEY

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ABSTRACT

The results of 473 homeowner-funded radon mitigations conducted in New Jersey from April, 1988 to November, 1989 are reported and compared to similar results previously reported for the period January, 1986 to March 1988 (1988 Study). Data presented is compiled from the New Jersey Department of Environmental Protection's (DEP) post remediation testing program. A review of the data compiled from the post remediation testing program indicates that soil depressurization is still the predominant mitigation method employed by certified firms, while soil depressurization and sealing only methods tie for predominant mitigation method employed by homeowners and non-certified firms.

Lowest floor radon concentrations following mitigation were below 4 picocuries per liter (pCi/l) in 56% of the homes, compared to only 36% in the 1988 study. This increase may be explained by the fact that radon mitigators are more experienced and knowledgeable in radon diagnostics and mitigation design. The average cost of mitigation, as determined from reports submitted by mitigation firms, was $1,100 compared to $1,300 in the 1988 study.

Introduction

In order to monitor and evaluate effective radon reduction techniques for homes, the DEP has developed a program to track radon mitigation efforts. Mitigation techniques monitored through this program include sealing only, soil depressurization, and forced air and crawl space ventilation. The latest procedures and guidelines for this technology have been provided to the public and private sectors of New Jersey through the dissemination of The United States Environmental Protection Agency (EPA) documents, and phone consultations provided by DEP technical staff.

The DEP instituted a voluntary mitigation certification program in 1986. Successful program applicants are listed in a brochure which is distributed to the public. One requirement of this program is the successful completion of a DEP approved mitigation training course, which, also serves as a means of technology transfer. A mandatory certification program will be instituted during 1990, and will require all individuals or firms who test for or reduce radon levels in the State to be certified by the DEP.

The DEP has compiled data on homeowner funded radon reduction efforts since January, 1986. Evaluation of this data has enabled the DEP to determine (1) what mitigation methods are being selected

by New Jersey residents, (2) who is performing the mitigation work, (3) the effectiveness of mitigation methods installed by both homeowners and voluntarily certified firms and, (4) the average cost of each mitigation technique.

The purpose of this paper is to report the results of data collected on 473 mitigations performed in New Jersey from April, 1988 to November 1989 and to compare these results with previously reported data collected from January, 1986 to March, 1988. Evaluation of the effectiveness of mitigation techniques will help the DEP to identify and target those areas where more training and information transfer may be needed.

Use of the term "certified firm" in this paper means a radon mitigation firm which has successfully participated in the DEP Voluntary Certification Program. "Non-certified firm" refers to those firms and individuals that either elected not be participate in the DEP voluntary program or failed to meet minimum requirements. "Effectiveness" means those post remediation radon levels in the lowest liveable area which are less than four picocuries per liter (4 pCi/l).

Sources of Data

The DEP's post remediation testing program is designed to track homeowner-funded radon reduction efforts in the State. The purposes of this program are to provide homeowners, at no cost, with radon testing to assess the effectiveness of mitigation measures installed and to monitor the performance of the mitigation industry in the State. Testing in the program was initially conducted through field visits by DEP staff to remediated homes. Two carbon canisters were deployed on the two lowest liveable levels of the home and a post-remediation survey form was completed.

Since March, 1988, post remediation testing has been provided through a mail-out program. Accordingly, homeowners are encouraged to contact the DEP and arrange for post-remediation testing. DEP staff complete phone information forms which include the resident's name, address, pre-mitigation test results, if available, mitigation technique installed, and the person or firm who installed the system. The resident is then required to submit to the DEP, a copy of his or her mitigation contract or a description of the system installed. Upon receiving this information, the homeowner is mailed two charcoal canisters with specific instructions on how to deploy and return the devices. A mitigation installation is determined to be effective when post remediation radon concentrations, under closed house conditions, are less than 4 pCi/l in the lowest "liveable" floor. The review of the data which follows has been derived from 473 post remediation surveys conducted by DEP from April, 1988 to November, 1989. Comparisons are made with similar data collected on 716 remediations from January, 1986 through March, 1988 (the 1988 Study).

A second source of data on mitigation activities was collected through the DEP's voluntary mitigation certification program. Firms participating in the program are required to submit quarterly survey reports on all radon remediations conducted in New Jersey. In addition to the information obtained through the DEP post remediation testing program, firms are required to include the cost of each mitigation system installed. Data has been compiled from firm reports submitted to DEP for 3,197 homes mitigated from April, 1988 to October, 1989. Because evaluation of this data relies on accuracy and the honesty of firm reporting, it is used only as a comparison to DEP post remediation program data and in determining mitigation costs.

Mitigation Methods

Methods employed to reduce indoor radon levels in the 473 homes monitored through the DEP post remediation testing program have been grouped into four major categories which include (1) sealing only techniques, (2) soil depressurization methods, (3) air to air heat exchangers and, (4) other methods.

Sealing only techniques typically consist of covering or filling in the sump pump pits and perimeter french drains, and sealing of floor/wall cracks and utility openings. The extent to which sealing measures were used varied considerably, especially with techniques and materials. According to phone conversations, homeowners/non certified firms were less likely to follow guidance measures outlined in EPA documents. Cracks were often not properly prepared before applying sealants and in some cases ordinary cement was used as the sealant rather than non-shrink urethane caulks.

Soil depressurization methods include the use of active and passive sub-slab ventilation, drain tile, sump pump, and block wall suction. Active sub-slab ventilation was the most widely employed soil depressurization method and was generally accompanied by sealing of major radon entry routes. However, after examining mitigation contracts and design descriptions, it became apparent that some certified firms and homeowner/non-certified firms did not always follow EPA installation guidelines. The locations of exhaust fans and exhaust ports was the most often noted non-conforming practice. Basement mounted fans often leak and improperly located exhaust ports may allow radon gas to re-enter a home. This could explain the ineffectiveness of some systems. Also, some homeowners and non-certified firms did not properly seal radon entry routes, thus reducing system effectiveness.

Air to air exchangers include those systems with heat recovery only. The principle of this design is to increase the ventilation rate in the house thus diluting the indoor radon concentration while decreasing the natural exfiltration of indoor air and reducing the pressure differential which causes soil gas to be sucked into the home. Only 14 such mitigation attempts were observed in this study. This may be explained by the fact that the installation of air to

air heat exchangers is often expensive and requires professional services for proper sizing and installation. Additionally, this type of mitigation is less effective than soil depressurization in reducing radon levels and is more costly to operate and maintain.

The last mitigation type considered in this study, "other" methods, includes forced air and crawl space ventilation. This type of mitigation includes passive venting or installing fans or blowers in basement and crawl space walls and windows. These measures usually require a minimal amount of technical skill and money, which may explain why they were most often installed by homeowners. Only 18 such mitigation attempts were reported.

Selection and installation of mitigation methods were influenced by who was performing the work. Homeowners/non-certified firms with some knowledge of buildings construction often performed their own mitigation work employing mainly sealing techniques. Certified firms overwhelmingly selected depressurization techniques as a means of remediation (166 out of 227 installations). Table 1 shows the homes remediated for each of the 4 mitigation methods discussed above. As shown, the most widely employed technique selected by homeowners/non-certified firms and certified firms was soil depressurization (58% of homes). Sealing only as a mitigation technique was used in 35% of the homes, air to air exchangers were installed in 3% of the homes and other techniques in 4% of the homes.

When compared to Table 2, which shows the 716 homes mitigated in the DEP's 1988 Study, some obvious conclusions can be drawn. Installation of soil depressurization systems remained relatively unchanged with 58% of the homes in this study and 59% of the homes in the 1988 study selecting this method. Sealing only was employed in 35% of the homes in this study and in 28% of the homes in the 1988 study, and was again the dominate method employed by homeowner/non-certified firms. Certified firms installed mitigation systems in 48% of the homes in this study and as in the 1988 study selected soil depressurization techniques most frequently, comprising 73% of all work which they performed. An interesting observation is in the difference in the percentage of homes that were mitigated by homeowner/non-certified firms and DEP certified firms. In the 1988 study, 47% of the homes were mitigated by homeowners/non-certified firms, and 53% by certified firms. In this study, 52% of the homes were mitigated by homeowner/non-certified firms and 48% by certified firms. Perhaps this is a result of further dissemination of radon reduction information to the public sector.

Effectiveness of Mitigation Systems

The performance of the mitigation systems installed in the 473 homes in this study was evaluated using post-mitigation radon levels measured by the DEP. Two canisters were provided to the homeowner with placement instructions in accordance with DEP/EPA testing protocols. Mitigated homes with radon concentrations less than 4 pCi/l in the lowest liveable level were considered effective

remediations. It should be emphasized that post remediation testing was conducted using short term charcoal canisters and therefore, these results are not indicative of annual averages.

The performance of all mitigation methods installed in this study is compared to similar data on the 716 homes surveyed in 1988 and is shown in Figure 1. The histograms show the distribution of post remediation radon levels in homes mitigated by homeowner/ non-certified firms and certified firms. The distribution of post remediation radon levels shows that in this study, 56% of the homes mitigated had radon levels below 4 pCi/l. This was a significant increase when compared with the 1988 study which shows only 36% of the mitigated homes with post remediation levels less than 4 pCi/l.

A closer look at the homes mitigated by certified firms only reveals an even greater increase in the number of homes mitigated below 4 pCi/l. Figure 2 compares levels in 225 homes mitigated by certified firms in this study with 382 homes mitigated by certified firms in the 1988 study. The distribution of radon levels shows that 78% of the homes in this study had post remediation levels less than 4 pCi/l compared to only 48% in the 1988 study. This shows an increase in mitigation effectiveness of 30%. This higher success rate may be attributed to the industry's increased experience in diagnosing, designing and installing proper mitigation systems.

A comparison of each mitigation method installed by homeowner/ non-certified firms and certified firms is presented in Figure 3. As can be seen, certified firms were significantly more effective in reducing indoor radon levels to below 4 pCi/l for all methods. Homeowner/non-certified firms were only 27% effective using sealing measures only while certified firms were 65% effective in reducing radon levels. Certified firms were even more successful in installing effective soil depressurization systems, with 81% of the systems reducing radon levels below 4 pCi/l. This is a somewhat greater performance rate when compared to all methods used by certified firms (78%). This is encouraging information since certified firms are generally employed by homeowners with high radon levels or when do-it-yourself attempts have failed. A conclusion that can be drawn from this information is that properly trained certified firms have had a consistently higher success rate than homeowner/non-certified firms for all mitigation methods in reducing radon levels below 4 pCi/l.

To further investigate the effectiveness of mitigation systems to reduce lowest floor radon levels to below 4 pCi/l, a comparison of the distribution of post remediation radon levels for each mitigation technique is presented in Figures 4, 5, 6 and 7. Sealing methods only is illustrated in Figure 4. A dramatic increase in performance can be seen as the percentage of homes with post remediation radon levels less than 4 pCi/l more than doubled from 15% in the 1988 study to 37% in this study. The continued high failure rate of sealing methods only, 63% in this study, might be attributed to the fact that this method is most often selected by inexperienced homeowner/non-certified firms who may not know how to properly seal or know when such techniques alone will be successful.

The effectiveness of air to air exchangers is shown in Figure 5. The distribution of post remediation results indicate an increase in performance in homes remediated from 23% in the 1988 study to 57% in this study. One point should be emphasized in explaining this significant increase. In this study only 14 air to air heat exchangers were examined while in the 1988 study 57 installations were examined. Of the 57 installations, 23 were of one particular design which often failed, thus accounting for 77% of the homes having levels greater than 4 pCi/l. This particular system was not noted in any of the designs surveyed in 1989.

The distribution of radon levels in homes in which soil depressurization systems were installed is shown in Figure 6. Although the performance of these systems has moderately increased from 50% in the 1988 study to 67% in this study, it is still not near the 90% effectiveness reported by firms which participated in EPA's pilot survey of private sector firms. One explanation for the 33% failure rate may be in the high number of soil depressurization attempts by inexperienced mitigators. Forty percent of all soil depressurization systems surveyed in this study were installed by homeowner/non-certified persons (see Table 1). Since these methods require diagnostic surveys and sealing measures to maximize performance, they are more likely to be improperly installed by inexperienced personnel.

Figure 7 shows the distribution of post remediation radon levels in homes utilizing "other" methods. In the 1988 survey only 20% of the methods were effective. In this study, 55% of the "other" methods reported post remediation radon levels less than 4 pCi/l. Although this may be impressive it should be emphasized that these techniques included passive and forced ventilation which usually cost the homeowner an additional heating expense. Consequently, these methods are usually temporary measures and may explain why they were only used in 18 of 473 remediations.

The performance of mitigation systems installed by certified firms was also evaluated from data compiled from quarterly mitigation reports submitted to the DEP by these same firms. Mitigation firms participating in the DEP voluntary certification program are required to report all radon mitigation work performed in New Jersey on a quarterly basis. Pre and post remediation radon levels, type cf mitigation design installed and the total cost of mitigation system are some of the data reported. A total of 3,197 residential remediations were reported to the DEP from April, 1988 to October, 1989.

The percentage of homes reported as having post remediation radon levels less than 4 pCi/l was significantly greater than that presented by the DEP. Certified firms reported effective remediations in 96% of all mitigation methods attempted compared to only 78% reported in DEP's post remediation data. This discrepancy in the two data sets may be explained when considering the following factors: various radon testing techniques were used by firms when performing post remediation tests; firm and DEP post remediation testing were often performed during different periods of the year;

the possibility that firms might inaccurately report results, and that firms may have not reported all post remediation radon levels greater than 4 pCi/l to the DEP.

Average Cost of Mitigation

The average cost of radon remediation charged to homeowners by certified firms was also computed from the quarterly survey reports submitted to the DEP. Table 3 compares the average costs of each mitigation method in this study to the 1988 study. The average cost of remediation for all mitigation methods was $1,100. This is appreciatively less than the $1,300 reported in the 1988 study where 942 remediations were evaluated. The average cost of sealing only methods in this study was $601 compared to $700 in the 1988 study. Soil depressurization methods decreased by more than 10% to $1,120 in this study from $1,270 in the 1988 study. Air to air heat exchangers decreased by about 20%. Their average cost in this study was $1,620 compared to $2,000 per installation in the 1988 study. Finally, remediation by "other" methods also cost less in this study. The average cost was only $695 compared to $1,900 in the 1988 study.

Conclusions

The proportion of homes effectively remediated for elevated indoor radon levels is increasing. Of the homes surveyed in this study compared to the 1988 study, radon remediation effectiveness by certified firms has increased from 48% to 78%. The proportion of soil depressurization systems installed is about the same, however, their effectiveness in reducing radon has increased significantly, and this method has remained the most effective method in reducing indoor radon levels below 4 pCi/l. Sealing only techniques were chosen most often by homeowners who performed their own mitigation work. Air to air heat exchangers were the least employed type of mitigation performed in this study. This may be because of the high costs of installation and maintenance along with their actual ineffectiveness in lowering indoor radon levels.

All mitigation methods decreased by 15% in cost from the previous year. The average cost of mitigation charged to New Jersey residents by certified firms in this study was $1,100.

Although this survey is encouraging for both the radon industry and New Jersey residents it also demonstrates the need for a program of continuing education and training. State and federal training programs will enable the radon industry to stay abreast of the latest scientific and technological research as well as changes in state and federal radon legislation. Support and participation in such programs will enable the radon industry to become more knowledgeable and effective in their remediation efforts and thus offer the residents of New Jersey the quality workmanship they deserve.

This work described in this paper was not funded by the United States Environmental Protection Agency, therefore, the contents do not necessarily reflect the views of the agency and no endorsement should be inferred.

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Table 1 Homeowner/Non-Certified Firm and DEP Certified Firm Mitigation Installations in 473 Homes Surveyed in 1989

	Sealing Only	Soil Depressurization	Air to Air Exchanger	Other	Total
Homeowner/ Non-Certified Firms	119	110	5	12	246[52]
DEP Certified Firms	46	166	9	6	227[48]
Total	165[35]	276[58]	14[3]	18[4]	473[100]

Bracketed numbers represent percent of total homes.

Table 2 Homeowner/Non-Certified Firm and DEP Certified Firm Mitigation Installations in 716 Homes Surveys in 1988.

	Sealing Only	Soil Depressurization	Air to Air Exchanger	Other	Total
Homeowner/ Non-Certified Firms	176	95	43	20	334[47]
DEP Certified Firms	27	326	14	15	382[53]
Total	203[28]	421[59]	57[8]	35[5]	716[100]

Bracketed numbers represent percent of total homes.

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Table 3 Average Cost of Radon Mitigation ($)

Mitigation Technique	1989 Study (3197 Homes)	1988 Study (942 Homes)
Sealing	601	730
Soil Depressurization	1120	1270
Air to Air Exchangers	1620	2000
Other	695	1900
Overall Average	1100	1300

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FIGURE 1

Post-Remediation Radon Levels in Homes Mitigated by Homeowners/Non-Certified Firms and Certified Firms for All Methods

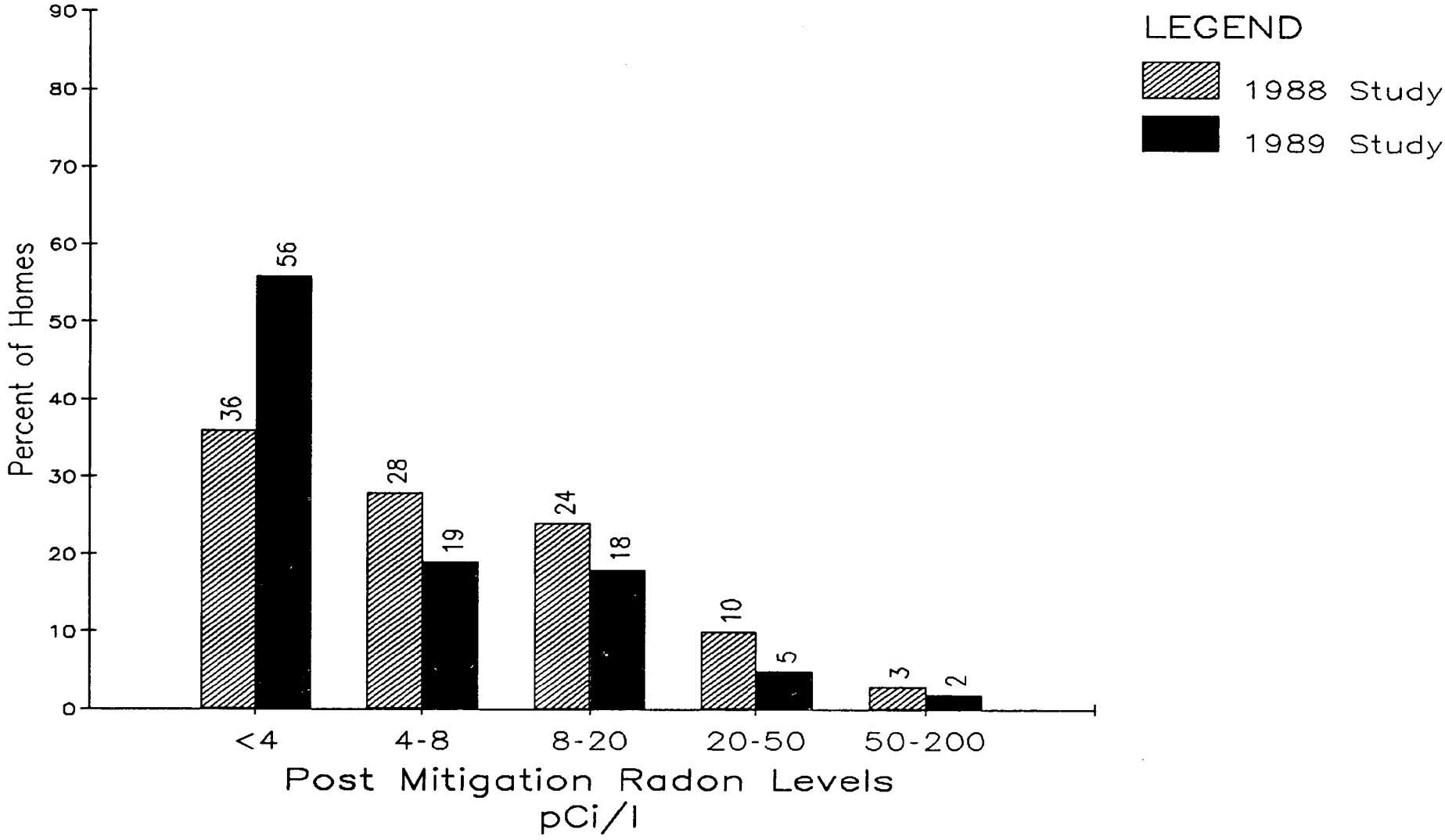


FIGURE 2

Post-Remediation Levels In Homes Mitigated by DEP Certified Firms for All Methods

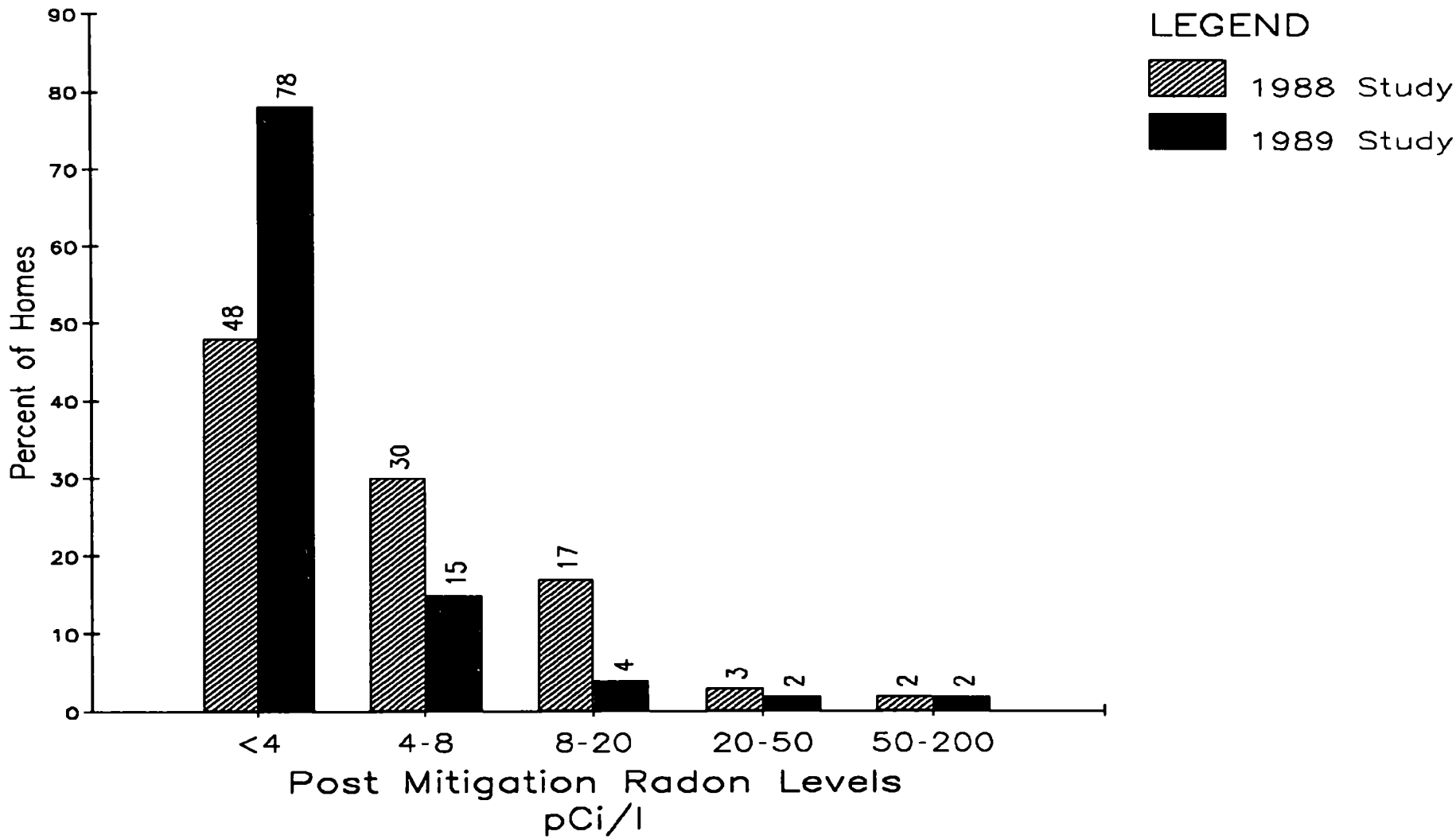


FIGURE 3

Effectiveness of Mitigation Measures

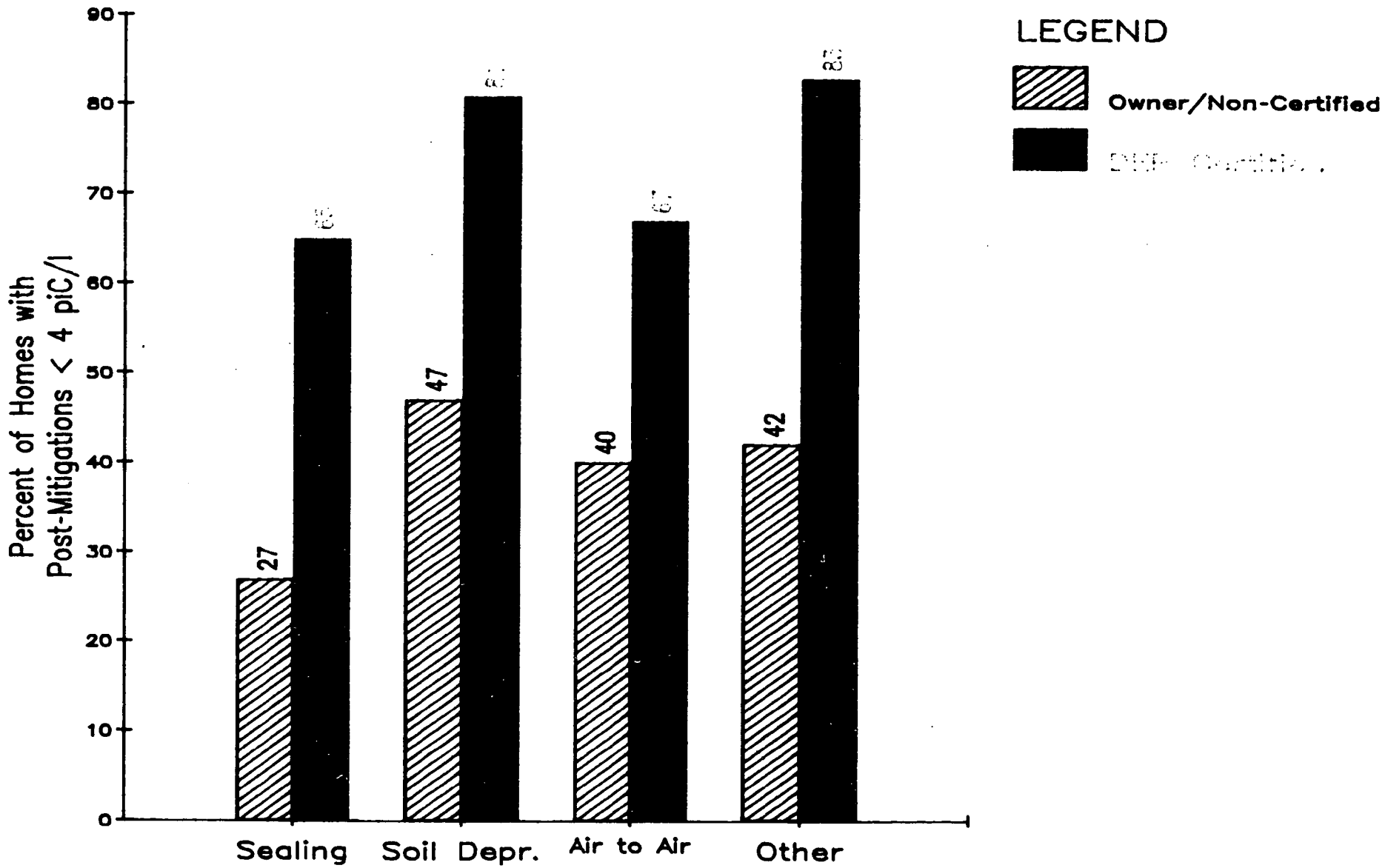


FIGURE 4

Post-Remediation Radon Levels in Homes Mitigated Using **Sealing Only**
(DEP Certified and Homeowner/Non-Certified)

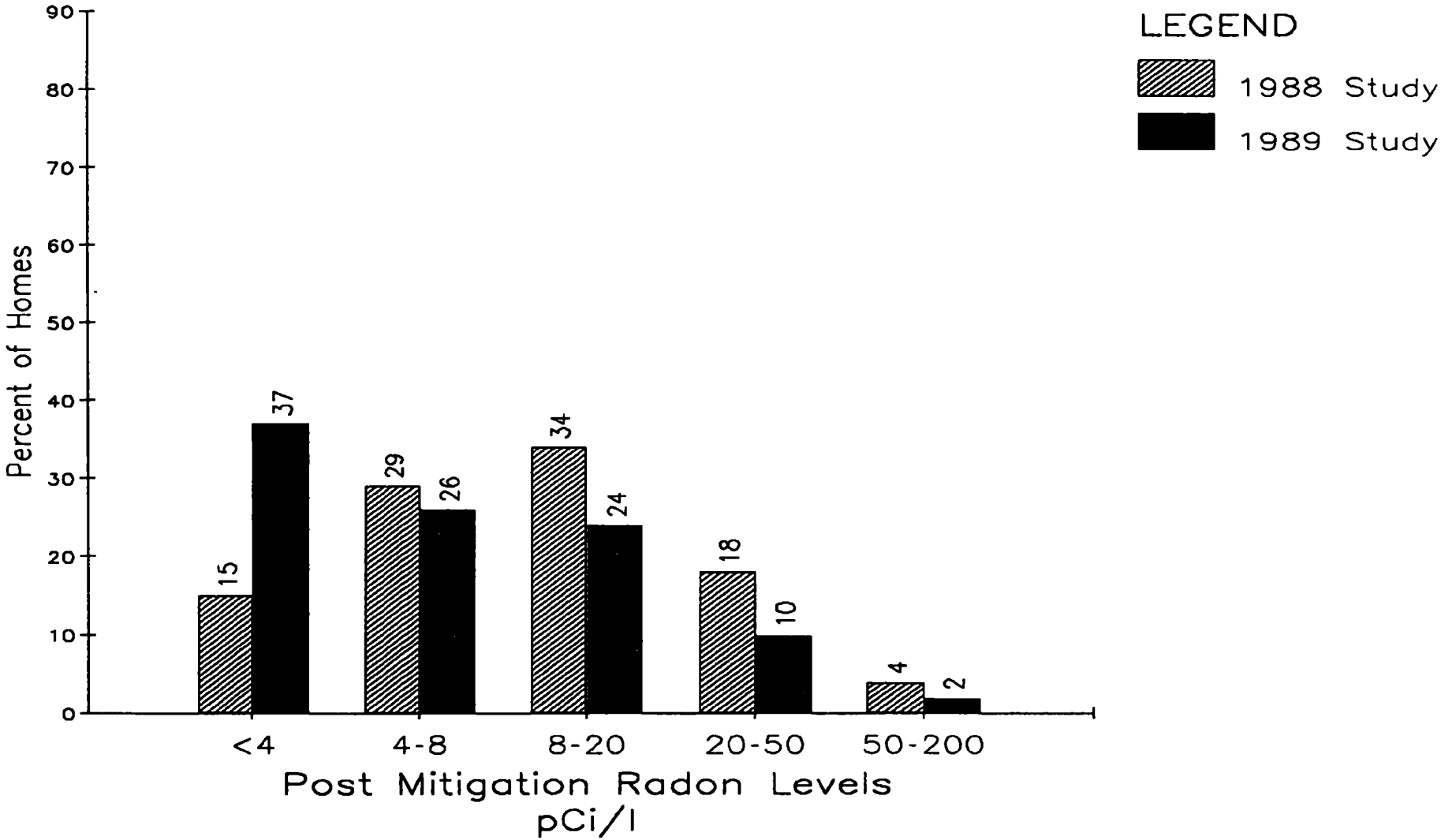


FIGURE 5

Post-Remediation Radon Levels in Homes Mitigated Using **Air to Air Heat Exchangers** (DEP Certified and Homeowner/Non-Certified)

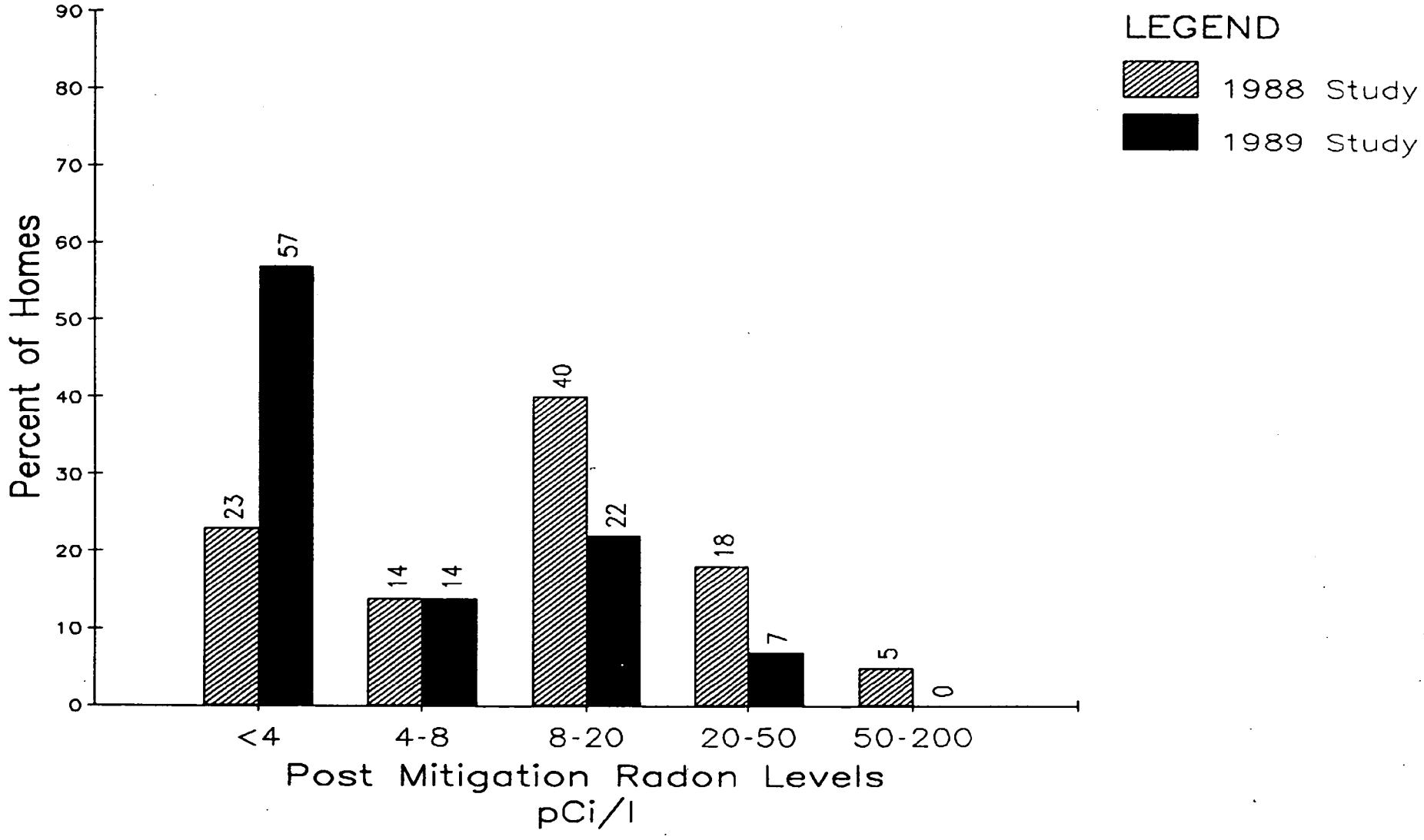


FIGURE 6

Post-Remediation Radon Levels in Homes Mitigated Using **Soil Depressurization** (DEP Certified and Homeowner/Non-Certified)

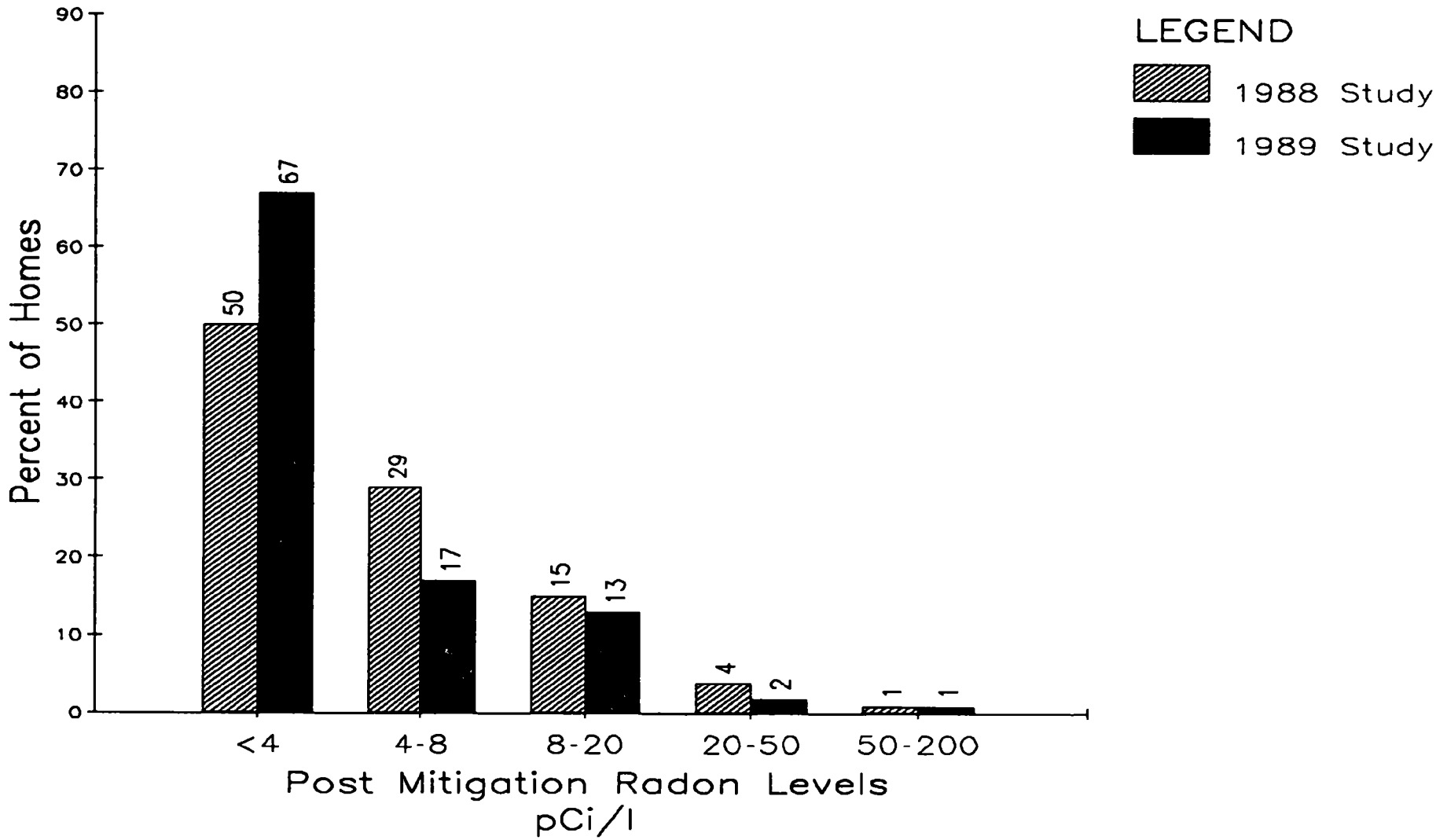
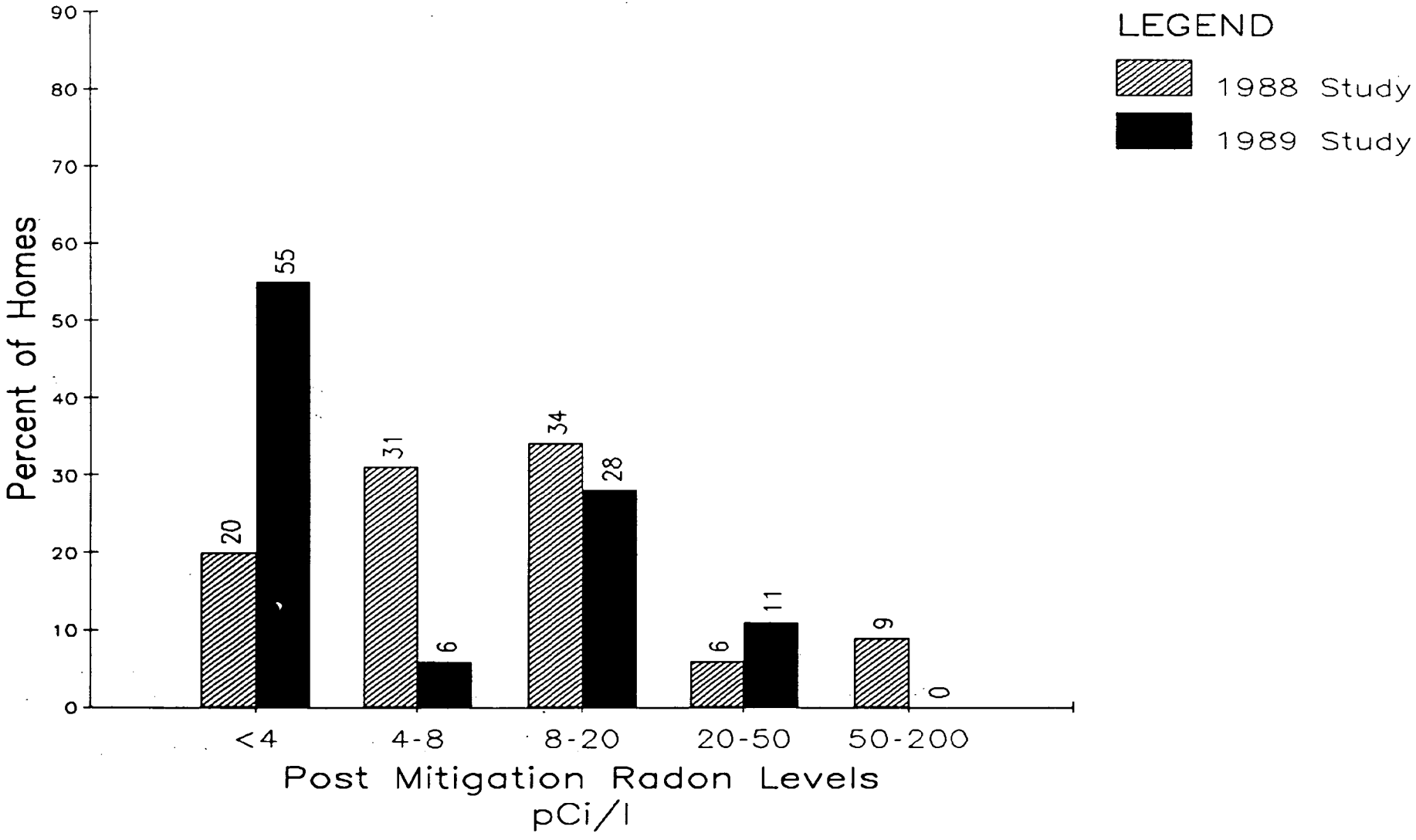


FIGURE 7

Post-Remediation Radon Levels in Homes Mitigated Using **Other Methods**
(DEP Certified and Homeowner/Non-Certified)



LONG-TERM PERFORMANCE AND DURABILITY OF ACTIVE RADON MITIGATION SYSTEMS IN EASTERN PENNSYLVANIA HOUSES

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ABSTRACT

Indoor radon reduction techniques were installed in 40 houses in the Reading Prong region of eastern Pennsylvania over the period 1985 to 1987. Active soil ventilation systems were installed in 36 of the houses; 3 had heat recovery ventilators (air-to-air heat exchangers), and 2 installations included carbon adsorption units to remove radon from well water. Follow-up measurements of the post-mitigation radon concentrations in these houses were conducted with alpha-track detectors during the winters of 1986/87, 1987/88, and 1988/89. The systems were inspected and the owners interviewed during each installation and collection visit.

In those houses where the radon reduction system was in continuous operation during the monitoring periods, the measured average radon concentration in each house compared well from year to year. High radon concentrations were measured if the system did not operate during a monitoring period. Overall, no general degradation in system performance was observed.

One manufacturer supplied 34 fans with the same motor and impeller assembly which were used in the active soil ventilation systems. There have been five fan failures in this population to date. The causes were capacitor failure in four fans, and noisy bearings leading to shutdown in one fan. Assuming an exponential lifetime distribution, the mean life of these fans (between repairs/replacements) is calculated as 15 years, based upon this experience. There have been no failures among three other fans from another manufacturer.

Of the three installed heat recovery ventilators, one fan bearing failed in early 1989. This experience suggests a mean life between repairs of 8 years.

The performance of one charcoal adsorption unit has deteriorated from <95% to 65% removal over 3 years. The second unit, which contains charcoal specially selected for radon removal, has maintained a 97% removal efficiency over the same period.

Five houses from this group of 39 houses (after 1 early dropout) have been sold over the period of the study, suggesting a mean occupancy life of 29 years in this study group.

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

Indoor radon reduction techniques were installed and tested in a total of 40 homes in communities on the Reading Prong in eastern Pennsylvania over the period of June 1985 to June 1987 as part of EPA Contract 68-02-4203. The primary mitigation method in 36 of these houses was active soil ventilation, with 3 houses receiving heat-recovery ventilators (air-to-air heat exchangers) and 1 house receiving just a radon-in-water removal unit. This project was reported in detail in EPA-600/8-88-002 (Reference 1).

Follow-up alpha-track-detector (ATD) radon concentration measurements have been made annually in 38 of the 40 demonstration homes during the heating seasons of 1987/88 (Reference 2) and 1988/89 (Reference 3). Two of the houses were no longer available for monitoring - one house had been removed from the original site, and the owner of a second house has discontinued participation in the project.

This paper examines the results in the 38 demonstration homes to make an assessment of long-term system performance and equipment durability.

MEASUREMENT PROCEDURE

Average radon concentrations are measured by Terradex 'Track-Etch' detectors exposed for 4 months during the heating season. The forces that urge radon from the soil into the home are highest during this time, and therefore this season presents the greatest challenge to radon mitigation systems.

Quality assurance and control (QA/QC) measures were instituted to ensure that the acquired data were of high quality. Unexposed detectors (blanks) were included in each set sent to Terradex for analysis, and a number of detectors from each batch were exposed to known concentrations in the radon chamber operated by the U.S. Department of Energy's Environmental Measurements Laboratory (EML) in New York. All these detectors were given fictitious house identifying numbers, so that they were "blind" samples to the processor. A "zero correction", equivalent to the mean reported exposure of the blanks, was subtracted from each ATD result reported by Terradex. A "gain correction" derived from the spiked samples (EML Exposure/Zero-Corrected Reported Terradex Exposure) was used as a multiplier to adjust the reported house concentrations to conformity with the EML.

As an additional QA/QC measure, detectors were exposed in groups of three (1986/87 and 1987/88) or two (1988/89) at each measurement location, and the results averaged to reduce the measurement uncertainties.

The demonstration houses were visited during December of each year to install Terradex "Type SF" Track-Etch detectors in accordance with the guidance given in the EPA Measurements Protocol (Reference 4). Detectors were placed in both the main living area and the basement, hung together in groups of three (two in 1988/89) from an interior wall or ceiling in the living area and a central joist in the basement. Each detector was marked with the installation date and the

house identification code. That information, plus the detector numbers and their locations, were recorded in a Track-Etch Record Book kept specifically for that purpose. During these visits the soil ventilation fans and the air-to-air heat exchangers were checked to see that they were operating. The houses were visited about 16 weeks later, at the end of the heating season, to remove the detectors. An ATD retrieval rate of 100% was achieved. The homeowners were interviewed to discover any events that might have affected the system performance during the monitoring period. Retrieved detectors were placed in pairs into the manufacturer's envelopes, which were then sealed by folding and taping in a low-radon atmosphere. The envelopes were returned to Terradex in one batch.

QA/QC RESULTS

The 1986/87 and 1987/88 blanks did not indicate a need for zero correction. The results from the QA/QC blanks in 1988/89 led to a zero correction of 10 Bq/m^3 (0.26 pCi/ℓ).

The detectors exposed at EML had known exposures which were always greater than the reported exposures, and so gain corrections were applied of 1.16 for 1986/87; 1.30 for 1987/88; and 1.21 for 1988/89.

One outlier was identified in a group of three detectors in the 1986/87 reported results and was discarded. No outlier was discovered in the 1987/88 results. In 1988/89 there were two probable outliers; these were of limited significance, since the measurements were both from houses where the mitigation system did not operate during the entire measurement period.

RESULTS

RADON REDUCTION PERFORMANCE

Table I shows the results by year for the 27 houses where the mitigation systems operated for the entire 3-year period and were monitored each winter, thus providing a fair measure of long-term mitigation system performance. Excluded from the table are the results from five houses where the system equipment failed during the 3 years, three houses in which the system was turned off during the monitoring period, three houses with measurements only in 1987 and 1988, and one house where the system was incomplete because the owner refused further work.

The average radon concentration in the basement of these 27 houses was 4.7, 4.7, and 4.9 pCi/ℓ in 1987, 1988, and 1989, respectively; in the living area, the average was 4.0, 3.9, and 3.9 pCi/ℓ. The small differences in the group average from year to year are without statistical significance. The constancy of the group average with time shows that there has been no general deterioration of system effectiveness in 3 years of operation.

Table I. ALPHA-TRACK MONITORING RESULTS

ID NO.	PREMIT. (pCi/ℓ)	POST-MITIGATION RADON RESULTS (pCi/ℓ) 1989 B*	1989 LA*	1988 B	1988 LA	1987 B	1987 LA	BAVE*	LAVE*
2	413	5.5	8.7	4.8	6.7	3.0	6.0	4.4	7.1
3	350	3.0	1.9	3.5	2.3	4.1	2.4	3.5	2.2
5	110	5.0	4.4	5.0	4.4	5.0	5.0	5.0	4.6
6	60	3.2	2.7	4.1	3.2	3.8	5.7	3.7	3.9
8	183	2.9	1.0	3.5	1.5	4.5	2.1	3.6	1.5
9	533	12.4	17.1	10.4	12.9	13.5	16.8	12.1	15.6
10	626	10.4	8.9	15.2	9.9	10.4	7.5	12.0	8.8
12	11	1.6	2.1	2.2	2.2	4.3	2.9	2.7	2.4
13	64	2.7	2.8	2.6	3.9	2.7	2.3	2.7	3.0
16	395	4.8	1.1	5.7	2.5	6.3	2.0	5.6	1.9
18	12	12.7	5.1	13.5	3.4	10.2	2.4	12.1	3.6
20	210	8.3	9.3	6.5	10.0	6.7	11.5	7.2	10.3
21	172	1.9	2.7	2.0	2.7	3.6	3.0	2.5	2.8
22	24	10.8	4.0	8.6	4.4	8.8	3.1	9.4	3.8
24	66	4.3	3.7	3.6	3.8	5.0	5.3	4.3	4.3
25	122	7.2	5.3	7.7	6.0	6.3	3.5	7.1	4.9
26	89	0.6	1.1	1.1	1.6	2.4	1.7	1.4	1.5
27	21	5.6	2.1	4.0	2.2	4.4	2.6	4.7	2.3
28	21	3.6	5.1	4.1	4.4	2.8	6.1	3.5	5.2
29	61	2.1	2.3	1.6	2.0	2.2	1.6	2.0	2.0
30	17	3.9	2.1	4.0	1.6	3.5	1.5	3.8	1.7
32	6	0.5	3.2	1.2	4.4	1.2	3.7	1.0	3.8
33	82	11.2	0.7	3.5	1.2	2.6	1.3	5.8	1.1
34	470	5.1	5.5	5.4	5.5	6.4	4.3	5.6	5.1
35	144	2.4	1.0	1.0	0.9	0.9	0.8	1.4	0.9
36	300	0.8	0.7	1.1	1.0	1.9	0.8	1.3	0.8
37	87	0.9	0.5	1.2	0.7	0.7	2.0	0.9	1.1
Average	- 172	4.9	3.9	4.7	3.9	4.7	4.0	4.8	3.9
%RDEV*	- 104	76	94	78	78	66	87	70	84

B=Basement; LA=Living Area; BAVE=Basement Average; LAVE=Living Area Average; %RDEV=Relative Standard Deviation (in %).

Conversion factor: Bq/m^3 = 37 x value in pCi/ℓ.

Table I shows the average radon concentrations in the basement and the living area of the individual houses. In general, the average concentration does not vary greatly from year to year in a given house, but House 33 is an exception. The radon concentration in 1989 in the basement increased by over 300% while concentrations in the living area remained similar to previous years.

A number of houses (2, 9, 20, 28, and 32) have higher radon concentrations upstairs than in the basement. This is more clearly seen in Table II, where the ratios of radon concentration in the living area to that in the basement are

Table II. RATIO OF RADON CONCENTRATIONS IN LIVING AREAS TO BASEMENTS

ID No.	LIVING AREA/BASEMENT RADON CONCENTRATION RATIOS 1987	1988	1989	Average
2	2.00	1.40	1.58	1.66
3	0.59	0.66	0.63	0.63
5	1.00	0.88	0.88	0.92
6	1.50	0.78	0.84	1.04
8	0.47	0.43	0.34	0.41
9	1.24	1.24	1.38	1.29
10	0.72	0.65	0.86	0.74
12	0.67	1.00	1.31	1.00
13	0.85	1.50	1.04	1.13
16	0.32	0.44	0.23	0.33
18	0.24	0.25	0.40	0.30
20	1.72	1.54	1.12	1.46
21	0.83	1.35	1.42	1.20
22	0.35	0.51	0.37	0.41
24	1.06	1.06	0.86	0.99
25	0.56	0.78	0.74	0.69
26	0.71	1.45	1.83	1.33
27	0.59	0.55	0.38	0.51
28	2.18	1.07	1.42	1.56
29	0.73	1.25	1.10	1.02
30	0.43	0.40	0.54	0.46
32	3.08	3.67	6.40	4.38
33	0.50	0.34	0.06	0.30
34	0.67	1.02	1.08	0.92
35	0.89	0.90	0.42	0.74
36	0.42	0.91	0.88	0.74
37	2.86	0.58	0.56	1.33
Average=	1.01	0.99	1.06	1.02
%RDEV*=	75	67	109	77

* %RDEV = Relative standard deviation (in %).

shown for individual houses, over a 3 year period. The ratios are consistently above unity in those five houses. Houses 9, 20, and 32 are known to have radon levels in well water above 20,000 pCi/ℓ, which could be contributing preferentially, through water-usage pattern, to higher concentrations upstairs. The concentration of radon in water at House 28, which has a well, is not known. In addition, Houses 2, 9, and 28 have block fireplace structures which could provide a direct soil-gas entry route upstairs without entering the basement. Houses 2 and 9 also have block wall pressurization systems which could force radon-laden air upstairs. House 20 has an adjoining paved crawl space which may not be fully treated. Although these are perhaps special cases, there are enough of them to indicate that basement measurements do not always provide a conservative estimate of the radon exposure to the occupants.

INOPERATIVE SYSTEMS

Some mitigation systems were inoperative during the monitoring periods, and are listed in Table III, where the post-mitigation radon results obtained during all monitoring periods are provided along with brief comments as to why the systems were not functioning. House 1, which was demolished and moved from its site before post-mitigation monitoring could begin, and House 11, where the owner refused further participation, have been included for completeness.

Table III. SYSTEMS INOPERATIVE DURING ONE OF THE ATD MONITORING PERIODS

ID NO.	PREMIT. (pCi/ℓ)	POST-MITIGATION RADON RESULTS (pCi/ℓ) 1989 B**	1989 LA**	1988 B	1988 LA	1987 B	1987 LA	ADDITIONAL COMMENTS
1	146	House moved from site						
2	413	5.5	8.7	4.8*	6.7*	3.0	6.0	1. Capacitor failure; repaired prior to monitoring. 2. Fan turned off by homeowner.
4	25	1.2	1.0	7.3*	3.1*	0.8	0.9	Capacitor failure.
7	402	103.1*	24.1*	4.9	3.8	4.8	3.2	Capacitor failure.
11	49	Owner no longer participating						
14	36	10.8*	8.0*	1.1	1.4	0.6	0.8	Fan turned off.
15	18	1.3	1.3	19.7*	11.0*	1.3	1.2	Bearing failure.
17	9	8.5*	4.9*	8.2	6.4	8.8	4.8	HRV bearing failure.
31	485	252.7*	93.3*	2.8	8.3	2.1	6.6	Capacitor failure.
39	111	7.5	1.8	46.1*	17.5*	--	--***	Fan turned off.

* Asterisk marks monitoring period system was inoperative.
** B = Basement; LA = Living Area. *** -- = No measurement during 1987.

In three houses, the soil ventilation fan was turned off by the homeowner, either deliberately or inadvertently. Reportedly, the fans at House 2 were turned off for 12 days during the 1988 measurement period while the family was away on vacation. However no increase in radon concentration was observed, indicating that the concentrations did not return promptly to the very high pre-mitigation levels. The results were similar to 1989 when the owners took care to have the fans running constantly throughout the monitoring period. Perhaps

only one of the two fans involved in this system was turned off. Likewise, at House 39, the system fan was turned off for an extended period while the owners were away. At House 14, the owner unintentionally disconnected the fan from the electrical outlet for some time during the 1989 monitoring period.

Besides the above three examples of soil ventilation systems being rendered inoperative due to owner intervention, there have been five instances of soil ventilation systems not working due to mechanical failure of the system fans - Houses 2, 4, 7, 15, and 31. The first failure occurred at House 2, and was corrected before the start of the 1987 monitoring season, the second two during the 1988 monitoring period (Houses 4 and 15), and two more during the 1989 period (Houses 7 and 31). In addition to these five mechanical failures in soil ventilation systems, there was one failure of a HRV fan (House 17).

When the fans did not operate during monitoring periods in these houses, the average radon concentrations were high, as would be expected. Levels at Houses 2, 4 and 15 returned to previous post-mitigation values after system repairs. The systems have been repaired at Houses 7 and 31, and await further monitoring.

FAILURE EXPERIENCE WITH SOIL VENTILATION FANS

Three different types of soil ventilation fans, from two different manufacturers, were used in the active soil ventilation systems installed in the demonstration houses in Pennsylvania. One type, from the first manufacturer, was installed in three of the houses; there have been no failures to date among these three fans.

Two types of fans, from the second manufacturer, use the same motor and impeller assembly in different housings. A total of 34 fans from this manufacturer have been installed in 31 houses as part of the Pennsylvania project. These 34 fans have suffered 5 failures (Houses 2, 4, 7, 15, and 31) since installation 2 to 4 years ago. The number of fans is greater than the number of houses because three houses each had two fans in their soil ventilation systems.

Four of the fan failures were due to failure of the electrolytic capacitor used in the split-phase electric motor. When the capacitor fails, the fan cannot be started. If the fan is operating when the capacitor fails, the fan will continue to operate for some time, but at significantly reduced performance.

One fan, at House 15, developed noisy bearings and was turned off by the owner while awaiting replacement.

In all instances the fans were repaired or replaced under warranty and are functioning properly once more.

If we assume an exponential probability distribution for fan lifetimes, we can write the probability for a failure after time, t, as

$$P(t)dt = A \exp(-At)dt$$

where A is the average failure rate. The mean lifetime between events requiring fan repair or replacement is given by T=1/A. If we take experience to date as extending from the time of installation until the end of the latest monitoring period (April 1989), then the accumulated experience is 897 fan-months or 75 fan-years. This sets the average failure rate, A, at 5 fan failures in 75 fan-years, and therefore indicates a mean lifetime, T, between repairs/replacements of 75/5 = 15 years.

This lifetime can be used to estimate the number of fan failures to be expected year by year, by integrating the probability above over time. The expectation value for the number of fans, N, failed by the end of time, t, is given by

$$\langle N(t) \rangle = N(0)[1-\exp(-t/T)],$$

where T is 15 years and N(0) stands for the number of fans installed, 34 in this instance. The expected number of failures can then be calculated as 2.2 after 1 year, 4.2 after 2 years, 6.2 after 3 years, and 8.0 after 4 years. These are in keeping with our findings to date.

HRV EXPERIENCE

The system breakdown at House 17 is the first failure of an HRV unit installed at three of the demonstration houses. The owner reported that the bearings seized on the motor which drives both the intake and exhaust fans, and the rotary heat exchange wheel, in this HRV design. The homeowner suspects that the fan shaft may have been bent by the contractor during the original installation, potentially causing the eventual deterioration of the bearings. The fan has since been replaced by the vendor, and the unit is now operating.

To date, then, our experience with HRV units indicates 1 failure requiring repair in 100 unit-months of operation. Although this failure apparently resulted from installation problems rather than from normal long-term wear, the installation problem is felt to be representative of the factors which can influence system lifetime; thus, this failure can be considered in the calculation of equipment lifetime between repairs. If one assumes an exponential distribution of lifetimes to failure, the mean lifetime, between required repairs, can be estimated as 100/1=100 months or 8 years. The expected number of failures after 3 years of operation would be 0.94 and after 9 years that would have grown to 2.0 failures.

WELL WATER TREATMENT BY CHARCOAL ADSORPTION

Adsorption on activated charcoal was chosen for removal of radon from well water at House 2, where it supplemented an active soil-ventilation mitigation system, and at House 30, where it was the sole means of reducing household radon. Two different suppliers for charcoal units were used. The first unit came from a local water purification supplier and contained charcoal of unknown origin, probably selected for organics removal. This was installed in House 2, where radon concentrations in the water were only moderately elevated at >200,000 Bq/m^3 (>50,000 pCi/ℓ). The initial radon removal efficiency was about 95%.

This system was checked in January 1988, and removal efficiency was 79%. By December 1988, the removal efficiency was 65%. This steady deterioration in performance is not altogether surprising, since the charcoal used was not specially selected for radon removal from water.

The second unit came from a firm in Maine which specialized in water treatment systems for radon removal. This unit contained coconut charcoal specifically selected to remove radon. This was installed in House 30 where radon concentrations in water were high - about 800,000 Bq/m^3 (200,000 pCi/ℓ). The initial removal efficiency ranged from 95% to 99%.

This second system was checked in 1987, and the removal efficiency was 99% at that time. In December 1988, the removal efficiency was 97%. This is consistent with a constant removal efficiency. There is no degradation in removal efficiency evident with this unit despite the high input concentration and the high water usage associated with a family with two young children. Perhaps this is attributable to the specially selected charcoal.

TURNOVER OF HOUSING STOCK

During the period of this study, starting from the initial selection of houses in April 1985 through the latest monitoring period in April 1989, 5 homeowners out of total of 39 have moved. (The 40th homeowner dropped out of the program within the first year, and is thus not included in this calculation.) Since the total occupancy to date is 146 owner-years, the average rate of moving during the study is 5/146 per year. Assuming an exponential distribution of occupancy times, the mean occupancy life, T, is 146/5 = 29 years.

CONCLUSIONS

For the 27 houses in which the mitigation systems operated continually during all three monitoring periods from 1986 to 1989, the post-mitigation ATD results did not change greatly from year to year. Only at House 33 was there a significant increase in radon concentration in 1989, and then only in the basement. There does not appear to be any general degradation in mitigation system performance with time alone.

There are 34 fans from one manufacturer used in the soil ventilation systems, and 5 failures (requiring repair or fan replacement) have occurred over the past 2 to 4 years. Four of these failures have been due to capacitor failure, and one due to bearing noise. Based upon this experience, these fans are estimated to have a mean lifetime of 15 years before repair/replacement.

There are three HRV units installed, and one of these units had a bearing seizure requiring repair after 3 years. The estimated mean HRV lifetime between such repairs, based upon this experience, is 8 years.

There are two charcoal adsorption units for removal of radon from well water. The removal efficiency of one has fallen from 95% to 65% over a period of 28

months from installation. The removal efficiency of the other unit, containing specially chosen charcoal, has remained constant at 97% over the same period.

There are 39 homeowners in the study group, and 5 of them have moved over the period. A mean occupancy period of 29 years is estimated.

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Session D-VII:

Radon Reduction Methods—POSTERS

ENERGY PENALTIES ASSOCIATED WITH THE USE OF A SUB-SLAB DEPRESSURIZATION SYSTEM

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ABSTRACT

One of the primary radon mitigation techniques used to reduce indoor radon concentrations in houses is a sub-slab depressurization system. In this type of system, a fan removes soil gases containing radon from beneath the floor slab and exhausts the gases to the outdoors by creating a pressure field beneath the slab that is negative relative to the basement air pressure. Because of this negative pressure, indoor conditioned air can be drawn through the floor penetrations and exhausted outdoors. In order to determine the amount of conditioned air that is being lost, a series of experiments utilizing tracer gases were performed in three houses. This paper presents the results of these experiments.

INTRODUCTION

One of the most accurate ways of determining a building's air exchange rate is through the use of a tracer gas. A gas is injected into the building's interior. Specialized equipment is used to monitor the concentration of the tracer gas. The rate of decay of the tracer gas can then be used to determine the building's air exchange rate. This procedure is commonly utilized to determine the building's overall air exchange rate. For the purpose of determining the amount of conditioned air being lost due to the

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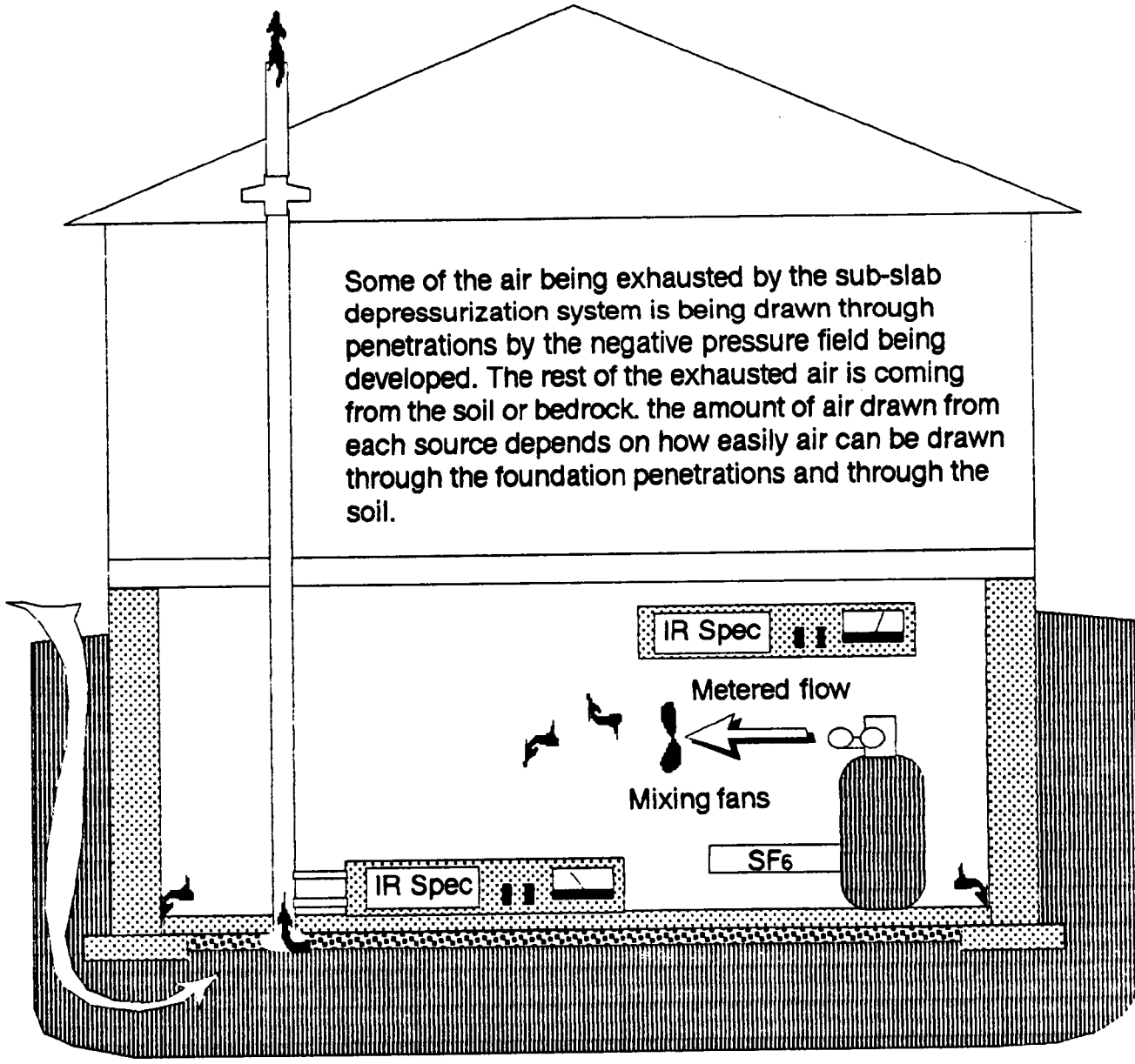
This paper has been reviewed in accordance with the U. S. Environmental Protection Agency peer and administrative review policies and approved for presentation and publication.

sub-slab depressurization system, the methods normally used were modified because the method described above would include the air lost from the basement to the superstructure of the house through thermal bypasses and other penetrations, and the air lost to the outdoors through above grade basement penetrations. What was required was a method that would disclose the amount of air that the sub-slab depressurization system was actually drawing out of the basement through the below grade penetrations due to the negative pressure field being developed by the sub-slab depressurization system.

GENERAL PROCEDURES

A series of tests utilizing sulfur hexafluoride (SF_6) as a tracer gas and Miran 101 specific gas analyzers to monitor the tracer gas concentrations were performed in each house. One analyzer would monitor the basement SF_6 concentration, and one analyzer would monitor the SF_6 concentration within the sub-slab depressurization system exhaust pipe. Figure 1 is a simplified schematic of the equipment setup. An amount of tracer gas was injected into the basement. The gas and basement air were mixed using several small fans. The tracer gas was continuously seeded until the basement and the exhaust pipe concentrations were stable. System airflow rates were measured, and the ratio of basement to exhaust pipe SF_6 concentrations at that airflow rate was then used to determine the amount of indoor conditioned air that was being lost due to the sub-slab depressurization system.



One analyzer monitors basement SF_6 concentrations and the other monitors the exhaust pipe concentration. A constant concentration is maintained in the basement. The ratio of the two concentrations reveals the amount of basement air being exhausted by the sub-slab depressurization system.

Figure 1. Equipment layout of tracer gas experiments.

Figure 2 illustrates the data gathered during a typical test. For this experiment, the sub-slab system was in the active mode. Data were collected for 5 minutes prior to injecting the SF_6 as a check on the stability of the analyzers. At the end of the first 5 minute period, SF_6 was seeded and the injection rate was adjusted until a stable concentration in the basement and exhaust pipe was obtained.

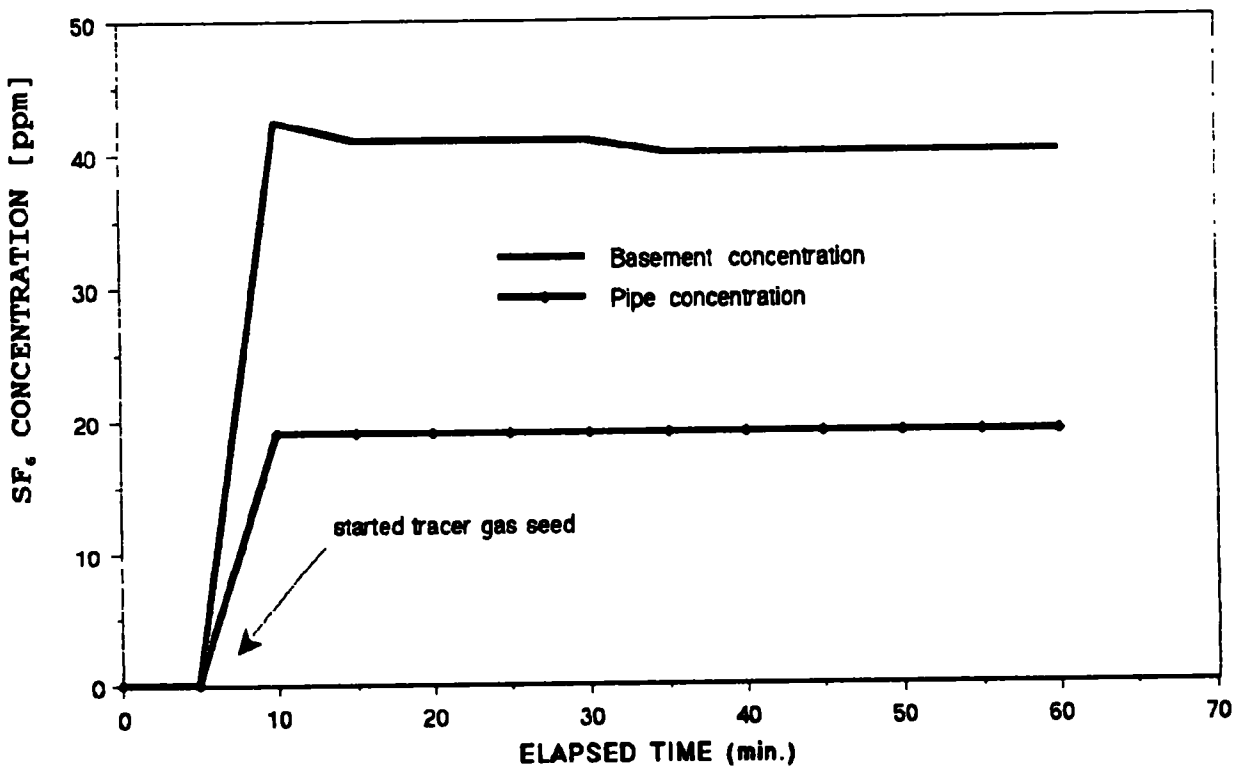


Figure 2. Tracer gas experiment performed in House VA2 to determine the energy penalty associated with the use of a sub-slab depressurization system.

Figure 3 illustrates a test performed at house VA2 to determine the effect that penetrations through the slab have on the sub-slab system. For this test the sub-slab system was in the active mode. SF_6 was continuously injected into the basement throughout the entire monitoring period. For the first 45 minutes of the test, the floor slab was left intact. At time 45, a 1/2-in.* diameter (0.2 sq in.) hole was drilled through the

* Readers more familiar with metric units may use the conversion factors at the end of this paper.

floor slab, and the SF_6 concentration in the exhaust pipe and basement air allowed to stabilize. At time 85, another 1/2 - in. diameter hole was drilled in the floor slab and the SF_6 concentrations again allowed to stabilize. At time 110 a 3.1 sq in. hole was opened in the sump cover, and the concentration stabilized. For the final test hole, at time 150, the 3.1 sq in. hole in the sump cover was reduced to 1 sq in., and again, the SF_6 concentration allowed to stabilize.

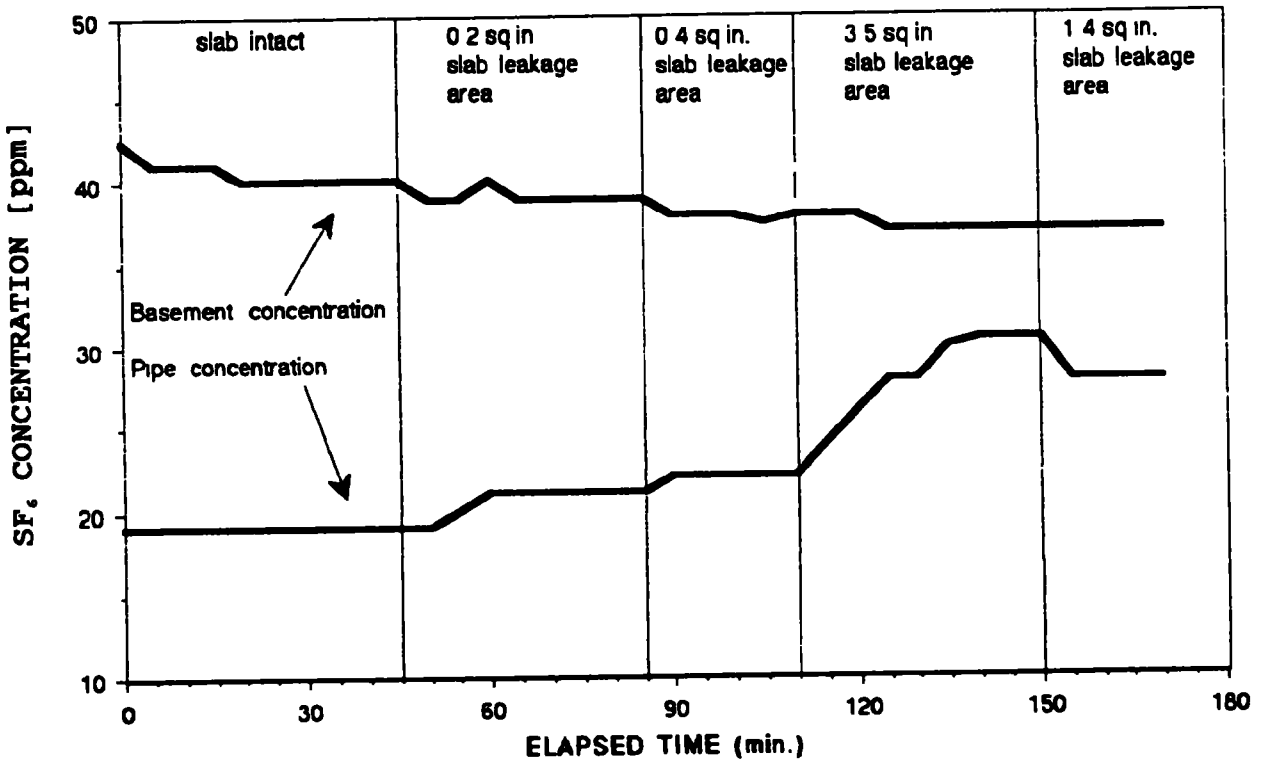


Figure 3. Tracer gas experiment performed in House VA2 to determine the effect slab penetrations have on the sub-slab depressurization system.

The same type of experiment was performed in House PA1. SF_6 was injected into the basement . A number of penetrations were made in the slab. The ratio of the basement to exhaust pipe SF6 concentration, along with the volume of air being exhausted by the sub-slab system, can be used to determine the additional energy

costs incurred by the use of a sub-slab depressurization system. The data collected during this experiment are illustrated in Figure 4.

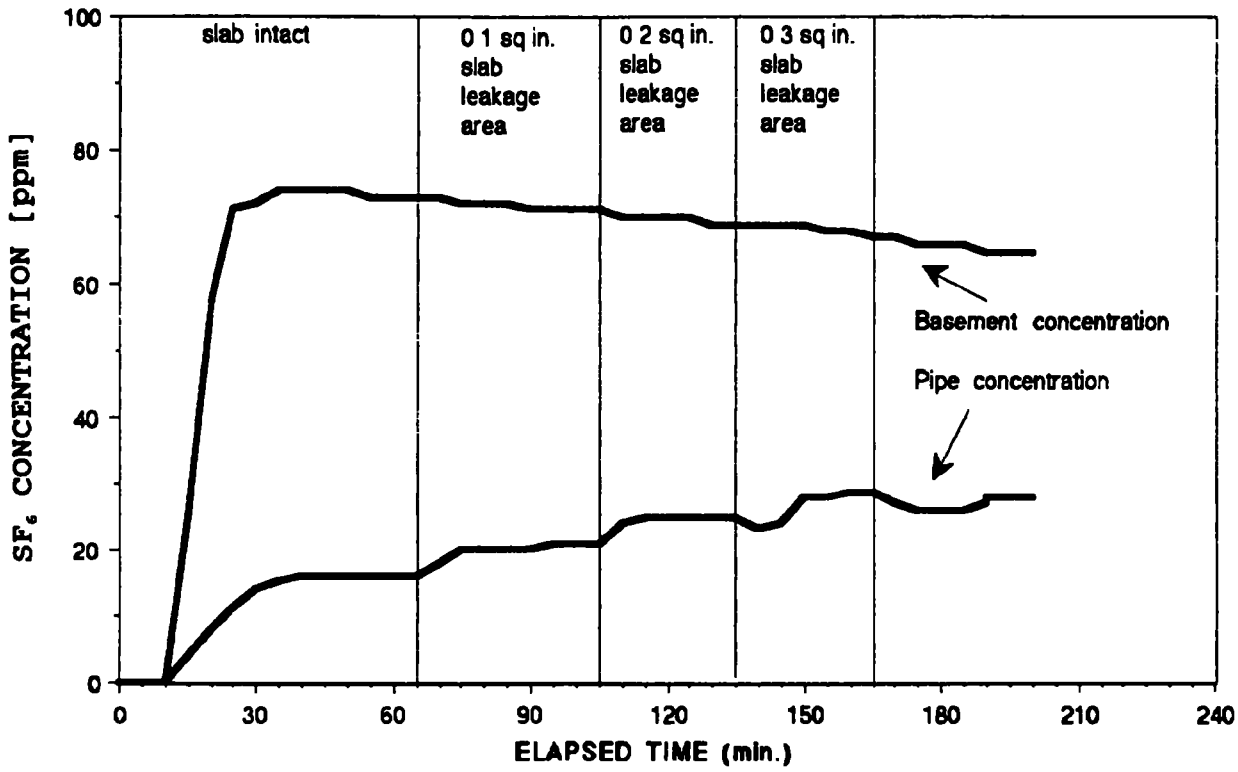


Figure 4. Tracer gas tests performed in House PA1 to determine the effect slab penetrations have on the performance of a sub-slab depressurization system.

RESULTS

The results of the tests for the energy losses performed in the three houses are presented in Table 1. The estimated energy costs were determined by using the degree day method. A furnace efficiency of 90% was used for Houses VA1 and VA2 and 75% for House PA1.

TABLE 1. APPROXIMATE ADDITIONAL ENERGY COSTS DUE TO LOSS OF CONDITIONED AIR THROUGH THE USE OF A SUB-SLAB DEPRESSURIZATION SYSTEM

HOUSE NO.	% CONDITIONED AIR BEING EXHAUSTED BY SYSTEM	AIR VOLUME LOSS (cfm)	HEATING DEGREE DAYS	EST.ADDITIONAL ENERGY USAGE (10^6 Btu)
VA1	43	34	5010	4.9
VA2	47	11	5010	1.6
PA1	21	3	5827	0.6

The results of the tests performed to determine the effect barrier penetrations have on the performance of the sub-slab system in House VA2 are presented in Table 2.

TABLE 2. SYSTEM PERFORMANCE AS EFFECTED BY FLOOR PENETRATIONS IN HOUSE VA2.

LEAKAGE AREA (sq in.)	AIR VOLUME AT EXHAUST (cfm)	PRESSURE DIFFERENTIAL PIPE TO BASEMENT (in. H_2O)
SLAB INTACT	24	0.212 ± 0.005
0.8	25	0.194 ± 0.004
1.6	27	0.180 ± 0.005
2.6	30	0.115 ± 0.004
4.7	30	0.071 ± 0.005

Equation 1 is used to determine the fraction of basement air being exhausted by the sub-slab depressurization system:

$$Cs = \frac{(Cb \times Qbs) + (Ca \times Qas)}{Qt} \qquad (1)$$

where:

- Cs = SF_6 concentration in the exhaust pipe stack
- Cb = SF_6 concentration in the basement
- Qbs = Volume of air flowing from the basement to the stack
- Ca = SF_6 concentration in the outdoor air getting back inside the stack
- Qas = Volume of outdoor air getting back inside the stack
- Qt = Total volume of air being exhausted by the system

Factoring this equation results in Equation 2 where:

$$\frac{Qt \times Cs}{Cb} = \frac{(Cb \times Qbs) + (Ca \times Qas)}{Cb} \qquad (2)$$

Assuming that Ca is zero, which is not quite true but close enough considering the miniscule amount of SF_6 being exhausted compared to the volume of outdoor air, and factoring again results in Equation 3:

$$\frac{Cs}{Cb} = \frac{Qbs}{Qt} \qquad (3)$$

Equation 3 translates to: the ratio of the SF_6 concentration in the stack to the concentration in the basement equals the ratio of the volume of air flowing from the basement into the stack to the total airflow out of the stack. Therefore, if the SF_6 concentration in the stack is 31 ppm and the SF_6 concentration in the basement is 72 ppm, applying Equation 3 results in a value of 0.43 or 43% of the air being exhausted by the sub-slab depressurization system is coming from the basement.

Equation 4, used for determining the additional cost of energy associated with the use of the sub-slab depressurization system,

is known as the degree day method where:

$$H_L = V \times 60 \times 24 \times 0.018 \times HDD \times Eff \qquad (4)$$

where:

H_L =	Heat loss due to exfiltration of air by sub-slab system for the heating season
V =	Volume of air being exhausted by system in cubic feet per minute
60 =	Number of minutes in an hour
24 =	Number of hours in a day
0.018 =	Heat capacity of air in British thermal units per cubic foot per degree fahrenheit. This means the number of British thermal units required to heat each 1 cu ft of air 1°F.
HDD =	Heating degree days. This is the average daily outdoor temperature in degrees fahrenheit, subtracted from the indoor temperature setpoint of 65 °F. This daily temperature difference is totalled for the entire heating season. HDDs should be thought of as the number of degrees fahrenheit for the heating season that outdoor air entering the house must be raised to reach the indoor temperature of 65 °F.
Eff =	Furnace efficiency. In this case 90%

Therefore, if the sub-slab depressurization system is exhausting basement air at a volume of 34 cu ft/min., as in House VA1, the volume of air being exhausted each day is 48,960 cu ft. To find the number of British thermal units required to heat the exhausted air 1°F, multiply the volume of air by the heat capacity of 1 cu ft of air. This results in a heat capacity of 881.3 Btu for each 1°F that the air must be heated. Finally, by multiplying the heat capacity of the exhausted air by the number of HDDs per heating season at the location of the house (for this house, 5010 HDD) and considering the efficiency of the furnace, the added amount of energy required to heat the air being exhausted by the sub-slab depressurization system is 4.9 million Btu.

Table 3 presents the amount of energy lost in House VA2 with the various size holes in the floor slab. Again, a heating degree day value of 5010 HDD and a furnace efficiency of 90% are used.

TABLE 3. APPROXIMATE ADDITIONAL ENERGY COSTS DUE TO LOSS OF CONDITIONED AIR IN HOUSE VA2 WITH VARIOUS SIZE FLOOR SLAB PENETRATIONS.

LEAKAGE AREA (sq in.)	% CONDITIONED AIR BEING EXHAUSTED BY SYSTEM	AIR VOLUME LOSS (cfm)	EST.ADDITIONAL ENERGY USAGE (10^6 Btu)
SLAB INTACT	47	11	1.6
0.8	52	13	1.9
1.6	57	15	2.1
2.6	75	23	3.3
4.7	77	23	3.3

The results of the tests performed to determine the effect barrier penetrations have on the performance of the sub-slab system in House PA1 are presented in Table 4.

TABLE 4. SUB-SLAB DEPRESSURIZATION SYSTEM PERFORMANCE AS AFFECTED BY FLOOR PENETRATIONS IN HOUSE PA1

LEAKAGE AREA (sq in.)	AIR VOLUME AT EXHAUST (cfm)	PRESSURE DIFFERENTIAL PIPE TO BASEMENT (in. H_2O)
SLAB INTACT	15	0.80 ± 0.01
0.4	16	0.81 ± 0.01
0.8	19	0.78 ± 0.02
1.2	20	0.77 ± 0.01

Table 5 presents the amount of energy lost in House PA1 with the various size holes in the floor slab. Again, a heating degree day value of 5827 HDD and a furnace efficiency of 75% are used

TABLE 5. APPROXIMATE ADDITIONAL ENERGY COSTS DUE TO LOSS OF CONDITIONED AIR IN HOUSE PA1 WITH VARIOUS SIZE FLOOR SLAB PENETRATIONS

LEAKAGE AREA (sq in.)	% CONDITIONED AIR BEING EXHAUSTED BY SYSTEM	AIR VOLUME LOSS (cfm)	EST.ADDITIONAL ENERGY USAGE (10^6 Btu)
SLAB INTACT	21	3	0.6
0.4	29	5	0.9
0.8	36	7	1.3
1.2	41	8	1.5

CONCLUSIONS

Although a large percentage of the air being exhausted by the sub-slab depressurization system can come from inside the building and not from beneath the slab, the amount of air that this percentage constitutes is relatively small. The estimated annual additional costs associated with the use of the sub-slab depressurization system for the three houses tested (not including electrical costs to run the fan) are illustrated in Figure 5. For the dollar costs, a value of $0.65 per therm ($10^5$ Btu) of gas is used.

The effect on the performance of the sub-slab system of even such small holes in the floor slab that were tested here seems to be a greater concern than the additional costs of energy. For example, at House VA2, a leakage area of 4.7 sq in. resulted in a drop in the negative pressure at the exhaust pipe of 67%. A loss of this much pressure could have serious effects on a marginally operating system.

METRIC CONVERSION FACTORS

Readers more familiar with metric units may use the following to convert to that system:

Nonmetric	Multiply by	Yields Metric
Btu	1.055	kJ
°F	5/9 (°F-32)	°C
ft^3	28.3	L
in.	2.54	cm
in. H_2O	6.45	cm^2
in. H_2O	2.5	Pa
therm	105,506	kJ

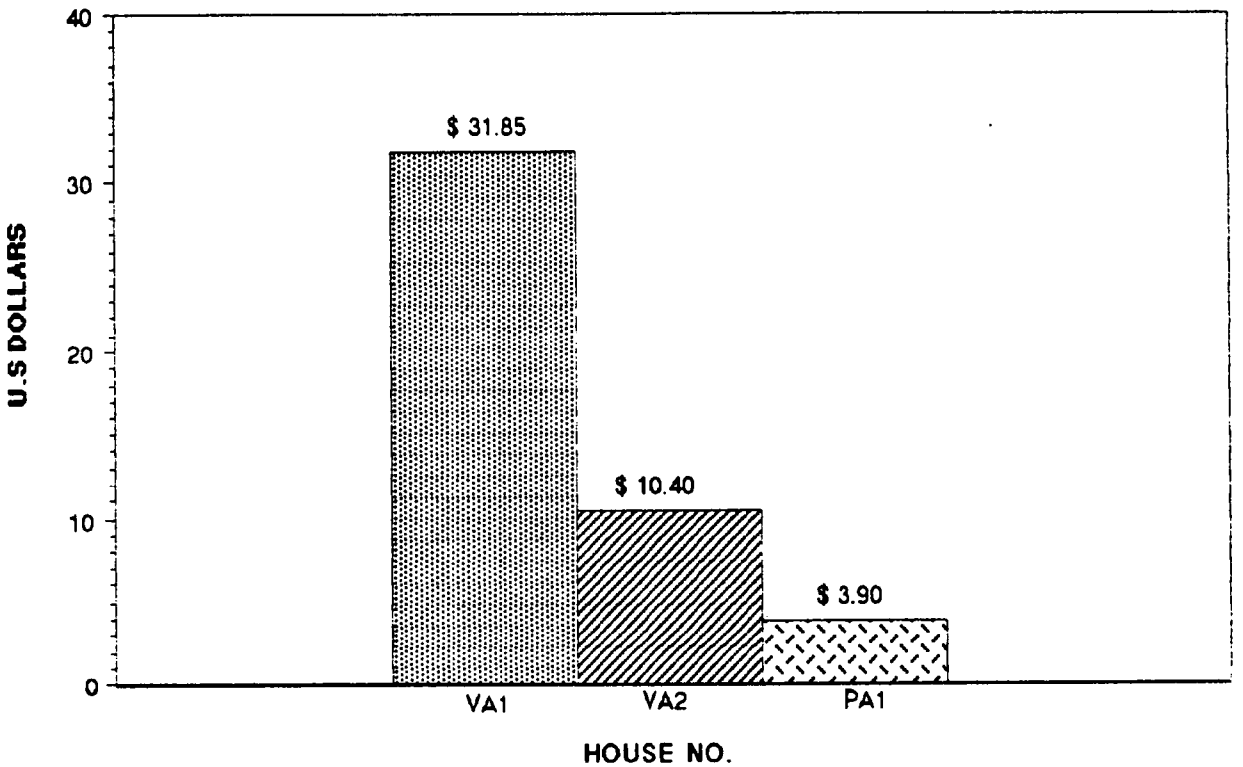


Figure 5. Estimated additional annual energy costs associated with the use of a sub-slab depressurization system. Electrical consumption of the fan in each system is not included.

EXHAUST OF CONDITIONED AIR BY RADON MITIGATION SYSTEMS IN HOMES

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LONG TERM DURABILITY AND PERFORMANCE OF RADON MITIGATION SUBSLAB DEPRESSURIZATION SYSTEMS

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ABSTRACT

Subslab depressurization (SSD) systems have become the most popular radon mitigation technique used by professional mitigators. Readily available supplies and equipment from other trades are commonly utilized in the installation of these systems. What is not currently known is the long-term performance of some of the caulks or sealants and the mechanical devices such as fans or controls. The operating environment for the fans is often different from that for which they were designed. Specifically, this involves studying whether the fans are still operating as installed, whether there has been an increase or decrease in the radon levels after several years of operation, and whether the house occupants are operating the systems the way the systems were originally designed.

To answer these questions, we have tested eight of the Piedmont Study houses as well as houses in which post-mitigation measurements by the New Jersey Department of Environmental Protection (NJDEP) have shown readings that were above the U.S. EPA guideline of 4 pCi/L. Quarterly visits to each house involved measurement of flows and pressures in the mitigation system, taking radon grab samples in the basement and of the mitigation system exhaust, interviews with the occupants, retrieving and installing track-etch detectors, and a visual inspection of the mitigation system and house substructure. This paper presents the findings of this research and discusses some of the durability aspects of SSD systems and their interaction with the house substructure.

This paper has been reviewed in accordance with the U.S. EPA peer and administrative review policies and approved for presentation and publication. Mention of trade names does not constitute endorsement by the Agency.

INTRODUCTION AND BACKGROUND

There is increasing evidence that the health risks in those houses with significant levels of radon gas (above the EPA guideline of 4 pCi/L) may constitute the most serious indoor air quality problem in the United States. Radon gas intrusion is often pictured as a seasonal phenomenon, with stack effect and other pressure-driven factors influencing soil gas entry to building substructures. A number of solutions have been proposed. These approaches involve energy use as well as indoor air quality concerns. The proposed solutions must be tailored for the specific nature of the radon source. If the radon enters the house via well water, one approach is necessary; radon in building materials may suggest other strategies. In this report our attention will be focused on radon entry with soil gas through the building substructure, and what that mechanism implies for radon mitigation.

Even limiting our scope to soil gas entry, many solutions exist to reducing radon gas concentrations in the house. Radon removal is one method and is often the preferred approach. Local exhaust, after radon entry into the living space, is another strategy. Ventilation used to dilute the radon gas concentrations is still another option. Each approach must be matched to a given radon condition in the individual building. This report will consider only the method of radon removal from under the slab in basements or crawl spaces. Known as subslab depressurization, SSD, this mitigation approach has been proven to be very effective, often removing enough soil gas containing radon so that substructure measurements of radon concentrations drop by 90% or more following mitigation.

1. Theory of Operation of SSD Systems for Radon Mitigation

The theory of operation for the SSD system is that, by penetrating the concrete floor slab with an exhaust pipe, one gains access to the area beneath the slab. The area, often a gravel bed, serves as a collection site for the soil gas containing radon. The negative pressure provided by the exhaust pipe causes the soil gas to be removed from the gravel bed and, if communication exists between the subslab volume and the walls of the building, soil gas will simultaneously be exhausted from the walls. The exhaust mechanism can be passive which implies that suction pressures beneath the slab will vary on a seasonal basis, with the greatest suction occurring during the coldest weather due to increased buoyancy of the air in the vertical exhaust stack. In the systems tested in this research, exhaust fans were used. These "active systems" were shown to maintain near constant suction pressures under the slabs all year long.

The key point to remember in the merits of year round radon removal is that there is no guarantee that radon problems will not be present even in the summer months. The radon levels found in individual houses are a complex result of radon source strength, soil transport, weather, and the way the house is operated. To be certain of maintaining low radon levels in the house normally requires that a SSD mitigation system work properly 24 hours per day, 365 days per year. It is for this reason that durability and system performance are such important considerations. Performance level goals are for 100% on-time operation for the life of the building. Thus we require excellent durability of system components and a reliable means for

determining whether the system is fully operational at all times.

The lack of long-term data on SSD systems is a major stumbling block in determining whether or not the SSD systems perform adequately. This project has been directed toward gathering such data from eight research houses that were part of the Piedmont Study(1), as well as houses tested by the NJDEP as a follow-up to mitigation activities.

2. Operational Environment

The question of durability of the mitigation system arises not only from the need for a lifetime operation in the house, but concerns about the environment to which the SSD system is subjected(2). Soil gas is often very moist, causing condensation problems in the piping and at the fan of the mitigation system. Also, particles can be drawn from the gravel bed; they in turn may line the pipes and deposit on the fan or possibly interfere with the fan bearings.

The moisture removed from the subslab can be very substantial, and could amount to many gallons of water per day(2). Unless the piping design allows for that water to drain back into the soil, the water could clog the piping or interfere with the fan operation. Evidence of the moisture and other debris has also been found in the staining of roofs near the exhaust pipes of the SSD systems. Drying soil could result in slab cracking.

The amount of sand and other particles sucked from the soil must be viewed as a possible cause of bearing failure or of the generation of bearing noise (such effects can also be caused by the moisture). Noise can directly influence the occupant to shut down the SSD system.

Another environmental effect that should not be overlooked is the amount of airflow through the fan. To remain at an appropriate operating temperature requires sufficient air to remove fan motor heat. Operating the fan in a way that the blades are stalled can result in high bearing loads and invites early fan failure.

OBJECTIVES

The following are our objectives for this research:

1. Our first objective has been to document the ability of the SSD radon mitigation system to maintain houses at radon concentration levels below the EPA guideline of 4 pCi/L. In these measurements we hoped to observe the influence of such parameters as seasonal factors. Local weather effects (e.g., rain storms) are covered in more detailed radon monitoring(2).

2. A second objective was to observe the long-term characteristics of radon levels in the SSD system exhaust. Source strength and transport properties of the soil may be determined from these measurements.

3. A third objective was to evaluate the long-term influences of the SSD system operation on the house substructure. Since our objective is long-term operation, we need to know of any associated consequences.

4. A fourth objective of the study is to determine critical parameters that can degrade SSD performance and recommend ways to minimize such degradation.

THE TWO-PRONGED APPROACH FOR DURABILITY TESTING

Our approach to evaluation of durability is based upon our own experience as to what might happen over time as well as on the experiences of others; e.g., New York State Energy Research and Development Authority's efforts to quantify durability(3), Lawrence Berkeley Laboratory research(4), and Swedish studies which were able to look at houses after 5 years of operation(5). Three short data sheets have been developed. One emphasizes the house and mitigation system as observed by the house occupants; the other data sheets involve a series of diagnostic tests to determine if the mitigation system is achieving the necessary radon mitigation goals.

1. The house occupant questionnaire

Reviewing the data sheet, Radon Durability Diagnostics - I, the emphasis is initially placed on whether the system has been running steadily. Swedish studies have pointed to this problem as an explanation of increasing radon concentrations(5). Our own experience is that occupants hate to admit shutting off the system although system noise, radio interference, and conserving electricity during the summer have been offered as reasons to turn off the fan.

The second question concerns noise perceived by the house occupant. If the system is becoming noisy, the occupant fears that the fan may be "on its last leg," or that any noise may prompt an occupant to shut down the system.

The third question involves moisture. We are seeking to gain insight into condensation, collection of water in the mitigation piping, or moisture related events taking place at the roof exhaust. Water in the piping can directly influence the amount of exhaust airflow possible. Condensation can be another cause for occupants to turn off the mitigation system.

The fourth question is aimed at finding out about possible power outages, construction in the house, or other events that could account for higher than expected radon levels.

Question five involves the house occupants' perception of the system and whether or not they have any questions about the way it functions.

2. Diagnostics and measurements

The second data sheet, Radon Durability Diagnostics - II, emphasizes diagnostic procedures employed by the visiting inspection team. The observations are initially visual: the house type, special features, location of the SSD system, etc. On subsequent visits the visual observations concentrate on location of cracks, sealed areas, etc. For example, are there new cracks or places through which radon might enter the house substructure? The inspection also concentrates on what sealing was done previously and how well it has held up.

The second item involves noise generation. A stethoscope is used in

order to better detect early signs of bearing squeal which is an indication that fan lifetime may be short.

Item three is a diagnostic check of the airflow in the mitigation system piping. A heated-wire anemometer inserted through an inspection hole to the center of the plastic pipe is used to measure the velocity. (In houses where durability tests are in progress, openings in the piping are sealed with duct tape to provide easy access during the study.) Care must be taken that the airflow probe is sealed where it enters the pipe in order to prevent erroneous airflow readings.

Item four makes use of those same openings in the piping to evaluate pressure differentials. In this case, a digital readout micromanometer is used. For this instrument, using the scale "inches of water," the readout is the most sensitive (0.004 in. of water = 1 Pa).

Item five deals with measurement of radon levels in the exhaust of the mitigation system. Over the long term, questions arise as to whether the radon is being depleted or whether the soil is drying out; the latter could lead to the system exhausting more distant radon gas. The radon levels in the system exhaust would be an indication of such changes. Both pumped grab samples and evacuated grab samples with Lucas cells are used in this testing.

The final item is general observations. This is an opportunity to note what a general inspection has revealed, and what may have influenced or interfered with the radon mitigation process.

We also use the data sheet, Radon Durability Diagnostics - III. We have been noting on this data sheet the serial numbers of alpha track detectors that were in place as well as the replacement detectors. Normally detectors have been placed in the basement/crawl space areas as well as on the first floor.

RESULTS FROM THE NEW JERSEY PIEDMONT HOUSES

As previously discussed, there are four objectives of the study on which we must focus attention. Perhaps the easiest way to review the results is to plot the radon levels measured over time for each of the Piedmont houses. Typical plots are shown in Figures 1-2 and summarized in Table 1.

1. Occupant Effects

Immediately evident (in looking at Table 1) is that, while the majority of the houses show more-or-less constant radon levels over time, two houses (Houses 3 and 5 in Figure 1) show major variations in radon levels. These variations include radon concentrations above the EPA guidelines as well as House 3's return to premitigation levels.

On checking the occupant questionnaire it was noted that the occupant of House 5 had turned off the SSD system because of radio interference and because the occupant felt that, under summer conditions with open basement windows, it was wasteful in terms of energy to operate the SSD system(6).

The occupant of House 3 gave no hint on the questionnaire that the SSD system wasn't working 100% of the time. Only when we informed the occupant of the return to pre-mitigation radon values did the occupant remember that the system had been turned off during a dinner party (room adjacent to the fan) when mitigation fan noise was annoying and they had forgotten to turn it back on for an extended period. We pursued this point further and found that the noise was the result of vibration between the SSD fan motor and the wood-framing in the attic above the garage. A small modification in the mounting eliminated the problem. Similar vibrational problems have also been experienced in one of our current research houses. The annoyance of the vibration had resulted in the system being turned off. The importance of avoiding such problems should be emphasized with the mitigator.

One point was very clear from even this very limited number of test houses. The SSD system should not be turned off even for short periods of time without immediately impacting the radon level. One occupant explained that the system was only turned off for radio weather broadcasts to avoid the static. The lesson is that the static should not be present through the use of a higher quality speed controller, and careful checking of the wiring arrangement would avoid interaction with sensitive electrical equipment.

2. Seasonal Variability

In order to look for such effects as seasonal variability, we must focus our attention on houses where the occupants have allowed the SSD systems to operate 100% of the time. Figure 2 (also see Table 1) indicates this type of operation. A very simple evaluation of events over the measurement period using Table 1 data (the basis for the figures) will demonstrate the stability of radon concentrations over time. In this exercise we have averaged readings for the first two periods and compared them to the last two measurement periods. Altogether 10 measurements can be compared if all basement and crawl space values are averaged equally. Thus comparing October 1987 through May 1988 to November 1988 through June 1989 (a similar weather period) we find that in 7 out of 10 measurements radon levels have dropped an average of 0.6 pCi/L. In 2 out of 10 houses, radon levels have increased by an average of 0.1 pCi/L while one value has stayed the same. Since the alpha track method of measuring radon levels has an error band that would include these variations, our conclusion would be that there is no significant change over the year.

Because of these same arguments of measurement error it is even more difficult to look for seasonal effects. However, any significant seasonal influences should be evident in these data. House 2, for example, indicates that winter readings are slightly higher than summer readings. But again using October-February and November-March basement values we find a 1.6 pCi/L average versus 1.2 pCi/L for May-November combined with March-June. This 0.4 pCi/L difference is well within the error band.

House 4 shows a general decline in radon concentrations with time and no sign of seasonal fluctuations.

House 6 shows only a slight increase in the November-June reading and a noticeable drop in radon level after the first October-February period.

House 7 also shows a very small increase in the November-June period in basement and crawl space radon concentrations. First floor concentrations are basically background levels. Note that the substructure concentration change is from approximately 0.5 to 1.0 pCi/L, again well within the error band of the alpha track radon sensors.

Only in Houses 8 and 10 (Figure 2) do we see variations in the November-March period that could be viewed as seasonal influences. In the case of House 8 similar increased concentrations were measured during the October-February period, the year prior. Averaging basement and first floor values for House 8 (from Table 1) for the "winter periods," we obtain an average value of 4.3 pCi/L, a value in excess of the EPA guideline. If we average "summer periods" the value is only 1.8 pCi/L. This house illustrates how seasonal influences can clearly affect SSD performance.

House 10 indicates only a slight increase in radon concentration in the October-February period; i.e., 2.2 pCi/L average versus 1.5 pCi/L for the "summer periods." However, the increase is more substantial in the November-March period where values of 2.7 pCi/L are observed. This house would also appear to exhibit seasonal effects that increase radon concentrations by approximately 1 pCi/L.

3. Radon Levels in the Mitigation Exhaust System

One measurement of durability testing that is of interest is the concentration of radon in the exhaust pipe from the subslab mitigation system. When this information is combined with the velocity (or flow measurement) at the same pipe location, we are in a position to calculate the total flow of radon gas from the mitigation system(7).

One question to be resolved is: Can we compare the amount of radon exhausted from any given house and understand fully the role played by the mitigation system? One such comparison involves the natural flow of radon through the same house. The physical meaning would be a radon flow rate equal to the quantity of radon exhausting through a "perfect mitigation pipe" through which the airflow rate is equal to air infiltration rate of the house. To make the calculation of the natural flow requires a knowledge of the average air infiltration rate for the house, the radon concentrations upstairs and in the basement/crawl space, and the volumes of those zones. The calculation is:

$$R = AI \times 10^3 \times \frac{(C_u \times V_u) + (C_{b/c} \times V_{b/c})}{V_u + V_{b/c}}$$

where R = radon flow, pCi/h
AI = air infiltration, m^3/h
C = radon concentration, pCi/L
V = volume, m^3
u = upstairs
b/c = basement/crawl space

Comparative results for five Piedmont houses are shown in Table 2. The ratio of the radon gas exhausted from each house via the mitigation system is compared to the radon natural flow value through the house. Ratios vary

from 1 to 9. The question that comes to mind is: "What is special about House 4 which has the same flow of radon gas both through the mitigation system or by natural means?" One answer could be, it is the house with the least porous soil -- basically pure wet clay. It is a house where high ventilation rates (such as using a blower door) depress the radon levels, and then it takes many hours for the house to return to the previous elevated levels. Such behavior has been interpreted as evidence of a limited radon entry rate. However, just comparing the natural radon entry rate with those of the other houses would not single out this house. In fact, looking at natural radon entry rates, it is only House 3 that stands out with a rate far above the others; i.e., 35×10^6 pCi/h versus $7.5 \pm 3 \times 10^6$ pCi/h for all the rest. House 3 has a soil condition of high porosity, (i.e., stone flour roughly 1/8-in. (0.3 cm) diameter and a good gravel bed), just the opposite conditions of House 4.

The total amount of radon gas mechanically exhausted from the soil varies by a factor of 7 in these houses. The lowest value is for House 4 with clay soil. The highest value of radon is for House 3 with very porous soil. The two highest houses (Houses 3 and 5) were those with recurring periods of above-guideline levels of radon. However, House 7 has clay soil mixed with shale and ranks third.

The method used to analyze the radon concentrations from the mitigation system exhaust involves Lucas cells. Analysis of the Lucas cells takes into account the time elapsed from the time the sample was taken to the time it was analyzed, the background level of the cell, and the efficiency of the measurement equipment. The relationship used is:

$$C_{actual} = \frac{(CPM_{read} - CPM_{bgd}) \times e^{(0.00803 \times \Delta t)}}{\epsilon_{eqpt}}$$

where C is the concentration, CPM is the counts per minute, Δt is the time in hours between when the reading was taken and when the Lucas cell was read, ϵ_{eqpt} is the efficiency of the measurement equipment (in our tests this value was 0.64), and subscripts are: <u>actual</u> level of radon; <u>read</u>, actual reading; and <u>bgd</u>, background of cell.

Several other points should be noted. Taking a 2-minute count, about 15 minutes after taking the sample which necessitates bringing the Pylon instrumentation to the field, provides a direct count reading that is roughly equal to that of the final corrected reading (i.e., $\pm$ 25%). This is useful when checking radon levels. The grab or pumped samples require the use of filters to avoid ingesting progeny which will invalidate the reading.

Data collection on the radon exhaust concentrations from the Piedmont houses involved both pumped and grab samples. Typical data are plotted in Figure 3 for Houses 2 through 5. Data are listed in Table 3. During the first 4-month period, the majority of the measurements indicated that the exhaust radon concentrations were reduced. The exceptions are House 4 where the concentration value increased less than 25 pCi/L during this initial

period and House 3 in which real levels have increased because of airflow variation. This will be discussed later.

In the second and third testing periods, when we measured exhaust concentrations of radon (3/89 through 6/89, and 6/89 through 11/89), the concentrations vary with the individual houses. Houses 3 and 10 show a decreasing trend, while Houses 2, 4, 5, 7, and 8 indicate increasing levels. Some seasonal effects may be present in that the lowest readings for the majority of the houses were in months 15 and 18 which is the warmer time of the year [the plots start at month 11 (November 1988); therefore, 15 is March 1989 and 18 is June 1989]. Throughout these discussions, radon concentration has been used since, hopefully, it provides the more physical meaning, and because airflow rates (necessary to provide total radon flow as shown in Table 2) tend to be constant in the houses. One exception to constant flow is House 3 where, after the fan had been turned off by the occupant and after radon levels had increased in the living space, the fan speed was increased. Duct velocities changed from 2.65 m/s in November 1988 to 8.2 m/s in November 1989 (intermediate readings were 7.2 m/s). The trend of falling concentration levels over time for House 3 does apply for the last three periods, with a peak at month 15. Because of the lower fan airflow rates present during month 11, radon flow rates are less than half the month 15 peak. The profile of House 3 is opposite to the general trend experienced in the majority of the test houses.

4. Substructure Changes

Based upon diagnostic team observation, only House 3 showed evidence of physical changes. Two cracks appeared in the basement slab near the slab edge extending toward the center of the room. Length of the cracks was approximately 6-ft (1.8 m) and the width exceeded 1/16-in. (0.2 cm) at some locations.

A noteworthy observation of what was happening in the basements or beneath the slab was that conditions were noticeably drier. Several occupants have stated that the need for summer dehumidification was eliminated in their houses. Where observations were possible, water in gravel beds was no longer visible. No quantitative measurements of relative humidity have been made.

PRELIMINARY RESULTS FROM NJDEP HOUSES (MITIGATED BY PROFESSIONALS)

The concern for durability and performance of radon mitigation systems was pointed out by Depierro and Cahill of the NJDEP(8). Based upon their findings, 64% of the houses mitigated by occupants and professional mitigators were not achieving the 4 pCi/L guideline. Even when only professionally mitigated houses were assessed, the percentage of houses failing to meet guidelines still exceeded 50%.

With this information as background, we undertook a program of upgrading the radon information. Our test houses were taken from the larger list of NJDEP-tested houses. From that list our criteria of selection were houses less than half an hour's drive from Princeton, houses with predominantly SSD systems installed, and houses with the highest post-mitigation radon levels. Our approach was to question the occupant on the

radon history in the house, to briefly inspect the mitigation system installation, and to leave a charcoal canister in the house which after 3 days the occupant would mail in for analysis. Two examples are given.

Test house A. This house has a SSD system which uses three slab penetrations routed to a fan mounted on a cinder block wall. Noise from the fan caused the occupant to build an insulated box around the fan. The house in early 1987 had measured radon levels from 40 to 120 pCi/L in the basement and 13 to 15 pCi/L upstairs. The values disagree between the state and the private mitigator. Measurements 1 year later, after mitigation, indicated levels reduced to less than the EPA guideline value. Our measurements in October 1989 confirmed that the guideline was being met.

Test house G. The SSD system in this house has two floor penetrations as well as a penetration at the wall under the crawl space. Early readings in September 1987 were 143 pCi/L in the basement and 75 pCi/L in the living room. Levels dropped to only 6-7 pCi/L in the basement and living room until an improved fan, Kanalflakt K-6, replaced the original fan and dropped levels to the 0.8 pCi/L level. Our tests in August 1989 indicated minimum detectable concentrations of 0.54 pCi/L.

To briefly review these data, we found no cases where the substructure radon levels were above the 4 pCi/L guideline. This was true even though we chose the highest radon houses on the list supplied by NJDEP. One reason for this was that occupants continued to have their systems checked and improved with better fans and higher flow rates. Fan lifetime appears to be short in several of the fans used, while the Kanalflakt fans continued to perform satisfactorily. Similar to the Piedmont houses and our other test houses, noisy fans can be a result of fan mounting, necessitating good installation procedures if this critical problem is to be avoided.

CONCLUSIONS AND RECOMMENDATIONS

1. House occupant interaction significantly affected the operation of the mitigation systems, based upon our survey.

One point that is very evident from the durability diagnostics program is that increases in radon levels can often be traced back to occupant intervention with the SSD radon mitigation system. In the majority of cases, noise from the system caused annoyance and the system was shut off, often for prolonged periods. Another instance was an occupant seeking to limit operation of the system in the summer period when he erroneously thought that open basement windows would suffice, and therefore the electricity to operate the SSD system could be saved. Even in this instance, radio interference -- a different kind of noise -- instituted the habit of this occupant to shut off the fan.

2. Installation and Building Anomalies

Every house is different from a radon standpoint. Even in the same area, where the weather is the same, the soil porosity and radon content often varies noticeably across an individual basement floor, wall systems below grade are highly variable, equipment used to space condition the house

can drastically alter interior pressures and that condition can vary from room-to-room, the house design can have a major impact, etc. Given this list of variables it is no wonder that any mitigation system must take these factors into account. The installation must also consider moisture in the soil gas. One of the Piedmont houses experienced major problems with water in the mitigation piping. The problem was lack of attention to the slope of the piping, causing condensation water to collect and not drain to the gravel bed.

Anomalies often can be associated with the unknown conditions that prevail beneath the basement and crawl space slabs. The amount of gravel, hidden pipes, or partial concrete pours that separate the total floor area into several zones requires that more than one slab penetration must be used. We observed other houses with wall suction at the wall adjacent to slab-on-grade construction. Here extra radon entry was expected and basically taken care of by the wall penetration. In another house, very similar when viewed casually, the SSD system may perform beautifully with one penetration and remove radon from the walls at the same time.

Space conditioning cannot only circulate radon in the house but can also directly influence the amount present in the house. We were aware that inadequate returns in warm air systems resulted in under-pressurization of the basement and more soil gas being drawn into the house.

3. Recommendations

Our recommendations to the installer of mitigation systems is to use long-service-life components. The fan should be designed to operate for long periods; the fewer replacements and the more trouble free, the safer the occupants. Since wide variations in fan flow rates were found between different regions of the country, the choice of fan must take this into account to avoid fan overheating and/or bearing failure. The same criteria of quality apply to sealants. This is a long-term installation and not the place to use cheap caulk. Installations at the sump require careful design so that the water-removal function of the sump pump does not compromise the SSD system and vice versa. When done properly we observe little or no degradation over time of these installations.

A clear perception of the characteristic of soil gas requires that the mitigation system installer must properly slope all piping to drain any condensing moisture into the gravel bed.

Electrical hookup of the SSD system should not generate electrical noise in sensitive household equipment such as radios. The installer should check with the occupant at the time of installation of the system that such problems do not exist. Mechanical noise and vibration should also be eliminated to prevent annoyance to the occupant and make certain noise is not a cause for system shutdown. Several of the Piedmont and research house installations suffered from fan vibration interacting with nearby structures, or with mitigation piping. These were easily corrected. Checking for such noise problems at the time of installation is highly recommended.

The occupant not only is sensitive to SSD system noise but also is normally very interested in maintaining the lowest possible radon levels.

We recommend that the occupant regularly retest for radon. In the NJDEP houses, retesting led directly to system improvements and system operation better suited to the long-term (improved fans, sound suppression, etc.). These houses lowered radon levels to values below EPA guidelines. Installation of a pressure switch-activated indicator light to inform the occupant when the system is not operating properly is highly recommended.

ACKNOWLEDGEMENTS

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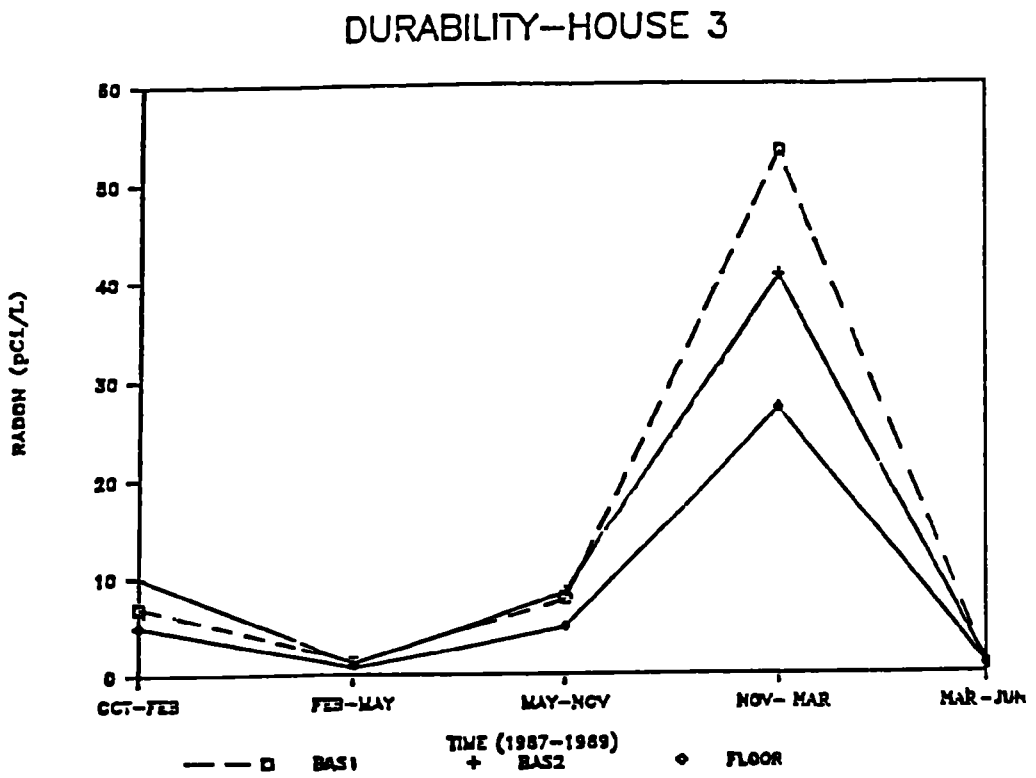


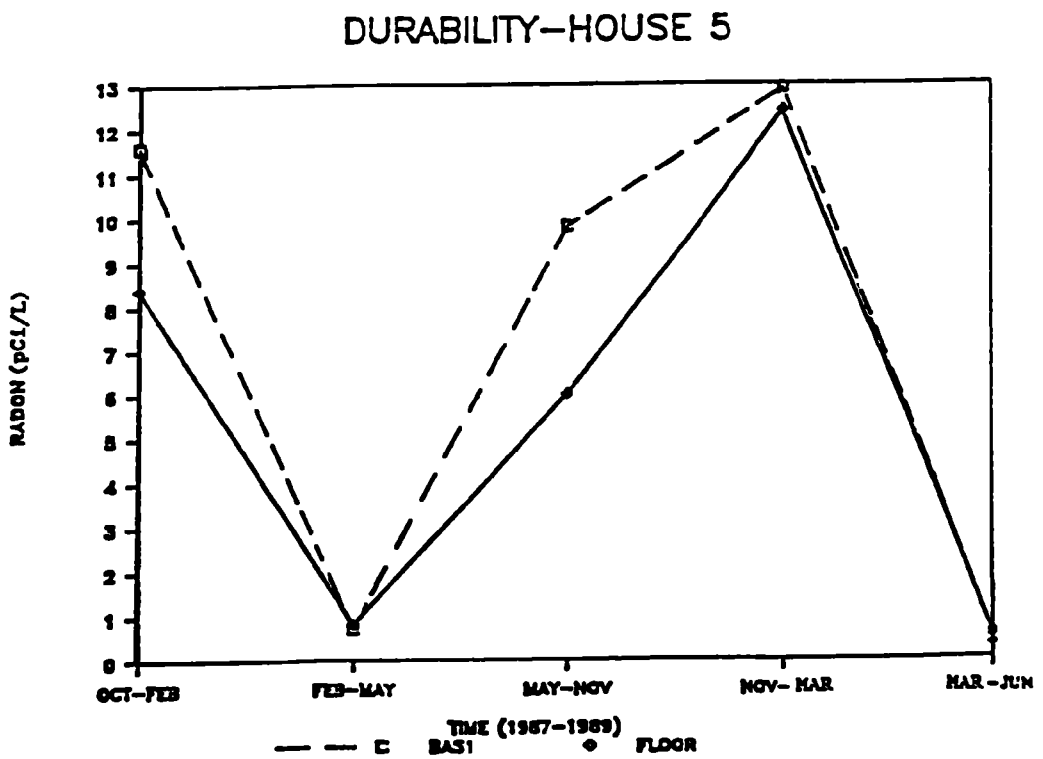
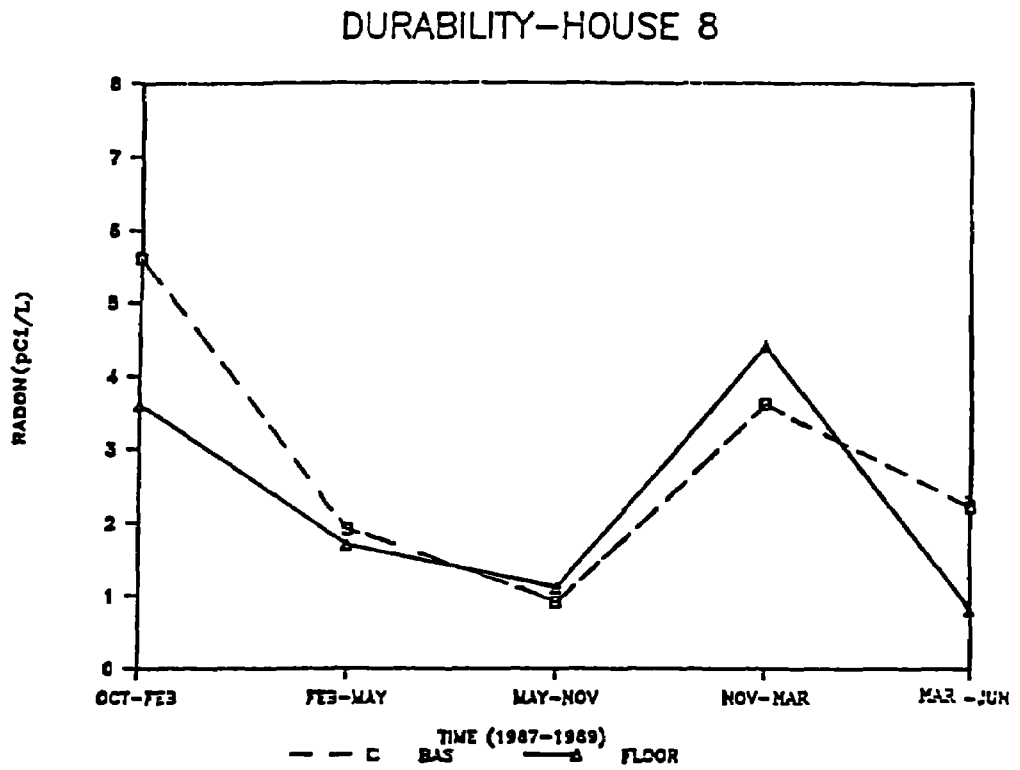


Figure 1 Radon levels in the interior space of Houses 3 and 5.



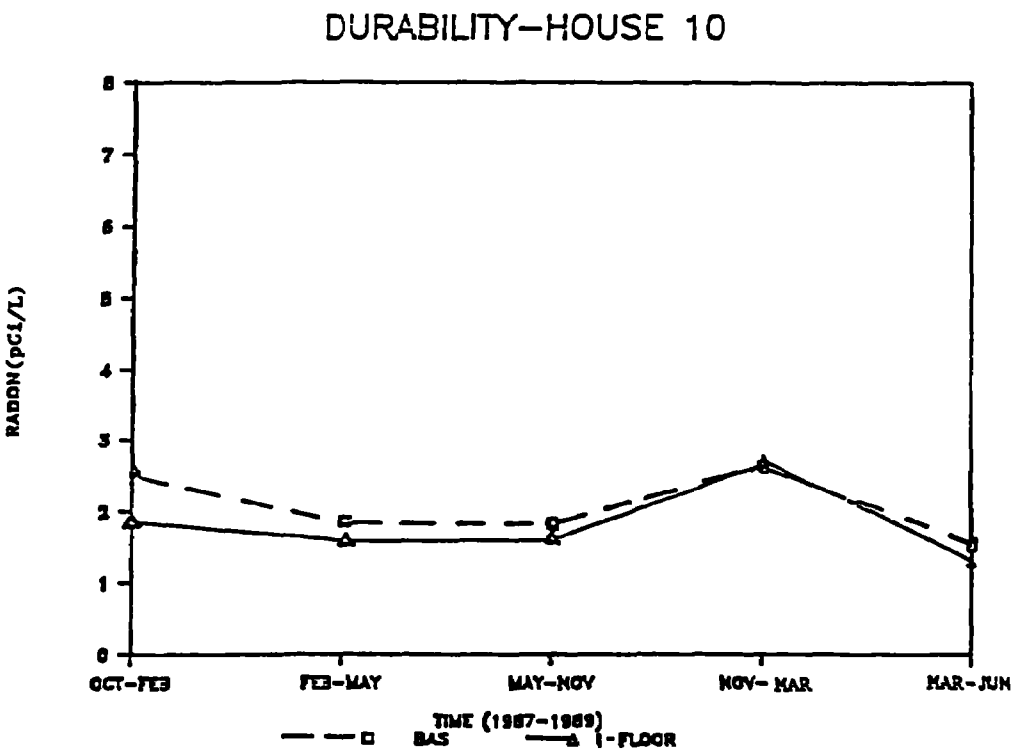


Figure 2 Radon levels in the interior spaces of Houses 8 and 10.

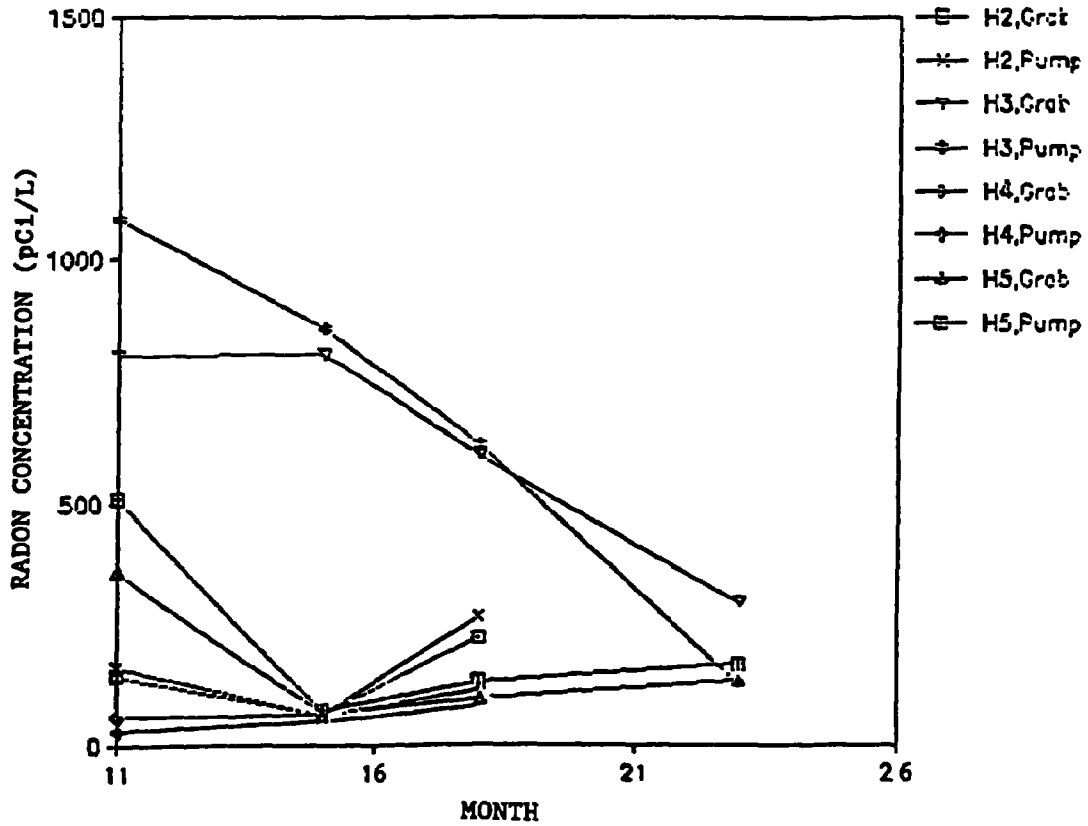


Figure 3 Radon levels in the SSD system exhausts of Houses 2 through 5.

TABLE 1

RADON CONCENTRATIONS IN EIGHT HOUSES

HOUSE	LOCATION	Oct '87 11 Feb '88	11 Feb '88 20 May '88	23 May '88 16 Nov '88	16 Nov '88 30 Mar '89	30 Mar '89 25 June '89
2	Basement	2.1	1.91	1.4	1.8	1.3
	Basement	2.4	1.3	1.0	2.0	1.1
	Dining Room			0.6	1.5	0.4
3	Basement	6.8	1.1	7.6	53.2	2.5
	Basement	9.9	1.2	8.4	40.6	3.6
	Living Room	4.8	0.6	4.7	27.0	0.8
4	Basement	3.1/3.0	2.3/2.6	2.8	2.6	-
	Living Room	2.8	3.1	2.7	1.8	1.0
	Breezeway	-	-	-	2.1	1.3
5	Basement	11.6	0.7	9.8	12.9	0.4
	Middle BR	8.4	0.8	6.0	12.4	0.6
	Crawl Space	6.8	2.8	2.2	-	-
6	Basement	4.8	1.9	1.7	2.7	3.1
	Basement	5.1	2.5	2.3	2.2	2.4
	Living Room	2.6	1.6	1.3	1.8	1.3
7	Basement	1.0	0.3	0.5	1.2	0.5
	Crawl Space	0.8/0.6	0.6/0.3	0.2/0.4	1.1/0.8	0.3
	Living Room	0.6	0.3	0.3	0.3	0.3
8	Basement	5.6	1.9	0.9	3.6	2.2
	Living Room	3.6	1.7	1.3	4.4	0.9
10	Basement	2.4	2.2	1.8	2.6	1.5
	Living Room	1.9	1.9	1.7	2.7	1.3

TABLE 2

COMPARISONS OF RADON QUANTITIES EXHAUSTED BY MITIGATION SYSTEMS AND BY NATURAL MEANS BASED ON FIVE HOUSES

House No.	Rn Level (pCi/L)		House Volume (m^3)		AI_{ave} (m³/h)	Rn Level Exhaust (pCi/L)	Exhaust Vel (m/s)	Rn Quantity (pCi/h)		Ratio: Mitigation/Natural
	Basement	Upstairs	Basement	Upstairs				Exhaust	Natural	
2	22	15	219	296	398	154	3.50	15,731,000	6,974,000	2.26
3	170	70	224	469	338	946	2.65	73,167,000	34,585,000	2.16
4	29	56	211	499	283	44	8.49	10,902,000	10,478,000	1.04
5	60	35	371	398	135	435	4.55	57,767,000	6,353,000	9.09
7	33	18	199	392	203	584	2.61	38,687,000	4,680,000	8.20

TABLE 3

DURABILITY RADON SAMPLES

House	Date	Month	Grab	Pump	
2	11/88	11	146	163	H2,Grab
	3/89	15	65	65	H2,Pump
	6/89	18	224	268	
3	11/88	11	808	1086	H3,Grab
	3/89	15	810	864	H3,Pump
	6/89	18	601	621	
	11/89	23	299	133	
4	11/88	11	28	60	H4,Grap
	3/89	15	50	61	H4,Pump
	6/89	18	84	119	
5	11/88	11	360	510	H5,Grab
	3/89	15	70	75	H5,Pump
	6/89	18	99	134	
	11/89	23	136	170	
6	11/88	11	N/A	N/A	
	3/89	15	N/A	N/A	
	6/89	18	458	300	H6,Grab
7	11/88	11	382	625	H7,Grab
	3/89	15	116	166	H7,Pump
	6/89	18	179	244	
	11/89	23	342	384	
8	11/88	11	N/A	N/A	
	3/89	15	N/A	N/A	
	6/89	18	485	566	H8,Grab
	11/89	23	978	1050	H8,Pump
10	11/88	11	N/A	N/A	
	3/89	15	542	614	H10,Grab
	6/89	18	305	360	H10,Pump

RADON ABATEMENT SYSTEM ANCILLARY ITEM

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ABSTRACT

The task of the radon researcher was to develop approaches to reduce indoor radon concentrations. As techniques were developed and tested, the mitigation industry developed around these approaches. In most cases, the research techniques were applied directly to the private sector. As the number of installations grew and the technology was understood, the focus changed from installation methods to ancillary items. These ancillary items pertain to system installation techniques as they pertain to standing building and fire codes. This paper deals with maintaining fire protection in a soil depressurization system.

RADON ABATEMENT SYSTEM ANCILLARY ITEM

The primary task of the early radon professional was to identify methods to reduce the indoor radon concentrations. In some cases, he was not sure that reductions could be made to the accepted 4 pCi/l level. The task at hand was to develop mitigation strategies that would control indoor radon concentrations. Through research programs and field installations a variety of techniques became known and generally accepted by an emerging mitigation industry. Soil pressure manipulation soon became the work horse of the industry. In particular, soil depressurization became the system of choice. As more was learned about soil depressurization, installation techniques and material system choices were modified in order to align with the level of effort required. The intent of this alignment was to make system installation less labor intense while still controlling indoor radon.

Mitigation system installation standards have eluded the industry as a whole. One of the contributing factors allowing this to take place is that the industry has sprinted ahead with little regard for standardized installation practices, unaware of possible unintended consequences. Typically the mitigation installation focuses on a high profit/low cost installation. Standards also are difficult to initiate and maintain possibly because of the installers limited capabilities based on background, knowledge and skills. EPA's recommendation for above eave exhaust location is a basic practice accepted in hazardous material discharge, yet today, some installers still do not follow this guideline.

Within the frame work of the mitigation system evolution, little attention has been placed on the appropriateness of the system with respect to the applicable building codes. This paper is written to address the code issue and in particular the fire barrier penetrations in both residential and commercial structures with respect to radon soil pressure manipulation systems. Emerging EPA guidelines recommend the installation of soil depressurization systems utilizing above eave exhaust locations. To accomplish this, pipe systems typically penetrate in place fire barriers within the structure both floor to floor in commercial construction and garage to occupied space in residential construction. When this takes place, the occupied quarters are placed at risk. The potential for loss of life because of an installed abatement system and less important, the liability issue, directed RFSimon Co., Inc., to identify installation techniques and practices that would eliminate this risk. In 1988, 4,955 lives were lost due to residential fires.

The BOCA (Building Officials and Code Administrators) for commercial and the CABO (Council of American Building Officials) for residential construction addressed this issue with the following quote from the BOCA National Fire Prevention Code: "The BOCA National Building Code was initially prepared and has been maintained on the premise that all matters pertaining to the construction of the building and built into it, either in its initial construction or through subsequent alterations, repair or extension, should be covered by the building code. This includes fire protection of the building elements as well as fire separation walls or other precautions required for protection against specific hazards of the particular use of the building."

F-105.1 General: Whenever the code official or the code official's designated representative shall find in any structure or upon any premises dangerous or hazardous conditions or materials as follows, the code official shall order such dangerous conditions or materials to be removed or remedied in accordance with the provisions of this code:

1. Dangerous conditions which are liable to cause or contribute to the spread of fire in or on said premises, building or structure or endanger the occupants thereof.

2. Hazardous conditions arising from defective or improperly used or installed electrical wiring, equipment or appliances.

To understand how a typical soil depressurization system would perform in a fire situation, a full size model was fabricated to simulate a typical Radon Vent Duct (RVD) routing. The model consisted of a floor deck utilizing 2x10 nom. joist and collar or band joist, 5/8" plywood decking and a 2x4 nom. wall system with wall insulation. The wall system and band joist were covered with fire code dry wall. This model represents a typical wall/floor construction detail in houses with attached garages. The building code typically requires the garage floor be 8" min. below the house floor in order to contain gasoline engine fume emissions. However, because of this required step, the garage/house common wall represents a direct exit from the basement to the garage area. Typical RVD systems are routed horizontally from the basement to the garage area, then vertically to the attic and terminated outside of the building shell. As part of the model, a 4" PVC pipe system was installed as described above. See Sketch SK-1. A Fan-Tech Model R-150 fan was installed approximately 10' above the horizontal pipe run. The pipe was insulated using a polyethylene covered fiberglass duct insulation. The effluent end was covered with a SIMON CAP while the inlet end was dampered to simulate expected operating static pressures within the system.

A fire was set at the base of the vertical stack just at the transitional 90° el through the dry wall/band joist area. The model was built to confirm what was thought would take place. The thought was that the PVC pipe would melt open. The open pipe would draw the fire and smoke up the pipe as a result of the force exerted by the fan thus spreading the fire and smoke to other areas of the structure.

The damper box is secured to the structure according to the manufacturer's recommendations. The box is fastened so that it will remain in position and function during a fire. Within the damper box rests a curtain type blade closure mechanism. A fusible link holds the blade closure mechanism in the open position. The blade closure mechanism is activated when the fusible link is destroyed through exposure to elevated temperatures. Typically the link will soften and release at 160° F. Vertical mount units depend on gravitational force to close the curtain within the housing. Horizontal mount units are fitted with a closing spring that draws the blades across the opening. One concern when incorporating these units in the Radon Vent Duct or RVD is the potential build up and continuing exposure to condensation. These units are fabricated utilizing galvanized metal enclosure and curtain dampers and the spring in the horizontal unit is stainless steel. However, long term exposure to typical system conditions could perhaps render the closing mechanism ineffective due to corrosion build-up, particularly in the horizontal mount units.

Some structural work may be necessary to meet manufacuturer installation requirements. The opening for the damper housing must be larger than the assembly, typically 1/8" per ft. of damper housing plus 1" for the maximum and a minimum of 1/4". These clearances are critical to allow for housing expansion and free curtain damper mobility in elevated temperatures. Mechanical fastening of the unit to the structure requires a metal sleeve and angle supports mechanically fastened to the damper housing. These supports are positioned on both sides of the penetration captivating the structure while allowing the damper housing to expand freely. Sealing between the RVD and the extended collar should be completed to maintain a closed RVD system. The cost of these units vary depending on size and mounting configuration. A 4" extended collar, horizontal mount unit cost is $40 and the vertical mount equivalent is slightly more. Ancillary materials, i.e., sleeves, mounting angle, screws and caulk will be in the $10-$12 range. Structural preparation will vary from site to site. The installation techniques required for proper installation add significantly to the installed cost. This type of installation would be utilized more in commercial RVD systems, particularly in through floor to floor applications. The question of durability and function will, however, require further study.

Another approach that was evaluated is the use of an intumescent fire stop system. This technique incorporates some of the elements required for the damper systems identified above. The installation requires 5 key elements consisting of the intumescent wrap, foil faced tape, galvanized retaining collar, adjustable stainless steel band and intumescent fire caulk. The installation is completed at the fire wall in the unprotected area. The procedure requires the application of the foil faced tape over the PVC pipe system to protect the pipe from softening due to volatiles within the intumescent. The preformed strips of intumescent are 2" x 20" x 1/4" thick and are cut to length to fit snuggly around the RVD at the fire wall penetration. Tape is used to temporarily secure the joint and hold the strip in place. Additional layers are installed with the joints staggered. The number of intumescent wraps depends on the pipe diameter; a 4" diameter RVD will require 3 bands of material.

When the system was ignited the polyethylene vapor barrier was consumed immediately in the area of the flame and heat. The duct insulation delayed the impact of the flame on the PVC pipe because of its inherent properties. Gradually the pipe was exposed to increased heat as indicated by the increasing density of effluent smoke. As the flames and heat exposure to the PVC pipe and elbow increased, the pipe system softened. The softening of the pipe continued until the structural integrity of the pipe system was below the level required to remain open. It began to collapse inward responding to the system induced negative pressure.

The PVC pipe continued to close in on itself until it was completely closed, causing the fan side of the system to be isolated from the fire source and from further damage. The system was heat softened and sealed, subsequently, operating under full negative pressure capacity of the fan. This was evidenced by the gradual and eventual complete termination of smoke from the stack. This event was in complete disagreement with anticipated results.

At this point, however, the flames had an open access through the in place fire wall and into the basement. The PVC pipe system burned and created a pathway for the fire to follow. The flames spread along the RVD into the occupied side of the fire wall. Within minutes the band joist and plywood sub-floor were ignited. Eventually, the model was consumed in flames.

Armed with this information the task ahead was to find an installation process that would eliminate this from taking place. Several approaches were investigated that would allow a mitigation system to overcome this potentially lethal installation flaw.

An obvious approach would be to completely enclose the pipe system in a fire code dry wall chase. There is, however, concern that this type of remedy is not acceptable in that a chase is created. The chase would still have the ability to transfer flames within itself and perhaps require special sealing at the pipe penetrations within the chase. From an installation standpoint this approach is labor intense and requires structural materials to complete. Also in some installations this approach would be impractical or impossible to implement.

Another approach would be to use a non-combustible pipe system through the non-fire protected areas, i.e., garage. This could be accomplished using a copper Drain, Waste, Vent or DWV pipe. The pipe would be connected to the standard PVC RVD system using flexible couplings to make the transition to PVC. A special intumescent sealant must be applied to stop flame spread through the fire wall/pipe penetration. This will serve to inhibit flame spread around the pipe through an irregular opening. Although this technique is feasible, the expense of the copper pipe, its weight and pipe support implications would make a significant contribution to the installation cost.

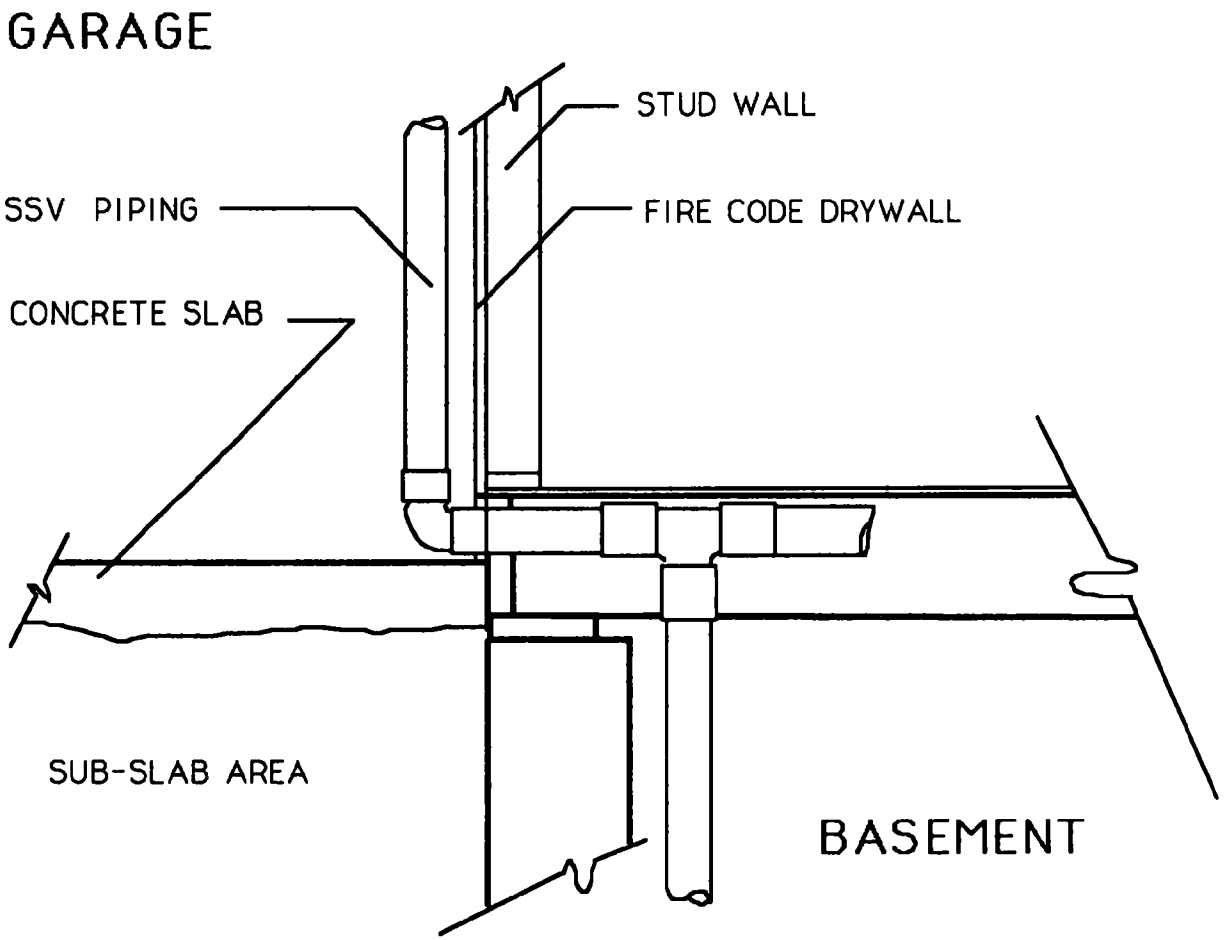
A mitigation system can be isolated from the occupied spaces utilizing an in-line fire damper. This device is a sealed metal box with 4" diameter extended collars at opposite ends.

When this is completed, a pre-stamped galvanized metal retaining collar is cut to length and folded to capture the intumescent and form attachment ears. The retaining collar is secured around the intumescent with a stainless steel adjustable band. The unit is then secured with screws through the attachment ears to the structure. The final step is to seal the area between the fire inhibiting wall or ceiling and the retaining collar. This requires an intumescent caulk material. The intumescent material and caulk system is designed to expand when exposed to elevated temperatures. This expansion is directed toward the PVC RVD pipe system reacting against the retaining collar and the stainless steel retainer band. The PVC RVD is softened as the temperature increases facilitating its forced closure. The intumescent forms a hard char material which, by design, remains intact throughout the flame exposure. The materials cost for this type of installation is $45. The number of installations will vary depending on the number of fire barrier penetrations.

The issue of risk prevention is an important element within the frame work of the mitigation installation. The approaches presented here have the ability to significantly reduce the potential loss of life due to system interaction with fire. The fire protection system chosen, as with many other mitigation options, is based on the site specific influences. In some cases the damper system may be appropriate while the intumescent system may be applicable in others. The cost associated with the installation is minimal when compared with the potential for loss of life and property. Professional design and mitigation companies should develop skills in the installation of fire protection systems recognizing this is not an option but a mandatory ingredient for code compliance.

The work described in this paper was not funded by the U. S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

SK-1


GARAGE
STUD WALL
SSV PIPING
FIRE CODE DRYWALL
CONCRETE SLAB
SUB-SLAB AREA
BASEMENT

Paper D-VII-5

LABORATORY STUDIES OF "BETWEEN THE ROOMS" RADON DECAY PRODUCT REMOVAL UNITS

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ABSTRACT

A temporary wall was constructed to divide a large laboratory chamber into two sections. Mounted in the wall were two fan-positive ion generator units, each blowing in opposite directions so as to maintain a balance in the airflow between the two sections. Data showed that the units provided PAEC reductions in the two sections of the chamber in excess of 90%. Estimates of the overall reductions in the lung doses were 86% (using the Jacobi-Eisfeld model), 88% (using the Harley-Pasternak model), and 92% (using the James-Birchall model).

INTRODUCTION

A temporary, 4-m wide wall was constructed in the Harvard Radon Chamber (1) to simulate two adjacent rooms in a residence. The left section of the chamber had a volume of 35.3 m^3 and the right section had a volume of 43.2 m^3. Two radon decay product (RDP) removal units (fan and positive ion generators) were installed 1.5 m apart in this wall at a height of 2.0 m above the floor (shown schematically in Figure 1). One fan directed an airflow of approximately 50 L/s from one section of the chamber into the other. The other fan directed an equal airflow in the opposite direction so that pressures in the two sections were equal. Positive air ions were dispersed into the respective airflows.

LABORATORY TESTS AND RESULTS

The sequence of tests consisted of an initial time period when the RDP removal unit ion generators were off (only the fans were operating) and a second time period when both the fans and ion generators were operating, with measurements being made in one section of the chamber. This

sequence was then repeated with measurements being made in the other section of the chamber. Radon concentrations in the laboratory chamber, as well as graphs of the potential alpha energy concentrations with the fans on, and with the fans and ion generators on, are shown in Figure 2. As may be noted, the radon concentrations (upper curve) were essentially constant throughout the studies, whereas the fans plus ion generators reduced the potential alpha energy concentrations by greater than 85%. Due to limitations on the availability of monitoring equipment, the PAECs were monitored in the left section of the chamber on the first two days, and in the right section on the subsequent two days.

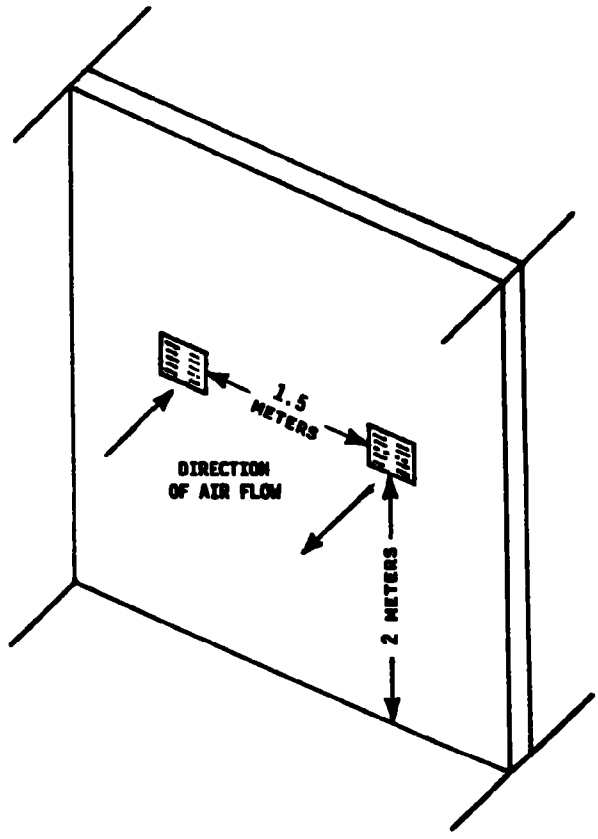

Figure 1. Schematic representation of "between the rooms" fan-ion generator airborne radon decay product removal units.

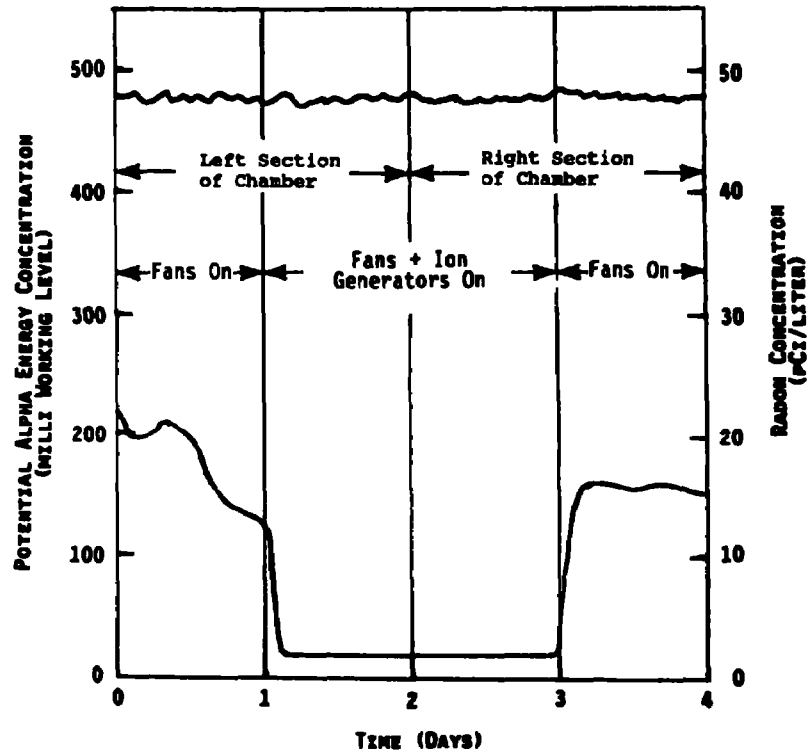

Figure 2. Radon and potential alpha energy concentrations in left and right sections of the laboratory chamber with either the fans or the fan-ion generator units in operation. Only the fans were in operation on the first and fourth days; both the fans and the ion generators were in operation during the second and third days.

Grab samples of radon and its decay products were analyzed by standard methods (1). Single-screen samples were analyzed for unattached decay products (2). These data were used to calculate reductions in total PAECs, and unattached PAECs which are summarized in Tables 1 and 2. Reductions in total PAECs averaged 87% and reductions in unattached PAECs averaged 56%. Estimates of the reductions in lung dose to the basal cells of the tracheobronchial region are summarized in Tables 3, 4 and 5. The percentage reductions given in Tables 1 - 5 are based on the use of the two "between rooms" RDP removal units (i.e., fans and ion generators) as compared to the use of the identical devices with the ion generator turned off (i.e., only the fans operating). If the reductions had been compared to "no treatment conditions" (i.e., both the fans and ion generators off), the calculated percentage reductions would have been greater. The range of probable reductions in the lung doses attributable to the fans and ion generators, based on linear forms of three dosimetric lung moels (3,4), and their corresponding limits are shown below. Estimates of the reductions, as compared to "no treatment conditions," were calculated on the assumption that the fans, alone, would have reduced both the total and unattached PAECs by 50% (5).

Dosimetric Lung Models and Model Limits	Percentage Reduction	Percentage Remaining
Minimum (i.e., effect on unattached PAEC)	79%	21%
Lung Dose		
Jacobi-Eisfeld Model (6)	86%	14%
Harley-Pasternak Model (7)	88%	12%
James-Birchall Model (8)	92%	8%
Maximum Effect (i.e., effect on total PAEC)	93%	7%

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Acknowledgments:

Assistance in the collection of the data reported in these studies was provided by Captain Carl A. Curling, U.S. Army, formerly a Doctoral Student, Department of Environmental Science and Physiology, Harvard School of Public Health.

TABLE 1. EFFECTIVENESS OF FAN-ION GENERATORS IN REDUCING TOTAL PAEC*

Experiment Number	Left Section of Chamber PAEC (mWL) Fan On	Left Section of Chamber PAEC (mWL) Fan + Ion Generator On	Left Section of Chamber Percent Reduction	Right Section of Chamber PAEC (mWL) Fan On	Right Section of Chamber PAEC (mWL) Fan + Ion Generator On	Right Section of Chamber Percent Reduction
1	180	19.1	90	191	22.5	88
2	219	26.8	88	237	30.5	87
3	201	22.6	89	201	27.7	86
Average	200	23	89	210	26.9	87

TABLE 2. EFFECTIVENESS OF FAN-ION GENERATORS IN REDUCING UNATTACHED PAEC*

Experiment Number	Left Section of Chamber PAEC (mWL) Fan On	Left Section of Chamber PAEC (mWL) Fan + Ion Generator On	Left Section of Chamber Percent Reduction	Right Section of Chamber PAEC (mWL) Fan On	Right Section of Chamber PAEC (mWL) Fan + Ion Generator On	Right Section of Chamber Percent Reduction
1	8.8	3.6	59	12.4	4.0	68
2	10.8	4.5	58	13.5	5.2	61
3	7.3	4.6	37	9.4	5.6	40
Average	9.0	4.2	51	11.8	4.9	56

*External air exchange rate was 0.2/h.

TABLE 3. EFFECTIVENESS OF FAN-ION GENERATORS IN REDUCING MEAN BRONCHIAL LUNG DOSE EQUIVALENT RATE (James-Birchall Model)(8)

	Left Section of Chamber			Right Section of Chamber		
	Treatment Conditions (Dose Rates in Sv/y)			Treatment Conditions (Dose Rates in Sv/y)		
Experiment Number	Fan On	Fan + Ion Generator On	Percent Reduction	Fan On	Fan + Ion Generator On	Percent Reduction
1	1.24	0.319	75	1.53	0.360	77
2	1.50	0.409	73	1.76	0.470	73
3	1.19	0.402	67	1.35	0.489	64
Average	1.31	0.377	72	1.55	0.439	71

Notes:

1. The external air exchange rate was 0.2/h.
2. Percent Reduction $= \frac{\text{Dose Rate (Fan)} - \text{Dose Rate (Fan + Ion Generator)}}{\text{Dose Rate (Fan)}}$ (100%).
3. James-Birchall Model Conversion Factor: $92 + 180\ f_p$ (mSv/WLM).

TABLE 4. EFFECTIVENESS OF FAN-ION GENERATORS IN REDUCING MEAN BRONCHIAL LUNG DOSE EQUIVALENT RATE (Harley-Pasternak Model)(7)

	Left Section of Chamber			Right Section of Chamber		
	Treatment Conditions (Dose Rates in Sv/y)			Treatment Conditions (Dose Rates in Sv/y)		
Experiment Number	Fan On	Fan + Ion Generator On	Percent Reduction	Fan On	Fan + Ion Generator On	Percent Reduction
1	1.01	0.216	79	1.20	0.245	80
2	1.23	0.281	77	1.40	0.322	77
3	1.02	0.270	74	1.11	0.329	70
Average	1.09	0.256	77	1.24	0.299	76

Notes:

1. The external air exchange rate was 0.2/h.
2. $\text{Percent Reduction} = \frac{\text{Dose Rate (Fan)} - \text{Dose Rate (Fan + Ion Generator)}}{\text{Dose Rate (Fan)}} (100\%)$.
3. Harley-Pasternak Model Conversion Factor: $70 + 795\ f_p$ (mSv/WLM).

TABLE 5. EFFECTIVENESS OF FAN-ION GENERATORS IN REDUCING MEAN BRONCHIAL LUNG DOSE EQUIVALENT RATE (Jacobi-Eisfeld Model)(6)

Experiment Number	Left Section of Chamber: Treatment Conditions (Dose Rates in Sv/y) Fan On	Left Section of Chamber: Treatment Conditions (Dose Rates in Sv/y) Fan + Ion Generator On	Left Section of Chamber: Percent Reduction	Right Section of Chamber: Treatment Conditions (Dose Rates in Sv/y) Fan On	Right Section of Chamber: Treatment Conditions (Dose Rates in Sv/y) Fan + Ion Generator On	Right Section of Chamber: Percent Reduction
1	0.935	0.124	87	1.02	0.144	86
2	1.14	0.169	85	1.25	0.193	85
3	1.02	0.150	85	1.04	0.183	82
Average	1.03	0.148	86	1.10	0.173	84

Notes:

1. The external air exchange rate was 0.2/h.
2. $\text{Percent Reduction} = \frac{\text{Dose Rate (Fan)} - \text{Dose Rate (Fan + Ion Generator)}}{\text{Dose Rate (Fan)}} (100\%)$.
3. Jacobi-Eisfeld Model Conversion Factor: $66 + 1370\ f_p$ (mSv/WLM).

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RADON MITIGATION TECHNIQUES FOR NORWEGIAN HOUSES

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ABSTRACT

Results of an experimental study of different techniques to reduce the radon levels in Norwegian houses are reported. A total sample of 30 detached houses, representing a broad range of different types of Norwegian houses accordring to construction techniques and architecture, were selected for the study. In this sample of houses, earlier measurements had shown average radon concentrations ranging from about 500 Bq/m³ to 15 000 Bq/m³. Passive measurements of radon were performed at different stages in the process. In a few houses more extensive measurements were carried out. This included contineous measurements of radon, radon daughters and air exchange rate, and grab sampling measurements of unattached fraction of radon daughters. Of the different solutions studied, the methods based on sub-slab ventilation/depressurisation were found to have the best reduction effect on the radon level in indoor air.

INTRODUCTION

In 1988, an extensive study on mitigation techniques for Norwegian houses was started. The study was organised as a collaboration between the Norwegian Building Research Institute and the National Institute of Radiation Hygiene. The aim of the study was to evaluate between different possible mitigation methods/techniques to reduce the radon level for different types of Norwegian houses and to give recommendations.

So far, most of the research work on mitigation methods/techniques in the Nordic countries have been carried out in Sweden (1,2). Most of the recommendations in Norway have been based on experience from there. However, the buidling stocks are quite different. The most important difference, as far as radon is concerned, is the fact that most detached houses in Sweden do not have a basement, while probably more than 80% of detached houses in Norway do have.

MATERIAL AND METHODS

SELECTION OF HOUSES

In Norway there is about 1.6 million dwellings. According to census data from the Central Bureau of Statistics (3), about 85% of the Norwegian housing stock is detached and undetached houses. In the most rural municipalities the percentage is nearly 100%. However, in Oslo, the largest town in Norway, about 65% of the dwellings are in blocks of flats. Influx of radon from the ground is found to be the most important source of indoor radon in detached and undetached houses. In houses where the radon concentration is found to be considerably higher than normal, the contribution from other sources can usually be neglected. For dwellings in blocks, on the other hand, building materials are usually the main source of indoor radon. However, in most cases the radon concentration is very low compared to detached and undetached houses. Therefore, blocks of flats were not included in the experimental sample of our study.

Most of the houses were selected from earlier and recent measurements from the National Institute of Radiation Hygiene. It was important to get a, as far as possible, representative sample of typical houses according to construction technique, architecture, age of the house and geology. It is assumed that the final sample of 30 houses meets these requirements fairly good. In table 1, the houses is classified into three categories according to type of house and radon concentration. As shown, most of the houses have basements.

TABLE 1. THE SAMPLE OF DETACHED HOUSES.

	NUMBER OF HOUSES		
	Radon concentration (Bq/m^3) 1)		
	< 1000	1000-5000	> 5000
With a basement floor below ground level	14	11	2
Concrete slab directly on ground	2		
On crawl space		2	

1)Representative averages of radon concentration for each house.

THE MEASUREMENTS

Passive measurements of radon were performed at different stages in he mitigation process in all of the 30 houses. The ETB-method, which is a combination of activated charcoal and TLD (4), were used in the measurements. The integration time in the measurements was between 7 and 10 days. In order to minimize the influence on the measurements from short term variations in the radon level, it was essensial that the they were performed at about equal meteorological/-climatical conditions. The uncertainties in the individual measurements were estimated to be about 15% at the 95% confidence level.

In a few selected houses, more extensive measurement programs were performed. This included contineous measurements of radon and radon daughters and measurements of the air exchange rate. At the diagnostic stage in the process, grab sampling measurements of radon were found to be especially valuable in characterising the source. The method and equipment has been described in an earlier paper by Stranden and Berteig (5).

RESULTS AND DISCUSSION

Generally, mitigation techniques may be divided into four groups:

(1) removal of radon sources
(2) methods to reduce the radon influx from the ground
(3) methods to increase the air exchange rate
(4) removal of radon daughters by electric fields/electrostatic filter

Methods involving a removal or exchange of source material from the building site and/or near the house may have a considerable reduction effect on the radon level in future houses if it is done at the site before the buidling work is started. For existing houses this kind of solution will usually be too expensive and too disruptive. However, for houses with a basement floor below ground level, where alum shale or other materials with a very high exhalation rate of radon has been used as filler on the outside of the foundation wall, removal or exchange of the source may be a successful solution.

If the air exchange rate is at a normal level, the relative reduction effect on the indoor level of radon by increasing the air exchange rate will usually be very low. Energy saving aspects, climatic conditions and indoor comfort limits the possibility to increase the air exchange rate in most situations. Due to an increase in the energy costs, and the campaign for saving energy in the 70's and 80's, a large proportion of old houses have been retrofitted in the last decade. At the same time period, modern houses have been made energy efficient. According to studies in Sweden (6), this may have reduced the air exchange rate in a significant part of the housing stock. In tight houses with no mechanical ventilation systems, average air exhange rates down to 1/10 of the normal level have been reported. In such houses, the effect of an increase in the air exchange rate to normal values, may lead to a reduction in the radon concentration by an order of magnitude. It is, however, important that the ventilation systems do not increase the underpressure inside. If so, then the influx of radon from the ground may increase.

For most houses in our study, diagnostic measurements showed that influx of radon from the ground was the most important source of radon. In 28 out of the 30 houses, different methods to reduce the influx from the ground were chosen. One of the main objectives of our study was to quantify the effect of different low cost solutions. This of course, did have an impact on the individual choice of solution. In several houses the mitigation process had to be carried out in different steps, starting with the cheapest possible one. In table 2, a general view of the different solutions is shown. In the following, a few examples from our study will be discussed in more detail.

TABLE 2. CLASSIFICATION OF THE DIFFERENT MITIGATION TECHNIGUES IN OUR STUDY

Category of mitigation solution	Number of houses
Sealing of cracks and openings in the foundation wall and the slab	3
Changing the pressure differences between indoor air and the ground 1)	20
Changing the ventilation conditions	2
A combination of different solutions 2)	5

1) Including four different methods: pressurize basement and/or crawl space (5 houss) sub-slab ventilation (13 houses), outdoor well (2 houses) and wall ventilation (1 house).
2) Combinations of sealing and sub-slab ventilation.

In figure 1, the reduction effect of a step-wise solution is illustrated in a house with a basement. The first step was based simply on sealing visable cracks and openings in the concrete slab and the foundation wall. In one of the rooms in the cellar, the average radon level was reduced from about 4,000 Bq/m^3 to 800 Bq/m^3. In this room a higly permeable wall of light expanded clay aggregate blocks, with direct contact below the slab, were assumed to be an important entry route. Most of the reduction effect can probably be explained by the plastering of this wall. However, the radon level was still too high and further actions were found necessary. As a second step, a sub-slab ventilation system (7) was installed. Due to the small base area of the house (about 80 m^3) and considerations about the permeability of the ground, one central exhaust pipe was assumed to give a sufficient suction. The pipe was connected to a fan on the loft. The flow rate was measured to 50-60 m^3/h. These type of solutions reduces the influx of soil gas by reducing the pressure differential between the basement and the ground and by reducing the concentration of radon below the slab by ventilation. After this second step, the radon concentration was reduced to about 150 Bq/m^3 in the basement and to about 100 Bq/m^3 on the first floor. On the average, in the four rooms where passive measurements were performed, the radon concentration was reduced by more than 90%. The actions were concluded to be very successful.

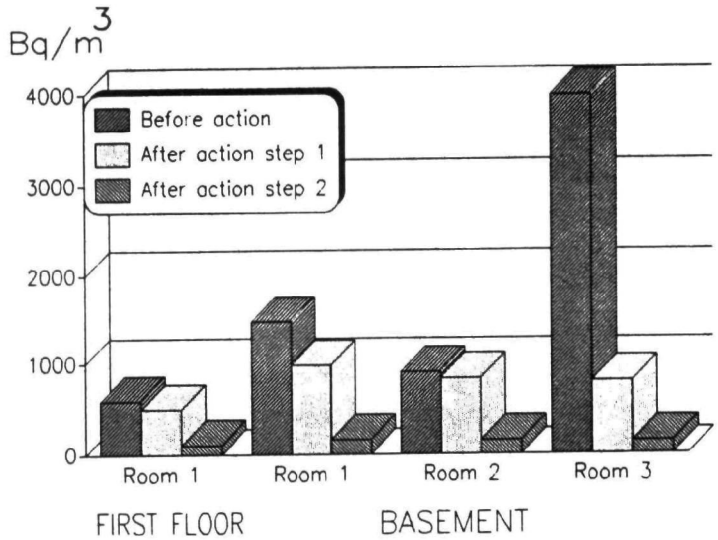

Figure 1. A two-step solution in a house with basement. Step 1: Sealing of cracks and openings in the concrete slab and the foundation wall. Step 2: Sub-slab ventilation (one exhaust pipe).

Figure 2 illustrates the effect of a pure solution based on sub-slab ventilation/-depressurisation. In this example, two exhaust pipes were connected to the fan on the loft. The fan is identical to the one in the previous case. For one of the rooms in the basement, the radon level was reduced from about 2,700 Bq/m³ to below 100 Bq/m³. This is a reduction of nearly 97%. The average radon concentration in the main living room on the first floor was reduced from 840 Bq/m³ to 80 Bq/m³. The solution was concluded to be very successful.

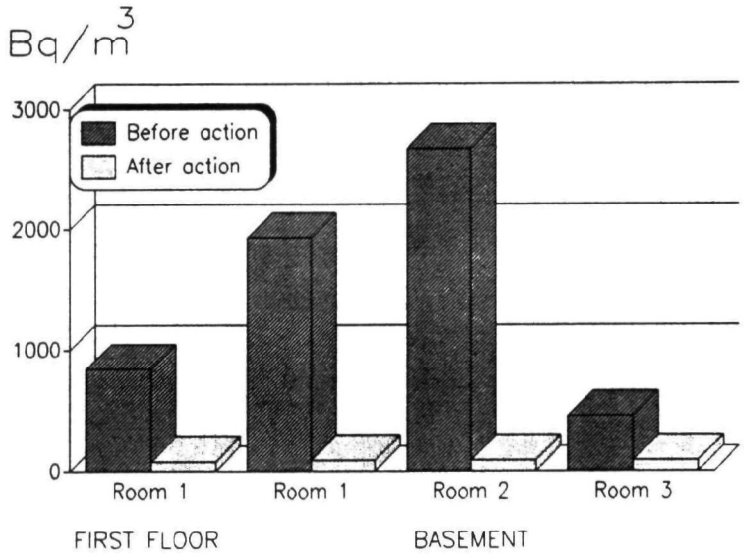

Figure 2. The effect of sub-slab ventilation/depressurisation (two exhaust pipes) in a house with basement.

It is important that the capacity of the fan is as low as possible. Not only because of energy saving, but also due to problems in the cold winter months if large quantities of cold air are beeing sucked beneath the basement floor. Outdoor temperatures below -30°C in the coldest winter months are not unusual in several parts of Norway. Our results have shown that fans with a very low capacity (about 30 Watt/60 m^3/h at Δp about 100 Pa) may be sufficient to solve the radon problem in many situations.

In one of the houses, the radon level was found to be very high. From contineous measurements, short time concentrations of radon up to 190 000 Bq/m^3 were found in the basement. Grab sampling measurements of radon and radon daughters confirmed these results. From passive measurements, the radon level in the basement was found to be between 10 000 and 15 000 Bq/m^3. Grab sampling measurements showed that an old and dry floor drain (without a water trap) in the basement floor probably was one of the main entry points. This floor drain was directly connected to alum shale rich soil. Since the floor drain was not in use any more, the first step was then to glog it and try to seal all visable cracks and openings in the concrete slab and the foundation wall. The results of this first step is illustrated in figure 3. In one of the rooms in the basement the radon level was reduced by almost 80%. In the other room in basement, sealing of the floor was found very difficult due to presence of numerios cracks and openings in the slab. In this room the average radon concentration was found to increase by about 15%. In addition to further sealing of the floor and the walls, an almost identical sub-slab ventilation/-depressurisation system as the example in figure 2, was installed. As illustrated, the radon concentration was reduced by nearly 95% in the basement and by about 90% on the first floor. However, the radon level is still too high and further work is needed. One of the possibilities is to increase the flow rate capacity of the fan.

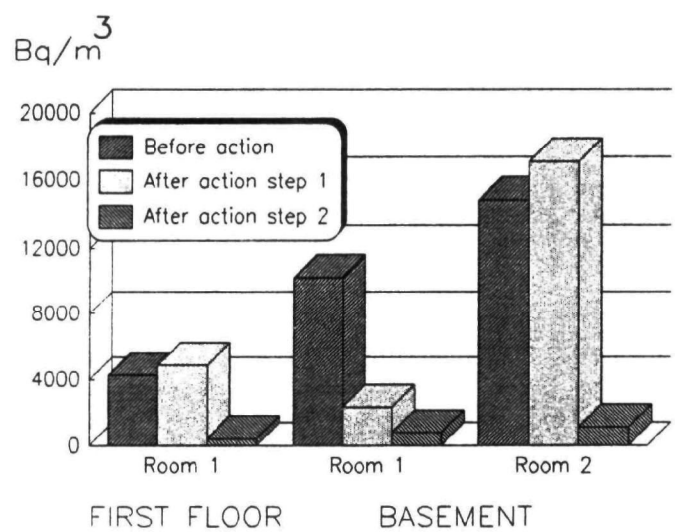

Figure 3. A two-step solution in a house with a basement. Step 1: glogging of a floor drain in the basement floor and sealing of different cracks and openings in the concrete slab and the foundation wall. Step 2: Sub-slab ventilation (two pipes).

The effect of sub-slab ventilation in the other houses where this type of technique as studied, was generally found to be successful. However, in a couple of houses were the ground most probably has a very low permeability, and the sealing of different cracks and openings in the slab were found to be very difficult, there was only a very slight reduction in the radon level.

For two of the houses in our study, the effect of a soil gas ventilation well on the outside of the foundation wall, were studied. The effect for one of these houses is ullustrated in figure 4. The well was at 3m depth and 1m in diameter. The exhaust pipe (diameter and lenght of 0.1m and 3m respectively), which was placed in the centre of the well reaching below basement floor level, was connected to a small fan (28 Watt) on the top. The flow rate was measured to about 50 m^3/h. In one of the rooms closest to the well in the basement, the radon concentration was reduced from 1300 Bq/m^3 to slightly below 350 Bq/m^3. On the first floor where the living room, bedrooms and kitchen were located, the radon level was reduced from 420 to 240 Bq/m^3.

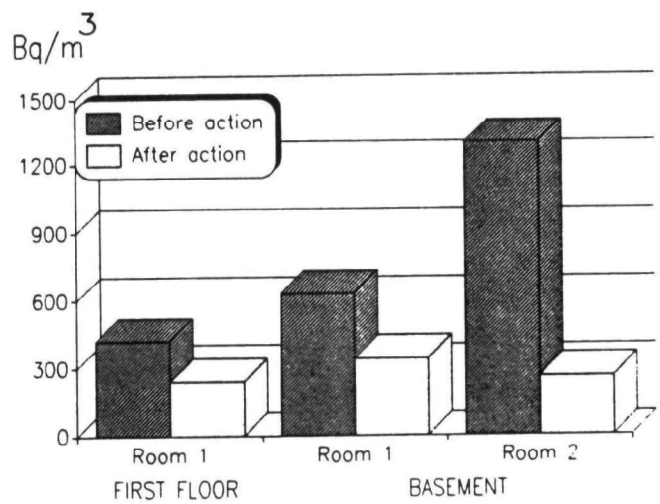

Figure 4. The effect of an outdoor soil gas ventilation well in a house with a basement.

In five houses, different techniques to pressurize the basement and/or the crawl space by supply of fresh air from the outside, were investigated. Due to the climatic condtions it was found necessary to include a heater unit in the fans, which of cource increases the energy costs. Preliminary results from these exsperiments seems to show that these types of solutions may have a relatively slight reduction effect on the radon level. In figure 5, the effect of pressurizing the basement and the crawl space in a house on alum-shale ground is illustrated. The fan (99 Watt) was installed in the foundation wall at the basement level. The flow rate was measured to 310 m^3/h. The radon concentration in the basement and the first floor were reduced by 50% and 30%, respectively. One of the main explanation of this low reduction effect may be leakage between the basement and the first floor.

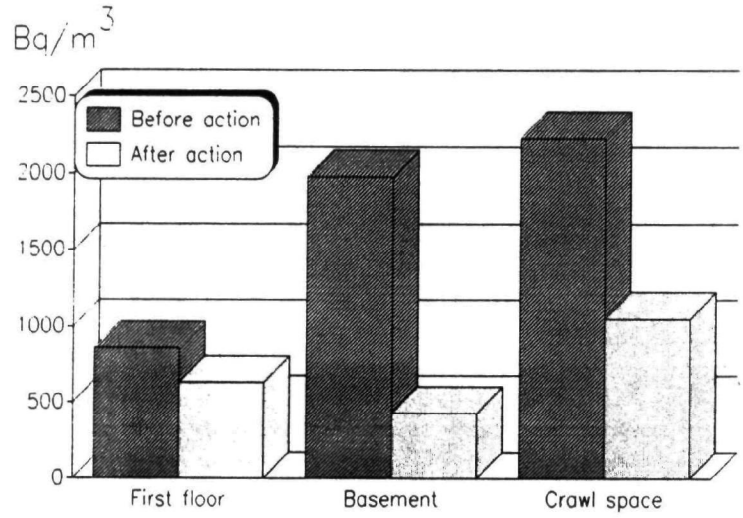

Figure 5. An example of a solution based on pressurizing the crawl space and the basement.

CONCLUSIONS

From the results and discussion of our study the following conclusions may be drawn:

1. Sealing of viseable cracks and openings in the slab and the foundation wall is recommended as a first step in any mitigation process. However, the results of our study shows that sealing alone in most situations will not be sufficient to solve the entire radon problem. This is especially true in cases where the radon level is very high.

2. Sub-slab ventilation by exhaust pipes connected to a small fan were generally found to be the most successful technique in our study. In most cases it is sufficient with only one or two exhaust pipes and a very small fan (30 Watt/60 m^3/h).

3. Preliminary results of our exprimental studies of techniques based on pressurizing crawl space and/or basement by supply of outdoor air have shown to have a relatively low reduction effect on the radon level.

The final results of our study will be presented later.

ACKNOWLEDGEMENTS

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Session D-IX:

Radon in Schools and Large Buildings—POSTERS

PREDICTION OF MAXIMUM RADON CONCENTRATIONS IN SCHOOLS USING PARTIAL SAMPLING METHODS

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ABSTRACT

The Environmental Protection Agency published interim guidance for radon measurements in schools in April of 1989. That guidance recommends testing of radon in all rooms that are frequently used. This paper describes a partial sampling technique which might help identify schools with a potential radon problem. Its use is not endorsed by EPA. It is an analytical tool which might be used as an initial step in facilitating implementation of the 1989 guidance.

Radon measurements were obtained for 198 schools in Pennsylvania and Virginia. Schools in Pennsylvania were generally located in the Reading Prong and were surveyed by the Pennsylvania Department of Environmental Resources. In each school, multiple rooms were measured using either charcoal adsorption, alpha track or grab working level. Virginia schools were surveyed by the Fairfax County, VA Public School System using charcoal samplers. These data were analyzed using a Monte Carlo method to determine the ability of partial sampling and statistical methods to predict the highest room in the school. A method was developed which yields reasonable success in detecting the probable presence of elevated rooms (above 4 pCi/l) when ten percent (or a minimum of ten) rooms are sampled. The confidence in the prediction (type a and type b errors) is quantified as a function of the parameters of the analysis. The implications of potential errors induced by partial sampling are discussed.

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

PREDICTION OF MAXIMUM RADON CONCENTRATIONS IN SCHOOLS USING PARTIAL SAMPLING METHODS

INTRODUCTION

On April 20, 1989, the Environmental Protection Agency (EPA) published preliminary guidance for monitoring of schools in the United States (1). This guidance recommends measurement of radon in all rooms that are frequently used and are on or below ground level. Frequently used rooms include classrooms, offices, cafeterias, libraries and gymnasiums. Rooms used for storage, broom closets, etc. would not be monitored. This recommendation is based on observations in schools in an EPA pilot study(2).

While EPA clearly prefers measurement of every room, the Agency recognizes that budgetary and other constraints may prevent this, at least in the immediate future. School officials who cannot measure all frequently used rooms are then encouraged to test those rooms with the highest potential for elevated radon. These include (1) basement classrooms, (2) occupied rooms that are isolated from the central ventilation system or on systems which only recirculate room air, (3) rooms on or near structural joints such as adjacent slabs, (4) rooms with a large floor/wall joint perimeter and (5) rooms that have floor slabs with significant cracks. The intent of this guidance is to maximize the probability of detecting rooms with elevated radon concentrations.

This paper reports a technique which may be useful in finding schools having rooms with elevated radon concentration when it has been determined it is not possible to test every room. The technique is not endorsed by the Environmental Protection Agency. The method described here makes use of the properties of the distribution of radon concentrations measured in schools. This distribution is used to predict the concentration in the room with maximum radon based on a partial sample.

The method could be applied using a sample of rooms chosen on a purely random basis, or it could be used to evaluate the remainder of the rooms in a school after the rooms with highest radon potential have been selected as described above. It could also be used as a screening tool to decide the order in which several schools should be tested more completely if it is not possible to test all at once. The method yields an approximation of the highest radon concentration in the school based on a sampling of ten percent, or a minimum of ten rooms.

DESCRIPTION OF THE METHOD

In radon screening procedures, one would prefer that there be a low probability of failing to detect rooms with elevated radon (false negatives) because potential health problems may go uncorrected. Incorrectly classifying a school as having elevated radon based on a preliminary screening procedure (false positive) may be more acceptable for it provides a more conservative approach in protecting public health.

The basis of the partial sampling technique is that the properties of a population (for example the radon concentration in the rooms of a school) can be estimated from a sample drawn from the population. Given a sample of radon measurements taken in some randomly selected rooms of a school, it should be possible to devise a method to estimate the distribution of radon in all the rooms within certain limits of uncertainty. It may also be possible to arrive at an estimate of the maximum radon level in the school based on empirical data. That is exactly what is attempted here.

For populations where the property being measured is normally distributed and the sample is chosen randomly, the mean and standard deviation of a sample yield an unbiased estimate of the mean and standard of the population. If the parameter is not normally distributed, the mean and standard deviation of the sample are not unbiased estimators of the population. Therefore, in order to utilize the mean and standard deviation as estimators, the population must be normally distributed. For the radon in schools data used here, the radon concentrations have been found not to be normally distributed. Most of these schools show an acceptable ($p=.05$) fit to a lognormal distribution, so lognormal statistics must be used. The most straightforward way to do this is to transform the radon data by taking the log (either natural or base 10) of the radon concentrations(3). The resulting data yield an acceptable fit to a normal distribution.

When the distribution of radon concentrations is known, it is straightforward to estimate the radon concentration at any percentile of the distribution. Conversely, if a percentile is chosen the radon concentration at this percentile can be estimated. The confidence limits of these estimates are a function of the degree of certainty with which the parameters of the distribution have been estimated, and how well the distribution conforms to the model (in this case lognormal). The allowable confidence limits can also be used to determine the necessary sample size.

However for the purpose of this paper it was desired to estimate the radon concentration in the maximum room in each school, not the radon at a fixed percentile. Since the number of rooms is variable, there is not a fixed percentile of the distribution that can be used. Instead it was decided to use an empirical approach to relate the maximum observed radon

concentration to the mean and standard deviation of the measured radon concentrations in each of a large number of schools. A similar empirical approach, described below, was used to demonstrate the resulting confidence limits.

Similarly, the number of rooms in the sample was not derived from sampling theory. It was based on the authors' estimate of what is practical. It was felt that a minimum of ten rooms, or a minimum of ten percent of the total number of basement and first floor rooms, might yield an estimate of the mean and standard deviation sufficient for the purpose at hand, an estimate of the radon concentration in the maximum room in each school. This approach is tested empirically using a Monte Carlo method and the resulting confidence limits are shown for each school individually. The number of rooms in the sample was varied and found not to be an important parameter in the schools with the "worst" predictions. The overview of all schools for which this calculation was done demonstrates the strengths and weaknesses of the method.

The mathematical form of the test is

(1) $\bar{X}_n + K\, s_n < C$ pass

and (2) $\bar{X}_n + K\, s_n \geq C$ fail

where $\bar{X}_n$ is the mean of the sample.

s_n is the standard deviation of the sample.

K is a multiplier (number of standard deviations) determined empirically to yield the desired sensitivity.

The method proposed here makes use of the technique outlined above, and has been structured to be of practical benefit. Many choices in this candidate method are purely arbitrary and based on practical considerations. For example a method requiring 90% sampling is of little practical use since any cost savings would be more than offset by the expense of confirmatory monitoring if a problem is detected. A sampling rate of 10% was chosen to yield a tangible benefit, and a 25% rate was also investigated and found to yield little improvement over a 10% rate.

The environment within which the method would be applied is as follows. If the estimate of the maximum radon is below 4 pCi/l school officials may test further if they so decide, but EPA believes it may be costly at this point to reduce the radon below these levels. If additional monitoring were performed it would be a relatively low priority compared to schools yielding a higher estimate. An estimate of the maximum room above 4 pCi/l would trigger confirmatory monitoring of the remaining rooms. It would not be the basis for mitigation. There would be two ways in which a radon problem could be "found". It could be directly

measured if one of the radon tests came out above 4 pCi/l or could be inferred from the statistical calculation of the highest room. This yields two ways in which problems can be found and increases the power of the test. If rooms with a high radon potential are also preselected for separate monitoring, the power of the method is further improved.

The first condition that must be satisfied is normality of the data distribution. Radon data in the schools here was found to be approximately log-normal, and so can be normalized by simply taking the logarithm. All data used in this analysis has been transformed in this way. This allows the use of the sample mean and standard deviation to estimate these parameters for the population. It is unimportant whether natural or base 10 logarithms are used here since the difference is only a scaling factor which cancels out in the later mathematics.

The second and more tenuous part of the analysis is to estimate the radon concentration in the worst room. To do this an empirical approach was selected. The logarithms of radon concentrations were calculated from a subset of the schools described below. The mean and standard deviation of the logarithms were calculated for each school. The logarithm of the maximum radon concentration was also calculated for each school. The number of standard deviations from the log mean to the log of the maximum observed radon concentration was then calculated for each school. For convenience this resulting statistic will be called K' because of its use in selecting a value of K used in estimating the maximum radon as described above. The values of K' were compiled and graphed separately for each method of measurement used in Pennsylvania, for the Virginia charcoal data and for data from the EPA phase I study of schools nationwide. There was a remarkable similarity in the results in spite of sampling methods and sample durations and radon levels which were quite dissimilar.

The derived values of K' are plotted on Figures 1 through 5. It can be seen that there is a distribution of this statistic with a maximum at K' = 2 to 2.5 standard deviations from the mean. This relationship appeared to hold well across the data examined here. This is the basis for the choice of the value of K in the predictive applications of the method. Note that the maximum value of the statistic K' is 4.5 standard deviations from the mean and several schools yielded K' of 4 standard deviations. This did not appear to be a function of the number of rooms in the school, but was related to the presence of rooms with unique characteristics that caused high radon. Given this distribution of K' the choice of K at 2.0 or 2.5 in the method above would yield a central value in the prediction of the highest radon in the school. The presence of schools with K' as high as 4.5 guarantees that the method cannot predict all rooms above 4 pCi/l all the time unless K is set at or above 4.5. The presence of schools with K' close to 1 will result in overprediction part of

the time. The probability if overprediction and underprediction at various values of K is the principal result of this paper.

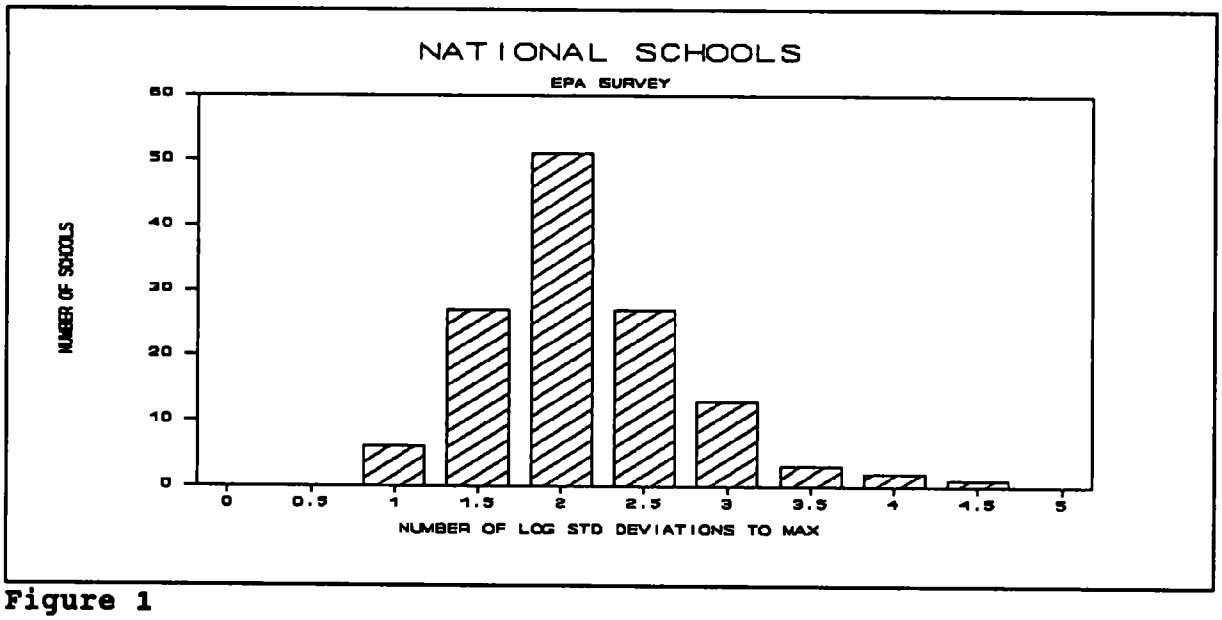

Figure 1

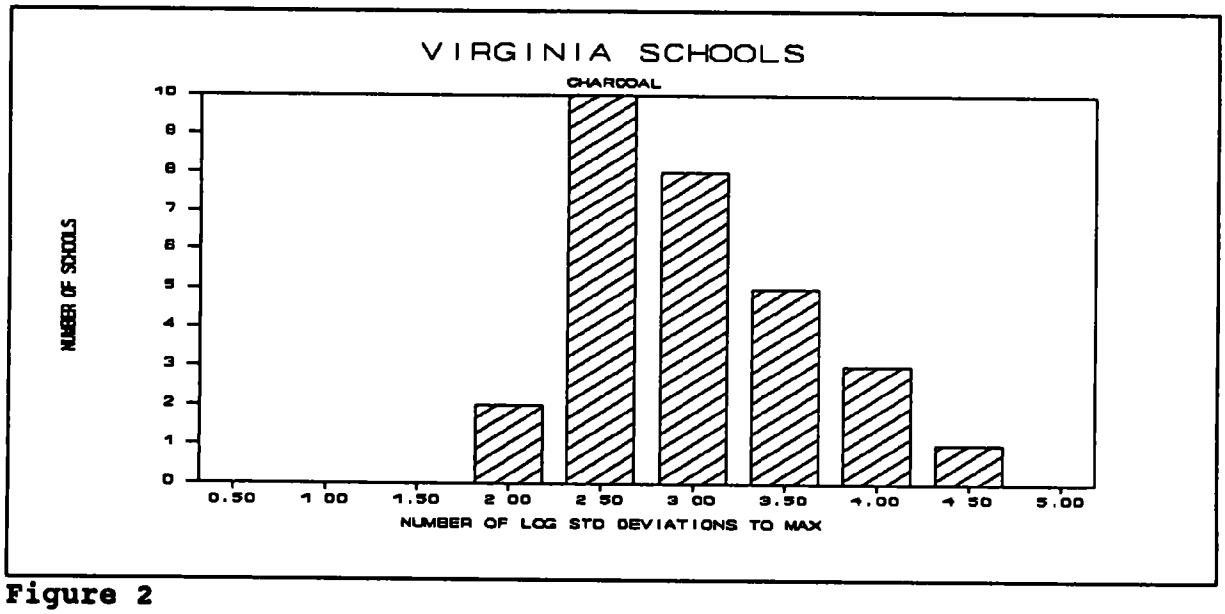

Figure 2

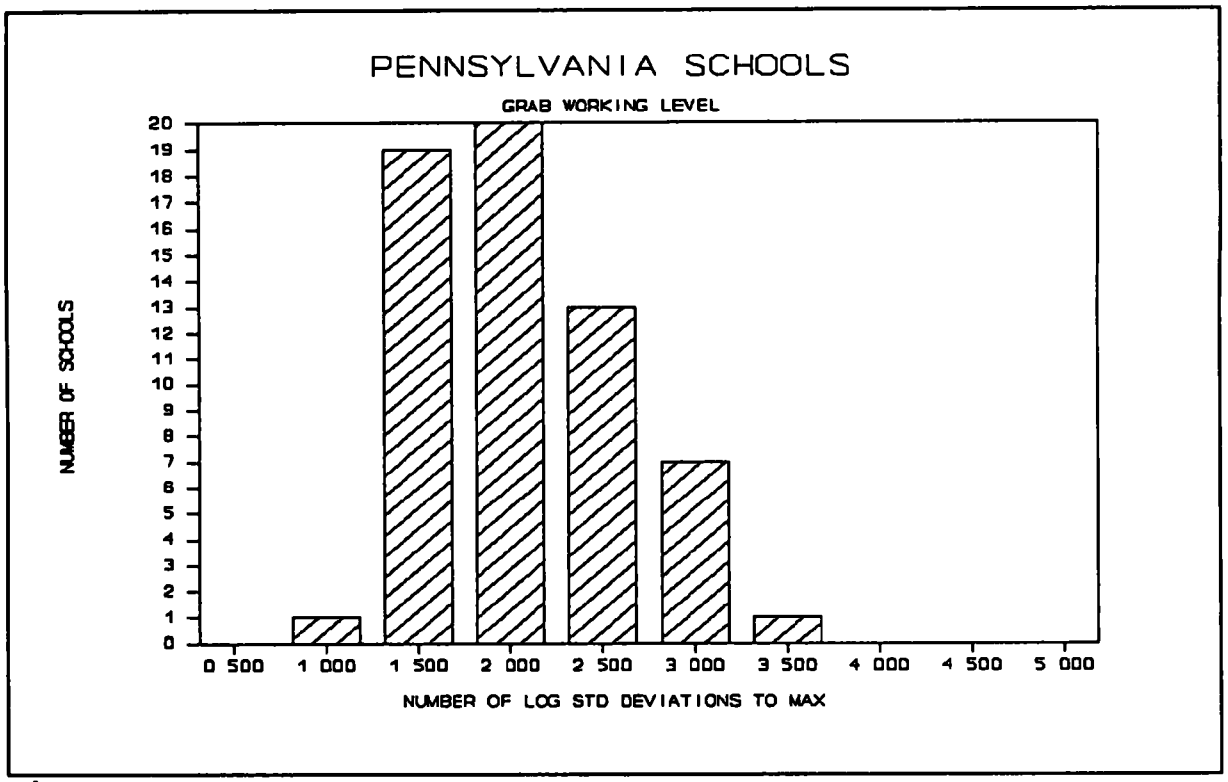

Figure 3

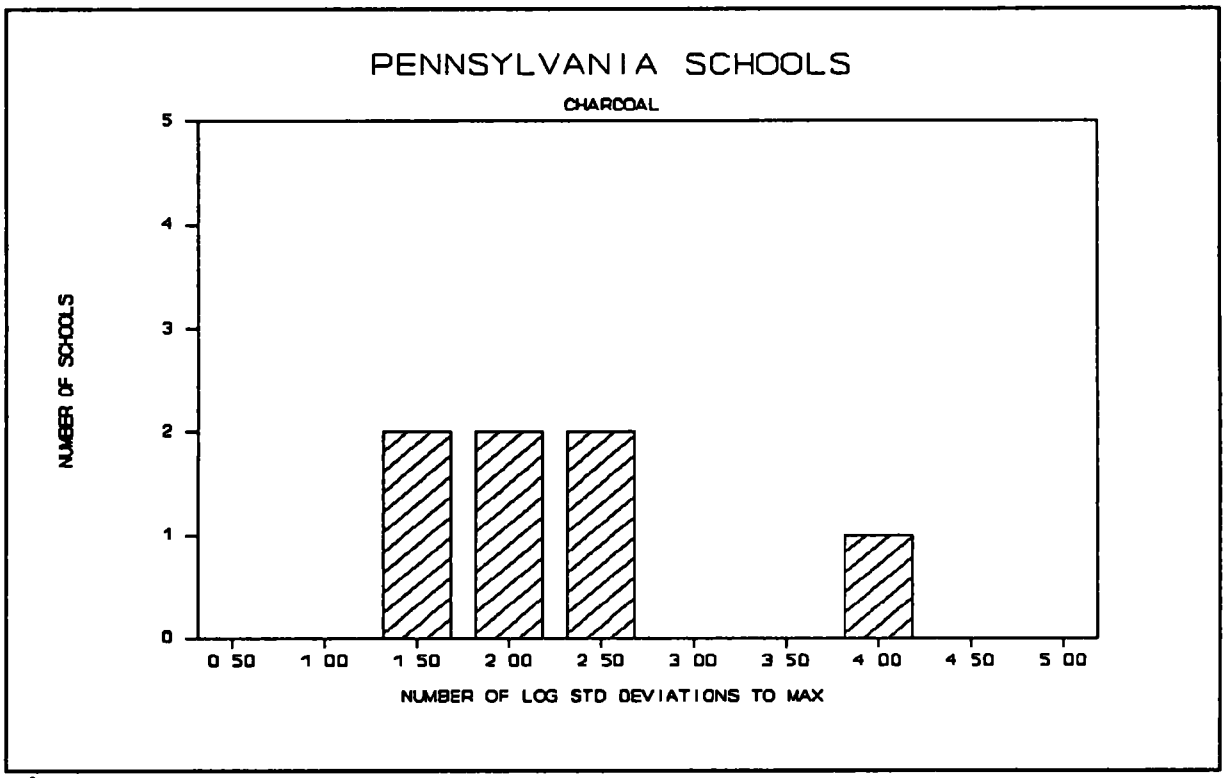

Figure 4

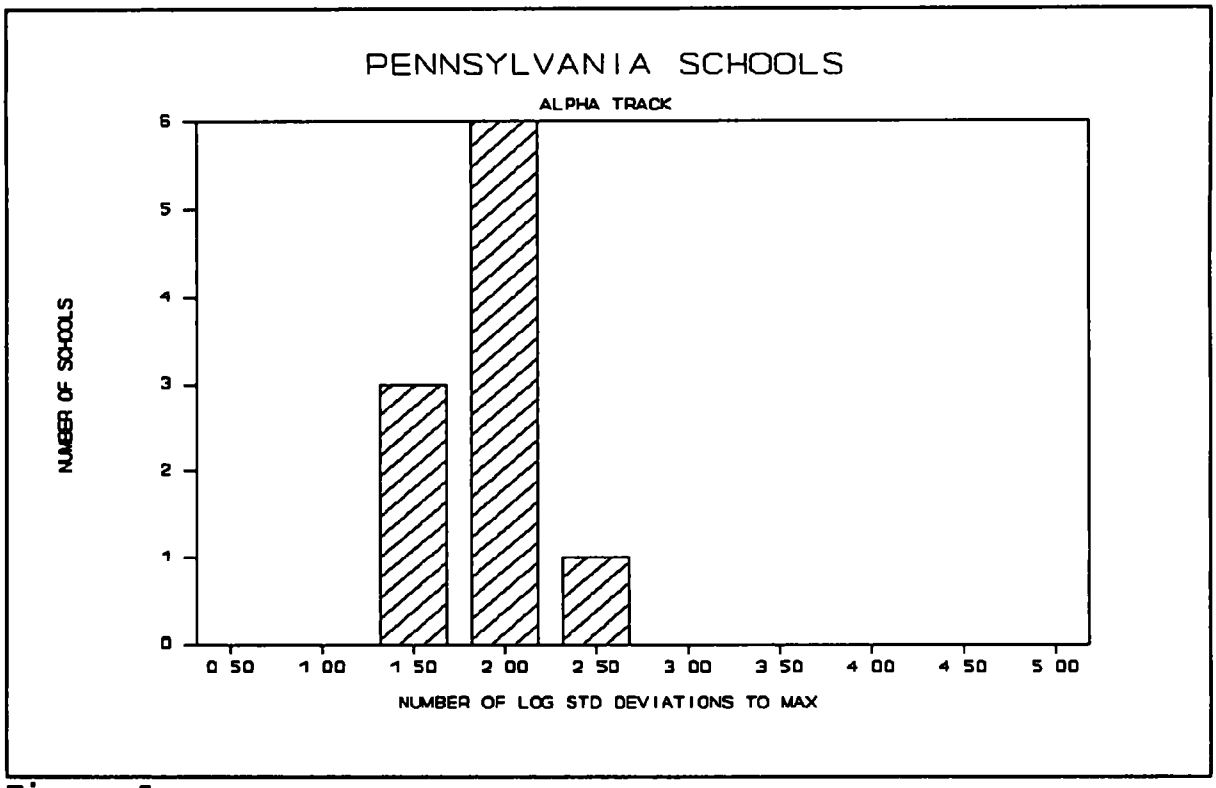

Figure 5

DATA USED FOR THE ANALYSIS

Radon measurements were obtained for eighty-seven schools in Virginia which were measured by the Fairfax County Virginia Public School System using bag-type charcoal detectors. The Environmental Protection Agency Phase I school data(4) for nine other areas of the country was also obtained. The radon in this dataset was measured with EPA charcoal canisters. Radon data was also obtained from the State of Pennsylvania for schools measured by the State as a part of its Reading Prong investigation. Seventy-nine schools were measured using three month alpha-track detectors, thirty-two schools were measured using charcoal detectors and fifty-five schools were measures with grab working level samples. At the time when these measurements were made, the grab working level was the principal tool for doing rapid radon assessments. In schools where elevated working levels were found in "high probability" rooms as defined by Pennsylvania (this may differ from the later EPA definition), every room in the school was tested. Where no elevated working levels were found, only a few rooms were tested. This data sometimes included boiler rooms which are infrequently inhabited. School grab samples were also followed up with alpha track detectors, so many of the working level and alpha track schools are common between the datasets. Charcoal tests were used later in the Pennsylvania program, and were made in a separate group of schools. For this analysis the grab samples and alpha track

results are treated as if they were not from the same schools because it was desired to test the method with both measurements. This did not affect the outcome of the analysis since the number of rooms tested with alpha track detectors was below the lower limit included in the Monte Carlo analysis but allowed the value of K' to be investigated for this measurement method.

A preliminary culling of data was performed to eliminate all schools where less than ten rooms were sampled. This was done because the first part of the analysis examined the mean and standard deviation of the logs of the concentrations. It was felt that the statistics would only be meaningful where there were at least ten items of data. This also served to eliminate schools where very few rooms were sampled. An additional restriction placed on the data was that the maximum radon concentration be at least 2.7 pCi/l or .014 WL. This was done to assure that the radon measurements were well above the lower limit of detection so that there would be some confidence in the radon measurements reported. After this first cut there were twenty-nine schools in the Virginia charcoal dataset, eleven Pennsylvania schools measured with alpha-track detectors, seven Pennsylvania schools measured with charcoal samplers and thirty-three Pennsylvania schools measured using a working level grab sample. This also left 110 schools in the Phase I national dataset which were measured with EPA charcoal canisters. Further culling was done for the Monte Carlo analysis below.

MONTE CARLO ANALYSIS

Monte Carlo analysis is a technique that allows analysis of data and distributions which are not regular or which are not easily manipulated using theoretical techniques(5). At this point it is important to recognize that the processes which determine the radon concentration in a school room are, for the most part, not random. Factors which determine the radon level include the radon concentration in the soil gas, the ease with which radon can move into the room, and the air pressure that drives the radon. Because the dominant factors governing the radon concentration are not random, there is no good reason to expect that the radon concentrations will exactly fit any of the commonly used statistical distributions. The observed fit to the lognormal distribution allows the data to be characterized using the geometric mean and geometric standard deviation, but does not allow an exact analysis of the real-world situation. In this case, Monte Carlo techniques allowed assessment of the performance of the proposed radon analysis method using real radon distributions rather than an idealized model.

The Monte Carlo simulation discussed below was restricted to schools where more than fifty rooms were sampled. This was done to improve the validity of the results, and because the utilization of the method proposed here will most likely occur where there are large buildings to measure. This selection of data also removed the schools from the dataset where all rooms in

the school were not sampled. This selection of schools resulted in a Monte Carlo analysis of twenty-nine Virginia schools measured with charcoal and four Pennsylvania schools measured for grab working levels. No schools in the Pennsylvania dataset had 50 rooms measured with charcoal or alpha track detectors. Because the Pennsylvania schools with all rooms measured were selected because of high working level measurements, this allowed examination of schools with very high radon concentrations as well as those with only moderate levels.

The selected schools had radon measurements in at least 50 rooms. From these populations, samples of ten rooms each were selected at random without replacement (no room could be selected twice in the same sample). One hundred of these random samples were generated for each school. This is as if the school had actually been sampled 100 times, each time with a different selection of rooms.

For each sample, the mean and standard deviation of the logarithms of the radon concentrations were calculated. For each sample, the mean was added to the standard deviation multiplied by 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0. This is in accord with the form of the test described above, and the multipliers are the values of K to be tested. The antilog of the result was taken for each sample and compared to 4 pCi/l or .02 WL. As the number of standard deviations increases, there is a greater probability that a result above 4 will be calculated.

Since there are 100 different samples for each value of K, the number of times the result is above 4 pCi/l or .02 WL represents the probability, p, (in percent) of a predicted maximum in excess of the selected limit at that school (a "hit"). This result is specific for that value of K. This analysis utilizes the real observed radon distribution in the school, and the result varies from school to school. For schools with no actual concentrations above 4 pCi/l or .02 WL, the number of "hits" represents the probability of a false positive at that school. For schools with measured rooms above 4 pCi/l or .02 WL, the complement of the probability of detection (1-p) represents the probability of a false negative. This data is presented in graphic form for a number of schools is in figures 6 through 8.

Figure 6 (school 4151) is typical of a school with no rooms above 4 pCi/l, but selected to have at least one room above 2.7 pCi/l. Because this school had no rooms above 4 pCi/l, the chart shows the probability of a false positive. Note that for K = 1.5 and below, none of the 100 trials resulted in a predicted maximum greater than 4 pCi/l. For K = 2.5 there were 34 hits, giving a 34% probability of a false positive for this school for this value of K. As K is increased to 3.0, there is a 67% probability of a false positive. Several similar schools yielded similar results. This suggests that K be chosen below 3.0 if the false positive rate is to be kept below 50% for schools with the highest room just under 4 pCi/l.

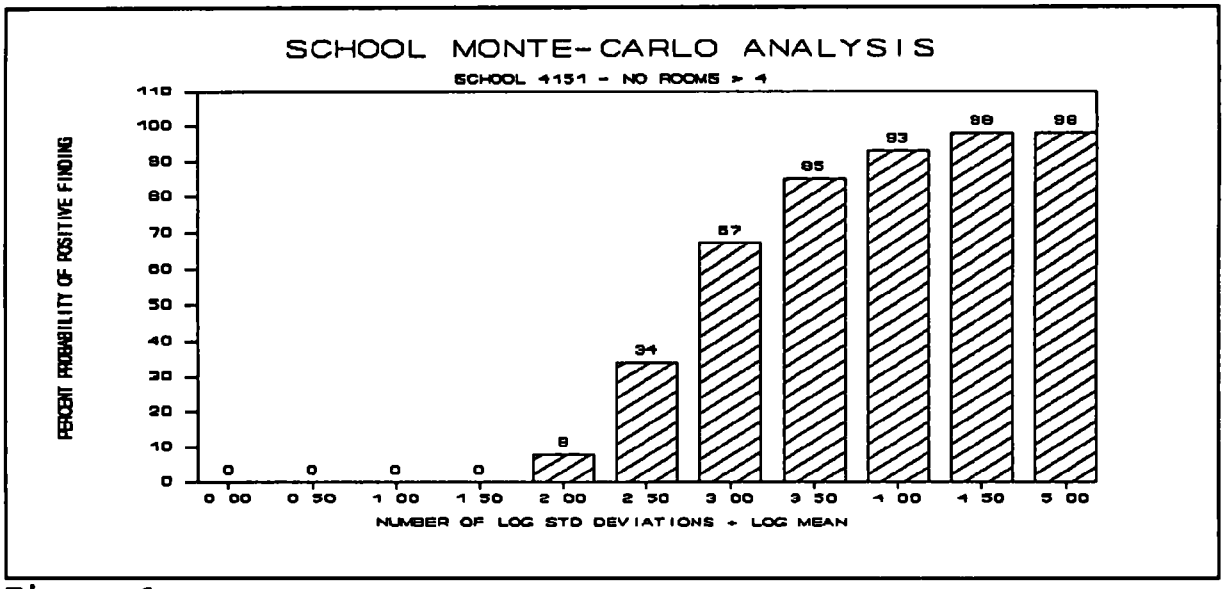

Figure 6

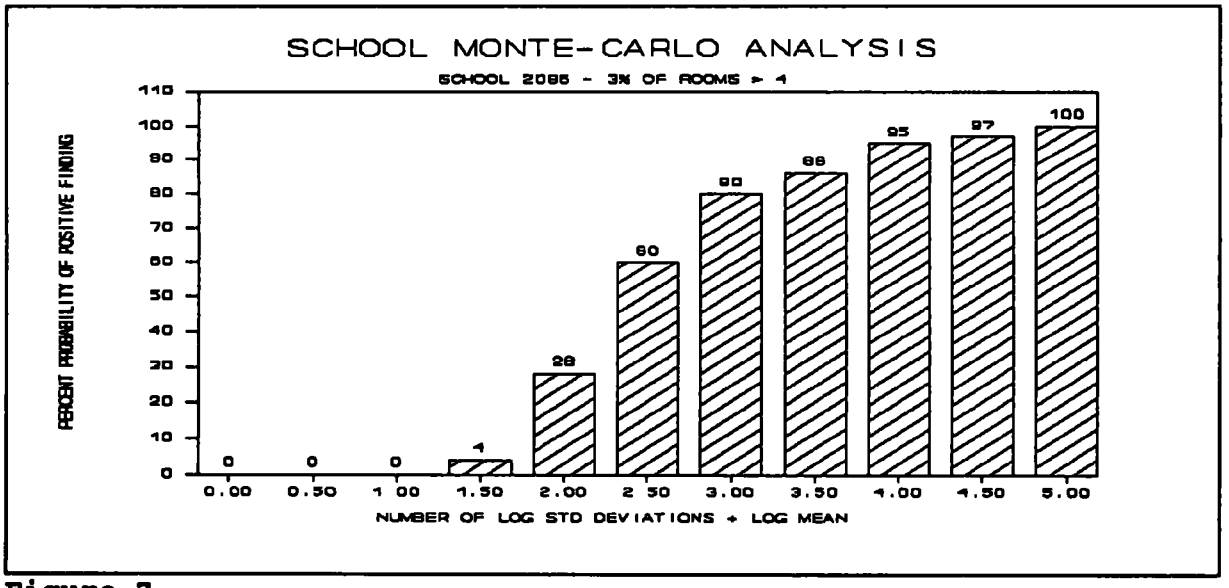

Figure 7

Figure 7 (school 2086) is typical of a school with only a few rooms slightly above 4 pCi/l. Only 3% if the rooms in this school are above 4 pCi/l. Because this school actually has rooms above the critical radon concentration, the chart shows the probability of correctly classifying the school. Subtracting these probabilities from one yields the probability of a false negative. In this case, a K of 2.0 gave a probability of detection of 28%, or a probability of a false negative of 62%. For K = 2.5 the probability of a false negative is 40%. For K = 3.0 it is 20%. Several similar schools yielded similar results. This suggests K be selected above 2.0 if marginal cases like this

are to be detected with a reasonable degree of certainty. Whether 40% probability of a false negative is acceptable in this case is a policy decision beyond the scope of this paper. The highest radon measured in this school was 5.4 pCi/l.

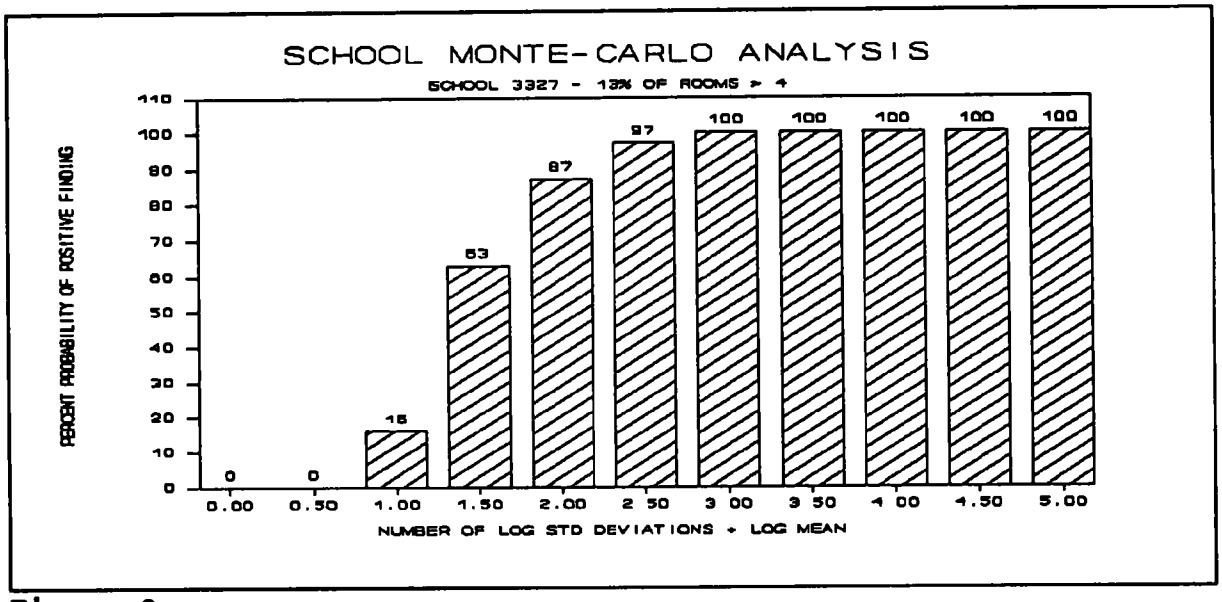

Figure 8

Figure 8 (school 3327) is clearly elevated in radon with 13% of rooms above 4 pCi/l. The highest radon concentration is 6.9 pCi/l. In this case, K = 2.5 gives a 97% probability of detecting this problem. There was another similar school which yielded similar results. This suggests the choice of about 2.5 for K yields a good probability of detecting schools with similar radon concentrations. Several Pennsylvania schools with much higher radon concentrations were included in the analysis. For these schools, the probability of detection is virtually 100% for K = 2.5.

There were four schools in the dataset which gave misleading results. One school with no rooms above 4 pCi/l yielded a probability of a false positive of 93% for K = 2.5. Decreasing K below 2.0 made only a slight improvement. This problem appears to be due to a wide spread in radon concentrations which gave a large standard deviation. The maximum radon was 3.7 pCi/l. It is possible that measurement at a different time would result in a room above 4 pCi/l. Three schools with 6%, 2% and 2.4% rooms above 4 pCi/l yielded probabilities of a false negative of 53%, 82% and 69% for K = 2.5. For these three schools, increasing K above 3 did not result in a great improvement. This appeared to be due to a large number of rooms with a similar radon concentration which yielded a small standard deviation. In each case there was a room which did not appear to fit the distribution. For all four of these schools, increasing the sampling rate to 25% of rooms with a minimum of 25 did not yield any improvement. None of these rooms exceeded 10 pCi/l. It is

the opinion of the authors that these rooms could not be detected except by measuring them. No system based on the distribution of the other rooms will detect them. Preselection of rooms based on high potential for radon entry gives the best chance of finding these rooms short of measuring every room, but depends heavily on the ability to identify such rooms based on known physical features. It was not possible to examine the effect of preselection in this study because the physical characteristics of the rooms which would allow preselection were not reported in the data used.

RESULTS

Examining a number of schools allows the pattern of false negatives and false positives to be determined at each multiplier of the standard deviation. If acceptable levels of error can be chosen, then a constant can be selected to yield that level of error. Figures 9, 10, and 11 are a summary of all schools analyzed with the Monte Carlo method.

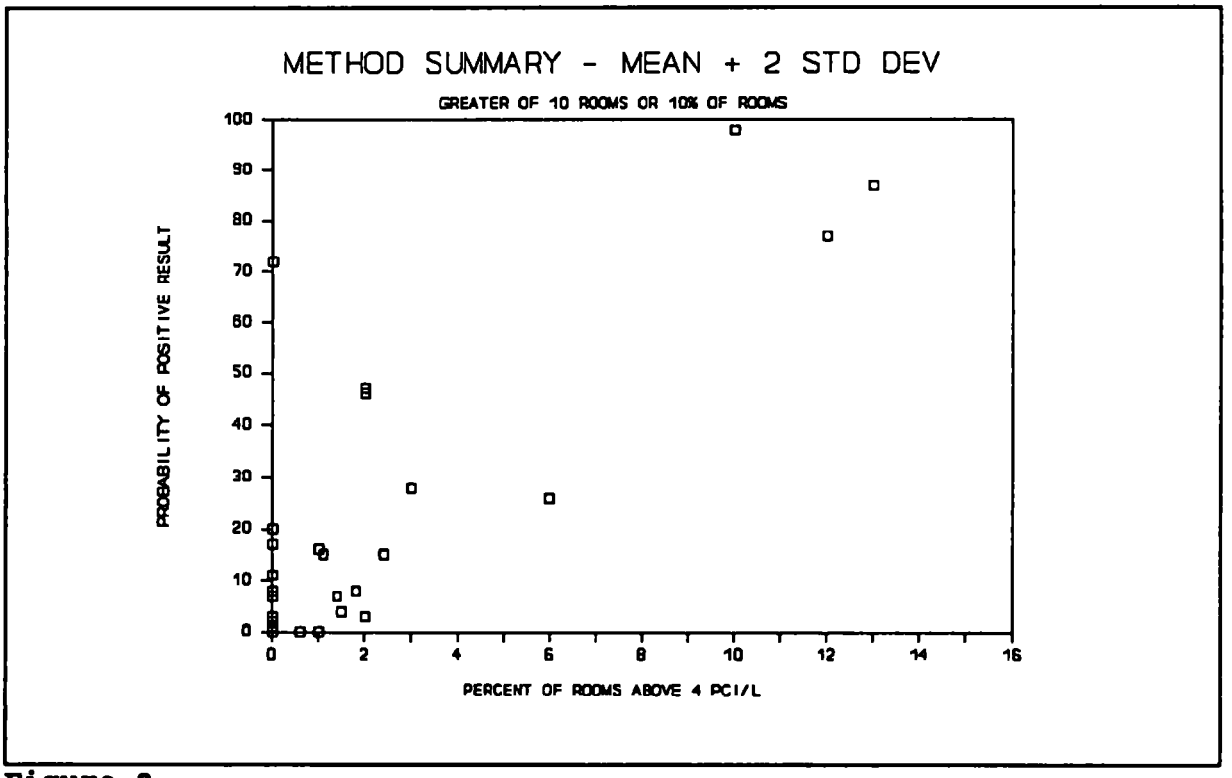

Figure 9

Figure 9 shows the performance of the method with K = 2.0. Each data point represents an individual school. The abscissa is the percentage of rooms above 4 pCi/l actually measured in the school. For the purpose of this analysis these radon concentrations are taken as truth, though in fact there are errors associated with the measurement methods and due to temporal variations. The ordinate is the probability of a "hit"

with K = 2.0. For schools on the Y axis, there were no rooms above 4 pCi/l, so the Y value is the probability of a false positive. For all other schools, there were rooms above 4, so the Y value represents the probability of correctly classifying the school. (The point at 0,72 is one of the exceptions mentioned above.)

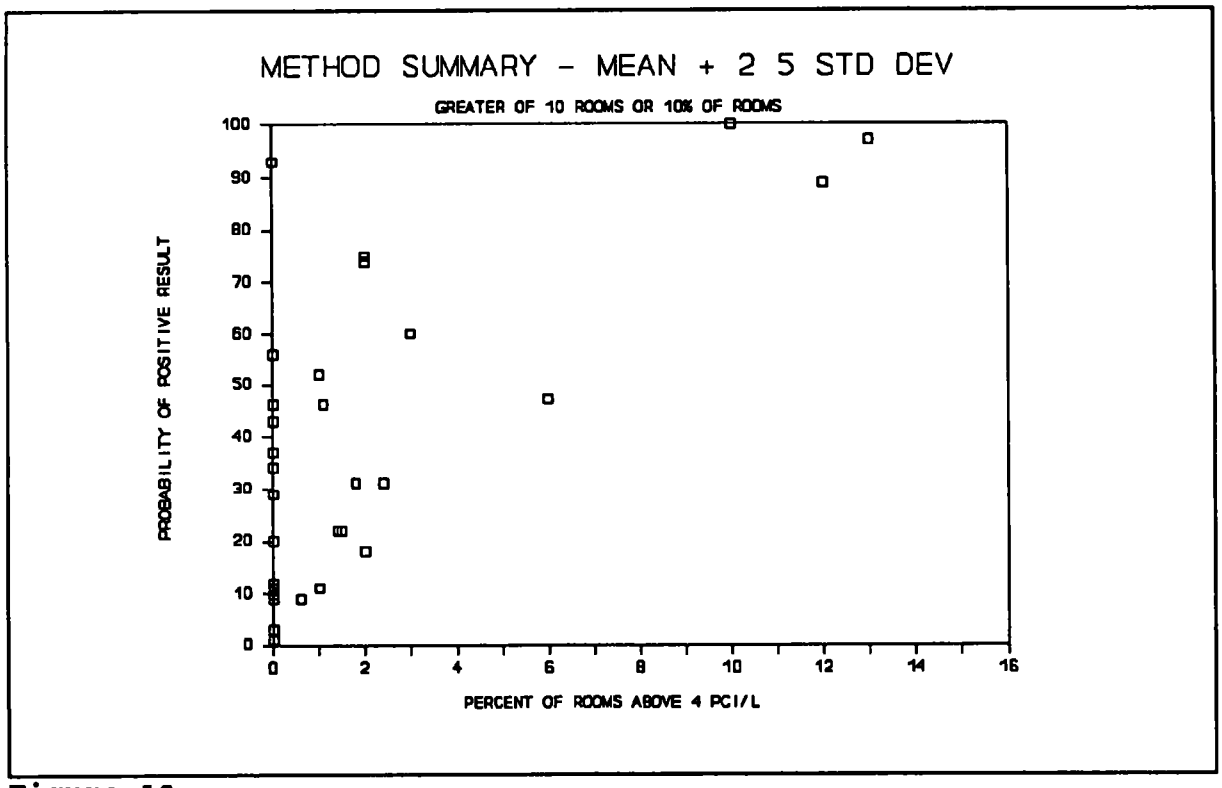

Figure 10

Figure 10 shows the results for K = 2.5. Note the increase in the number of false positives and the increase in confidence in detecting schools with elevated radon. The school at 6,47 is one of the exceptions discussed above. Except for this one school, there is a high confidence in detecting schools with more than 4% of the rooms elevated.

Figure 11 shows the results for K = 3.0. Note the still higher occurrence of false positives, and the further increase in confidence in detecting elevated rooms. The school at 6,50 is the same exceptional school. The probability of false positives becomes high enough to be cause for concern at this value of K, but it must be kept in mind that the lowest school included had radon above 2.7 pCi/l in at least one room. The schools with very low radon have all been excluded from the dataset. Inclusion of these schools would yield a smaller proportion of false positives.

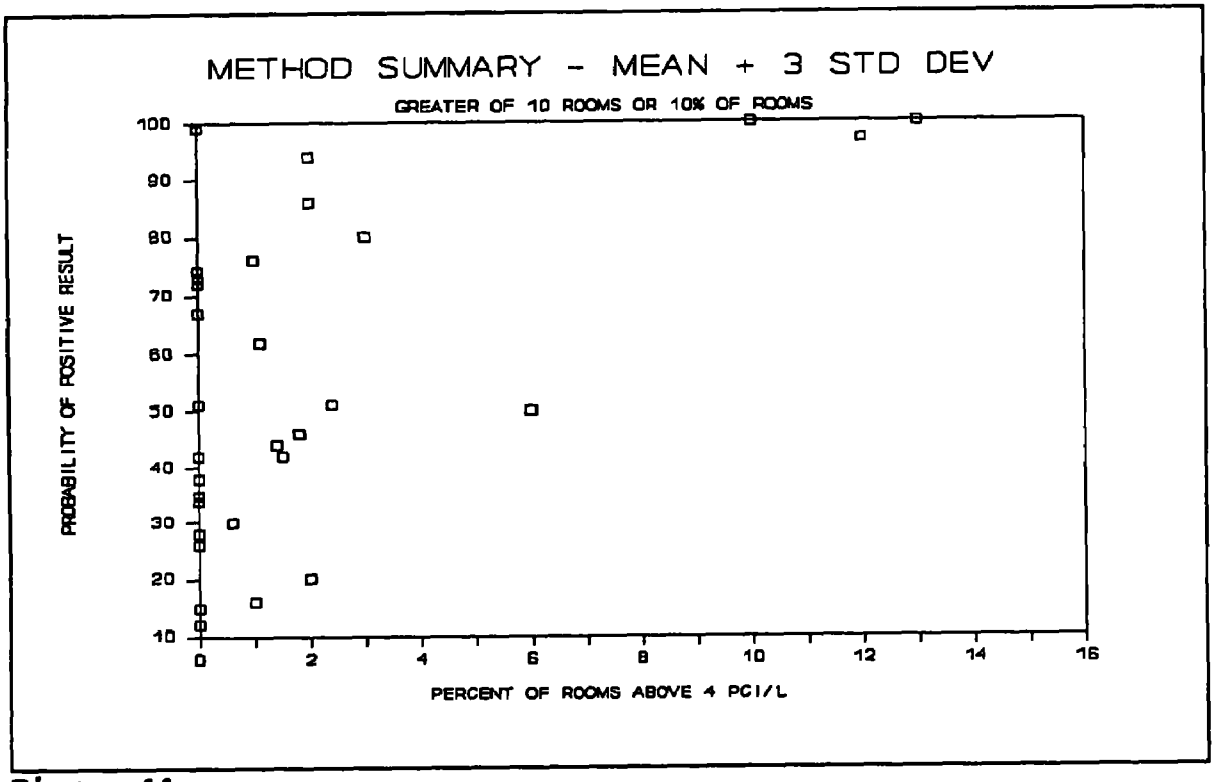

Figure 11

APPLICATION OF THE METHOD

The method might be applied as follows:

1. Choose rooms with high potential for high radon concentration and measure them. This step is optional but very desirable. It will identify obvious problems but will not identify rooms which are "high" in radon for hidden causes.

2. Select a random sample from the remaining rooms of the school. Measure ten percent of the rooms or ten, whichever is greater. Ten percent was chosen because it would result in a substantial savings over complete testing. The minimum of ten rooms avoids very small samples. Choices other than ten percent or ten samples are possible but have not been investigated here to quantify the uncertainties.

3. Measure the radon in the selected rooms. Examine the radon results for unacceptable concentrations which clearly indicate a problem. If a radon problem is found in this way there is no need for the statistical analysis below.

4. Calculate the logarithm (natural or base 10) of each concentration in the random sample. Do not include the rooms selected for high radon potential. Calculate the mean and standard deviation of the log radon concentrations of this

sample. Add "K" standard deviations to the mean. Calculate the antilog of this value. This is the expected radon concentration of the highest room in the population from which the sample was drawn. The choice of "K", the number of standard deviations, determines the sensitivity if the test. K = 2.0 yields fewer false positives at the risk of greater chance of a false negative. K = 3.0 yields greater sensitivity at the expense of more false positives. A value of 2.5 for K seemed to give a good balance, but choice of K should be made based on the error probabilities which are acceptable to the decision-maker.

DISCUSSION

It can be seen from the results above that partial sampling does not give one hundred percent certainty of identifying schools with rooms above 4 pCi/l. Such a result is to be expected. Even when every room is sampled, the errors inherent in measurements and the variability of radon in time prevent positive determination in marginal cases. When measurements are made, uncertainties cannot be avoided. The method investigated here can identify most schools with rooms above 4 pCi/l with partial sampling. The errors of commission and omission are quantified here and are available for use in deciding what choice of rooms to be sampled is appropriate. It is the task of school administrators and policy-makers to decide what constitutes an acceptable uncertainties. The uncertainties associated with this method are similar in magnitude to the uncertainties in short-term measurements.

The uncertainties associated with application of the method can be reduced by preselecting rooms with a potential for high radon concentrations. In this case, the rooms not preselected could be sampled and analyzed using this technique. Since the EPA guidance allows monitoring of only the high radon potential rooms as an acceptable but less preferred option, use of this method on the remaining rooms would be expected to yield an improved result and represents a middle ground. Its use is not precluded in the guidance nor is it endorsed by EPA. It is also possible that school districts may not have the funds to measure all rooms in a number of large schools at the same time. Using the method outlined here, it is possible to conduct partial sampling on all schools with the object of prioritizing the more complete measurements. Schools with suspected problems might be measured first and others would be deferred until funds are available for measuring every room. Partial sampling can identify schools at which we suspect the presence of rooms above 4 pCi/l, but the only way to identify specific rooms is to test them individually.

The choice of 4 pCi/l was made within the context of EPA guidance at the time. The method can be applied equally well for a cut point at another radon concentration, or expressed in another unit. Note that in this case the method did not need to be changed to accommodate a 4 pCi/l limit and a .02 WL limit.

To the extent that schools represent other large buildings, this analysis may be transferable. There would have to be some investigation of the proper choice of K, and the tolerable errors may be somewhat different.

ACKNOWLEDGEMENTS

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COMMERCIAL MITIGATION TECHNIQUES USED IN REMEDIATING A 2200 pCi/L PUBLIC BUILDING

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ABSTRACT

In March of 1989 EPA and Pa. DER officials were amazed to discover a school in Pennsylvania with levels in its library of 2200 pCi/L. The library was a 30 year old, three story slab on-grade structure more like a commercial building than a typical school structure. It had three separate and complex HVAC systems. Initial diagnostics indicated radon levels under the slab at over 80,000 pCi/L. Further investigations revealed major entry routes and a HVAC system terribly out of balance.

Remediation consisted of installing a complex sub-slab depressurization system with an exterior commercical fan unit, major entry route sealing, and working closely with a mechanical contractor to bring the HVAC systems back into balance. Initial post remediation testing showed a 99% drop in radon levels. Refinements to the system are still in progress.

As the EPA and various states begin urging the testing of all schools nationwide; and, as laws are passed mandating the testing of commercial buildings, facility directors will ultimately have to grapple with radon remediation in complex buildings. Unlike residential remediation where mitigation techniques are becoming standardized, little work has been done in schools with complex HVAC systems or in commercial buildings with hundreds of thousands of square feet of office space. In dealing with existing commercial buildings or with commercial buildings under construction, new mitigation techniques are still evolving, as is the retrofitting of residential techniques for commercial applications. The following presentation is the result of a recent school mitigation in Pennsylvania in which this building had the highest radon levels found to date in a school or commercial building.

In March of 1988, a student attending Westminster Theological Seminary in Philadelphia, Pennsylvania placed a charcoal canister on his desk on the ground floor of the school's library. To his amazement, the levels came back at over 2,000 pCi/L. He alerted school officials who conducted theri own test with similar results. School officials immediately contacted the Pennsylvania Department of Environmental Resources who in turn contacted the EPA. Very quickly, EPA officials from the regional office, Washington and the research division in North Carolina converged on the scene to perform diagnostics and confirmatory testing using an AB-5 Pylon Radon Monitor. Their testing showed levels over 2200 pCi/L. Gas samples from under the slab, peaked out at over 80,000 pCi/L. Students were evacuated from the ground floor of the building and as word of the problem leaked, newspaper and T.V. crews arrived at the school. The story hit the nightly news and was in every local paper the next day.

THE BUILDING

The library is a three (3) story 30,000 square feet slab on grade building constructed about 30 years ago. The first floor is partially built into a bank so entry is on both the first and second floors, most of the building is open as is typical of libraries. Each floor has its own HVAC system. The HVAC unit for the first floor is on the first floor while units for the second and third floors are located in a penthouse on the roof. There is a large exhaust fan in the penthouse which is ducted to all of the bathrooms for a bathroom exhaust. This fan is on a timer with a two (2) hour on/off cycle.

DIAGNOSTIC TESTING

While residential testing has on occassion revealed radon levels in the 2,000 - 3,000 pCi/L range, commercial buildings were thought to pose less of a problem. Because of the large expanse of the building area, the complexities of the buildings HVAC

systems, and the problem of finding and sealing radon entry routes, this mitigation, as with other commercial buildings, required more building investigation, more diagnostic testing and, consequently more sophisticated solutions then any residential dwelling.

While EPA testing data showed ambient first floor radon levels in the library fluctuating between 1500-2200 pCi/L, second floor measurements were about 100 pCi/L. Sub-slab measurements of 80,000 pCi/L indicated we were dealing with an extremely hot slab. Numerous floor cracks were observed as was a large expansion pour joint in the first floor storage room. When a section of the rubberoid baseboard was removed a 3/4" separation between the wall and expansion joint was observed. Communication testing[1] revealed fair to marginal (.oo2" H_2O) between the main storage and mechanical room, meaning we had either little aggregate under the slab or a very strong negative pressure. Building plans, while very detailed, nowhere indicated the amount nor the size of aggregate under the slab. Drilling at the communication sites suggested 4" - 6" of coarse aggregate base. Micro-roentgen gamma readings inside and outside the building while elevated, did not indicate any unusual source.

The HVAC system was of considerable concern because the air handling units were way out of balance with no fresh air coming into the building. Over a 30 year period there was never a maintainance contract on the system but instead, whenever there was a problem, a different mechanical contractor was hired. The problem was obvious: a strong source under the slab, numerous entry routes and a HVAC system totally out of balance exerting a negative pressure on the building.

REMEDIATION PLAN

Any remediation plan had to take into account a major sealing effort, a sub-slab depressurization system (SSD) to remove the high radon concentrations under the slab, and a balanced HVAC system.

To achieve suitable depressurization under the slab, all wall/floor joints in the lower level had to be sealed, as well as any floor cracks and entry routes around electrical conduits, etc. on the first floor. All exposed floor cracks were ground out and filled with a flowable urethane. All 4" rubberoid baseboards were also removed and the wall/slab expansion joint filled with a flowable urethane, as well. Great care was taken to seal as many entry routes as possible to improve the operation of the depressurization system as well as limit the influx of the gas.

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[1]Communication Tests - Communication tests are used to determine the ease or difficulty with which gas can move through the soil, aggregate under the slab or within a cavity such as a block wall. Typically two holes are drilled 20' apart and suction applied to one hole while micromanometer measurements are made at the other.

The principal of a sub-slab depressurization system (SSD) is to create enough negative pressure under the slab to pull radon out before the negative pressure of the building can pull the gas into the structure. The keys to this system functioning properly are 1) an aggregate base that allows for the establishment of an adequate pressure field and 2) a fan that will have sufficient CFM to draw the gas from all sub-slab areas, up three stories and out of the building.

The depressurization system designed for the building had four suction points. The vertical piping from these holes was 4" PVC manifolded into 6" PVC horizontal pipe located along the first floor ceiling. The 6" PVC piping was then routed to a 4' x 6' pipe chase behind the elevator shaft, and then up to the roof penthouse. Before a fan was chosen, the 4" holes were cut in the slab to determine the type of thickness of the aggregate. The building had 6" of 1½" crushed stone which was a plus for the SSD. With this information, a wall mounted fan (Penn Ventilator WAQ-24L-800 CFM/1.00: S.P.) was installed on the north wall of the penthouse. By using a wall mounted unit, the EDPM roofing did not have to be penetrated and its guarantee was not breached.

The HVAC system, due for scheduled repairs, was only partially corrected. The correction involved opening the fresh air intakes and rough balancing the system by a new mechanical contractor. Fine tuning of the system is still to be accomplished.

POST REMEDIATION TESTING

Installation of the system took 3 men/3 days. Much of this time was spent answering questions of media personnel. Once the system was operational we immediately retested all areas of the building and found the first floor levels had dropped from 2200 to 10 pCi/L and the second floor from 100+ to 5 pCi/L. Subsequent diagnostic measurements revealed good communication with the under slab and the ground floor ambient air with pressure differntial ranging from 4-28 pascals. Static pressure measurements between the interior riser pipes ranged from 50-83 pascals with 325 pascals at the fan. Fine tuning of the HVAC system should drop these still slightly elevated levels below the EPA guideline.

IN CLOSING

The remediation techniques used in this mitigation were designed and based on detailed information supplied from sophisticated diagnostic measurements. While the sealing and SSD systems were somewhat similar to residential remediation techniques the HVAC system was the curve ball. As more commercial buildings and schools with complex HVAC systems are shown to have radon problems, the radon mitigator in partnership with the mechanical contractor will be required to be a detective and problem solver all in one. Commercial mitigation is surely going to be the new frontier of radon.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

EPA'S PROTOCOL DEVELOPMENT STUDY FOR RADON IN SCHOOLS

Anita Schmidt

U. S. Environmental Protection Agency

ABSTRACT

A year long radon measurement study is being conducted in 21 schools in 7 states geographically dispersed across the United States. These schools were selected nonrandomly from 130 schools previously screened for radon during the Winter of 1989 in the first Phase of the study. The purpose of this study is to gather seasonal radon data and compare measurement methods to update and refine EPA's measurement guidance for schools.

In Phase II of the study, initiated in June 1989, comprehensive long- and short-term measurements are being made for a year using a variety of devices. Long-term measurements are being made with alpha track detectors and electret-ion chambers. Short-term measurements, using charcoal canisters, electret-ion chambers, and continuous monitors for radon and radon progeny, are being made under different ventilation conditions. The results of these different measurement methods will be compared for their applicability in schools. The impact of school construction type and ventilation systems on radon measurement will also be evaluated.

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

RADON LEVELS IN NON-RESIDENTIAL BUILDINGS IN NEW JERSEY

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New Jersey Department of Environmental Protection

ABSTRACT

Radon testing in various structures has been conducted throughout the State of New Jersey including non-residential buildings. Non-residential buildings differ significantly in construction from private homes, therefore radon levels seen in non-residential buildings may not reflect radon levels seen in surrounding residential structures. Testing has demonstrated that radon/radon decay products can build up to unacceptable levels in non-residential as well as in residential structures. The concentration of radon was measured in over 120 non-residential buildings, including schools, hospitals, and municipal buildings in New Jersey. All structures tested had initial radon levels in excess of the USEPA's 4.0 picocuries/liter continuous exposure guideline for residential structures.

The distribution of radon levels for various non-residential structures is examined and the efficiency of remedial measures taken described. Data indicate that radon levels measured in non-residential buildings are generally lower than those found in residential structures. Correlation is seen between geographic areas and elevated radon levels.

ELECTRET ION CHAMBERS FOR RADON MEASUREMENTS IN SCHOOLS DURING OCCUPIED AND UNOCCUPIED PERIODS

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ABSTRACT

Continuous radon measurements made in some school buildings have shown large diurnal variations due to factors such as occupancy patterns, HVAC system design and operation, and weather. Since many radon screening measurements are made with relatively inexpensive detectors that integrate the daytime and nighttime exposures, the test results may not reflect the actual exposure of students and teachers during occupancy hours.

This paper discusses the results of radon measurements made in schools with electret ion chambers (EICs) and continuous radon monitors (CRMs) during both occupied and unoccupied periods. Ten school buildings in Iowa, Maryland, and North Carolina were tested in this study. The results show that radon levels in these schools during occupied and unoccupied periods may vary significantly depending on the specific building (i.e., whether the building is pressurized or depressurized during the given testing period) giving both false positives and false negatives.

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

INTRODUCTION

In April 1989, the Environmental Protection Agency (EPA) released an interim report for radon testing in schools[1]. Two types of radon screening measurement devices and two respective methods of radon testing during the winter months are recommended: (1) 2-day exposure open-faced charcoal canister exposed over a 2-day weekend with the school's mechanical system operated in the same manner as it is operated when school is in session; and (2) an alpha track detector exposed for 3 months. It is recommended that frequently used rooms on and below ground-level be tested.

As an alternative to conducting radon screening measurements in schools with charcoal canisters or alpha track detectors, radon measurements in this study were made in 10 schools using electret ion chambers (EICs). Seven of the school buildings are in Iowa, two are in Maryland, and one is in North Carolina. The measurements in the Maryland and North Carolina schools were part of an EPA research project on radon reduction methods in schools. A continuous radon monitor (CRM) was used for comparison with the EICs in the measurements conducted in the Maryland schools.

EICs were used for the radon screening measurements in this study since they provide one method of measuring radon levels during occupied and unoccupied periods without investing in an expensive CRM. Because the EIC measurements in the three states were conducted independently, they are discussed separately.

BACKGROUND ON EICs

EICs require no power and function as true integrating detectors, measuring the average concentration during the measurement period. EICs contain a permanently charged electret which collects ions formed in the chamber by radiation emitted from radon decay products. When the device is exposed, radon diffuses into the chamber through filtered openings. Ions which are generated continuously by the decay of radon and radon decay products are drawn to the surface of the electret and reduce its surface voltage. The amount of voltage reduction is directly related to the average radon concentration present during the exposure period. Both short-term (2 to 7 day) and long-term (1 to 12 month) EICs are currently marketed. The thickness of the electret affects the usable measurement period. Short-term EICs were used in this study.

The electret must be removed from the canister and the electret voltage must be measured with a special surface voltmeter both before and after exposure. The difference between the initial and final voltage is divided first by a calibration factor and then by the number of exposure days to determine the average radon concentration during the exposure period. For a 7-day exposure period using a short-term EIC, the lower level of detection is about 0.3 picocuries per liter, pCi/L (1 pCi/L = 37 becquerels per cubic meter, Bq/m^3). (2)

MEASUREMENTS IN IOWA SCHOOLS

METHODOLOGY AND RESULTS

Phase 1. EICs were used for all radon testing in the Iowa schools. Every classroom in the six building Urbandale Community School system and all the offices in the Administration building were tested for radon over two intervals: (1) from a Friday after classes to late Sunday afternoon; and (2) from late Sunday afternoon to Wednesday after classes. The EIC electret voltages were measured on-site late Sunday afternoon; the EICs were left in place and picked up Wednesday after classes and returned to the laboratory for final electret voltage reading. Testing was conducted while school was in session in December 1988.

The first step in the analysis of the Urbandale radon concentration data was to extract from the database values greater than 3.0 pCi/L. These data were sorted into two groups: (1) weekday radon concentration greater than weekend radon concentration, and (2) weekend radon concentration greater than weekday radon concentration.

Figures 1 and 2 show the values greater than 3.0 pCi/L in bar graph form. A building specificity for weekday radon concentration being greater than weekend radon concentration or the converse is apparent in both figures. A mechanism seems to function at the building level to determine the radon concentration for the respective time periods.

Phase 2

The radon concentration was measured during the occupied time and during the unoccupied time (approximately daytime and nighttime) in several of the school buildings. Buildings were selected that represented both radon concentrations greater on the weekday than on the weekend and radon concentrations greater on the weekend than the weekday. Each frequently used room of the Administration and Olmsted buildings was tested with EICs during the occupied and the unoccupied time of the 5-day workweek. Two EICs were placed side-by-side with a log sheet for recording opening and closure of the EICs. One EIC was marked "day" (occupied time) and the other EIC was marked "night" (unoccupied time). School personnel opened and closed the EICs and kept records on a log sheet indicating dates and times of openings and closures of the respective EICs. This part of Phase 2 was conducted in February and March 1989. The testing in the Administration building, replicated in March 1989, showed the pattern seen in Figure 3. The Olmstead building radon concentration data are shown in Figure 4.

Phase 3

All rooms in the Ballard School System's Kelley Elementary School were measured for radon concentration as described in Phase 2. These data are presented in Figure 5.

DISCUSSION

A total of 196 classrooms were tested in the Urbandale School System. Figure 1 shows data from 13 rooms with radon concentrations greater than 4 pCi/L during the weekdays but less than 4 pCi/L during the weekend. The weekend operation of the mechanical system was the same as during the week, and the classrooms in the schools are generally unoccupied during the weekend. The weekday testing period includes night and day (24 hour weekdays) in this plot. Students and teachers are in school during the weekdays; therefore, the weekday testing period may better represent estimated exposure to radon concentration. If the weekday testing period is more predictive of occupational exposure to radon than the weekend testing period, 16 false negatives would have been indicated by weekend testing only. Likewise, 6 false positives would have been indicated by testing on the weekend only (see Figure 2). The data in Figures 1 and 2 (16 false negatives and 6 false positives, respectively) show the uncertainty introduced when using either time period for predicting occupational exposure to radon concentration.

Figure 3 shows data from the Administration building tested during the night (unoccupied time) and day (occupied time). Four of seven rooms showed substantially greater radon concentration during the occupied time than during the unoccupied time. A replicate measurement showed a similar pattern of radon concentration response.

Figure 4 shows data from the Olmsted classroom building tested during the night (unoccupied time) and day (occupied time). Unoccupied time (night) radon concentration values were greater than the occupied time (day) radon concentration values in this school.

Figure 5 shows that five of six rooms had a greater radon concentration during the occupied time than during the unoccupied time. (The sixth room was a second floor 6th grade room that had its windows open during the day. Note that typically second floor classrooms would not be tested; however, the 6th grade science teacher wanted to test that room.) A replicate measurement of all rooms conducted in April 1989 during relatively warm weather was similar but with less exaggeration of the differences. The Kelley Elementary School has a boiler located at one end of the building with a tunnel that extends under some of the rooms. The temperature setback at the end of the day and the setup at the beginning of the day may explain why the radon concentration increases during the day (warm soil-gas laden air in the tunnel may rise into the classrooms above).

MEASUREMENTS IN MARYLAND SCHOOLS

The radon measurements in the Maryland schools were made with EICs and a CRM for comparison. One school is in Prince Georges County and the other is in Washington County. Both schools are currently being researched as part of EPA's radon mitigation research program in schools.

METHODOLOGY

The radon measurements were made in one room in each of these two schools and covered a 2-week period. A CRM collected hourly radon measurements over the entire 2-week period; one EIC was exposed during the entire 2-week period; one EIC was exposed only during the day on Monday through Friday; and finally, one EIC was exposed only during the night on Monday through Thursday. School personnel were instructed on opening and closing of the EICs and kept a log of exposure times. The measurements were made in late May 1989.

RESULTS AND DISCUSSION

The results measured in the Prince Georges County classroom are displayed in Figure 6. Note that radon levels rose sharply at night and decreased during the daytime. The actual radon exposure during the daytime was 2.1 and 2.5 pCi/L for the CRM and EIC, respectively. The nighttime exposure for both devices was 4.4 pCi/L. The average radon level for the entire 2-week period was 4.1 and 4.2 pCi/L for the CRM and EIC, respectively. These data show excellent correlation between the CRM and EIC.

Comparing the daytime (only), nighttime (only), and cumulative (total) exposures during the 2-week period indicates that a measurement device integrating radon levels over 24-hour periods would overestimate actual radon exposure (i.e., produce a false positive).

Figure 7 shows CRM and EIC data from an office in a Washington County school. The radon level measured during the daytime periods was 2.1 and 6.2 pCi/L for the CRM and EIC, respectively. The nighttime measurements for the CRM and EIC, respectively, were 2.0 and 4.1 pCi/L; and the average radon level for the entire 2-week period was 2.0 and 4.1 pCi/L for the CRM and EIC, respectively.

The daytime and nighttime comparisons for these data are less conclusive than those shown in Figure 6, since the EIC measurements range from 0.3 to 4.1 pCi/L greater than the CRM averages. In any event, had the radon measurements been collected with an integrating device over the 2-week period, a false negative would have been produced.

MEASUREMENTS IN NORTH CAROLINA SCHOOL

A school in Forsyth County that is currently part of EPA's radon mitigation research program was selected for the EIC measurements in North Carolina. The classrooms in this school are located in three pods connected to a central media area. There are eight classrooms in each pod. Initial charcoal canister measurements during the summer of 1989 with the HVAC system off showed that all of the 24 classrooms in the pod area ranged from 3.5 to 10 pCi/L. The building has a central heating, ventilating, and air-conditioning (HVAC) system and appears to operate at a very slight positive or neutral pressure relative to the outdoors.

METHODOLOGY

Four of the eight classrooms in each of the three pods were measured for 1 week. The data were collected in late October and early November 1989. One EIC was exposed for the entire week; one EIC was exposed only during the day; and finally, one EIC was exposed only during the night. School personnel were instructed on opening and closing the EICs and kept a log of exposure times.

RESULTS AND DISCUSSION

Figure 8 shows the results of the integrated, daytime, and nighttime measurements in each of the classrooms. (Note that data for 11 of the 12 rooms are presented since the data were not recorded properly in the log sheet in one of the classrooms.) The averaged data for each of the pods are presented in Figure 7. The overall averages for the classrooms are relatively close during all three measurement periods averaging 6.0, 5.4, and 5.8 pCi/L for the integrated, daytime, and nighttime periods, respectively.

Although these averages are very close, some trends can be observed in Figure 8. Looking at the daytime versus nighttime radon levels for 10 of the rooms (they are nearly the same for Room 36), the nighttime level is higher than the daytime level in 7 of the 10 rooms. The averaged data in Figure 9 also follow this trend. As mentioned above, the nighttime average was 0.4 pCi/L greater than the daytime average for all the classrooms. This is consistent with the understanding that the building is operated under a slight positive pressure. However, when radon levels build up overnight, they are not sufficiently diluted during the daytime. Inspection of the HVAC system revealed that the outdoor air controls for most of the multi-zone air handlers appeared to be operating in an economizer mode with no minimum outdoor air position.

Except for one notable excursion (daytime levels in Room 25 were about 11 pCi/L above nighttime levels), the integrated, daytime, and nighttime measurements in this school were relatively close. Based on these results, if only integrated screening measurements had been made in this school, only one false positive and no false negatives would have been produced.

CONCLUSIONS

The following conclusions are based on the EIC measurements made in 10 Iowa, Maryland, and North Carolina schools under occupied and unoccupied conditions. Their applicability to other schools will depend on the unique characteristics of each school.

(1) Although there was generally good cooperation from the school personnel in the opening and closing of the EICs and logging of times, this method is not flawless and introduces additional uncertainty into the measurements. Depending on the school, it may be better to have one person open and close all the EICs.

(2) Building-specific responses during occupied and unoccupied periods were found in most cases. Some schools had greater radon concentrations during the occupied time (day) than during the

unoccupied time (night), and the converse was true of other buildings. Consequently, radon measurements that integrate levels over a 24-hour period have the potential to produce false negatives or false positives.

(3) Operating the building for 48 hours as it is operated during school hours as recommended by EPA should most closely correlate with student exposure.

(4) Where a CRM was placed side-by-side with the EICs, the correlations were generally good (Maryland schools). However, some of the EIC measurements in Washington County were consistently higher than the CRM measurements during the same period.

Some potential advantages and disadvantages of EICs are apparent from this study and prior experience with EICs. Advantages include: (1) EICs are supposed to be an integrating detector unlike charcoal which weights the later exposures more than the earlier, and (2) EICs can be opened and closed to start and stop their integration and enabling actual exposures to be estimated. Potential disadvantages include: (1) Since EICs are calibrated based on an equilibrium of radon and progeny, their response to radon concentrations is not instantaneous (this lag is thought to be similar to that of the CRM: about 0.5 hr for equilibrium with radon and about 4 hr for that radon to reach equilibrium with progeny. (2) If the radon levels are varying significantly, the CRM might be expected to follow changes better than an EIC that is opened and closed each day and has a start-up period each day while the CRM is open all the time. (3) Can school personnel be relied upon to record the daily openings accurately enough to allow the EIC exposure average to be computed? (4) Will frequent handling affect the EIC readings (this might be expected to increase the voltage losses and lead to overestimates of radon levels)? (5) Are the changes in school radon levels so rapid when school starts in the morning and the HVAC systems are turned on that this type of measurement is invalidated (due to the decay delays in the CRMs and EICs since they depend on an equilibrium calibration)? (6) If exposure is to be estimated for occupied time, how many exposure days must be averaged to achieve enough EIC voltage drop to give an accurate estimate for radon levels around 4 pCi/L? Hopefully, these questions will be addressed in future research.

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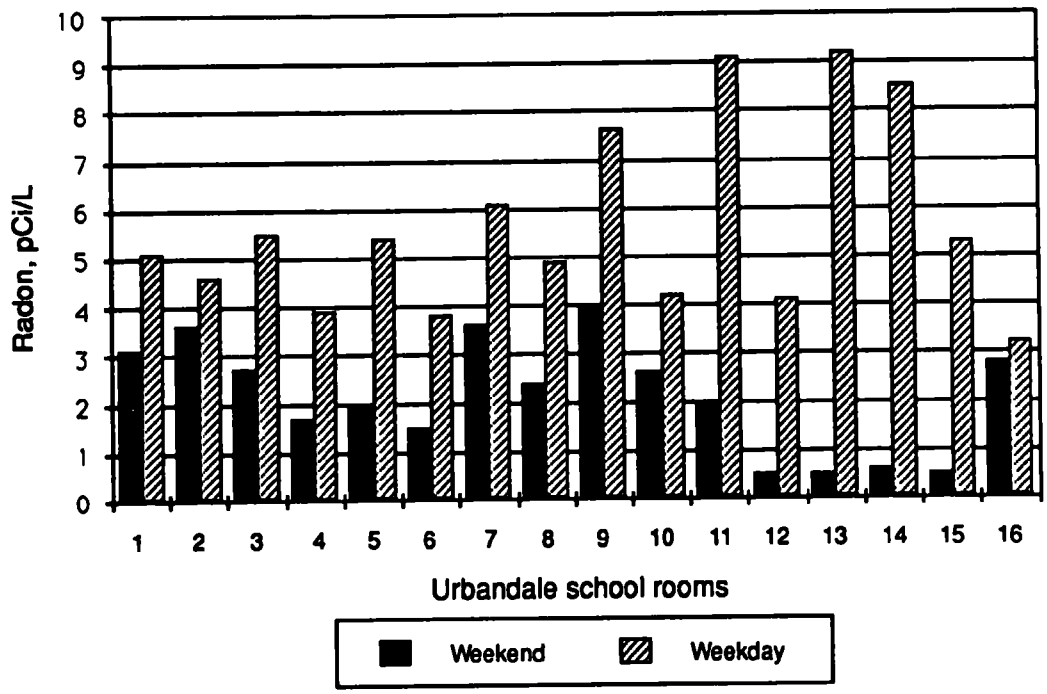
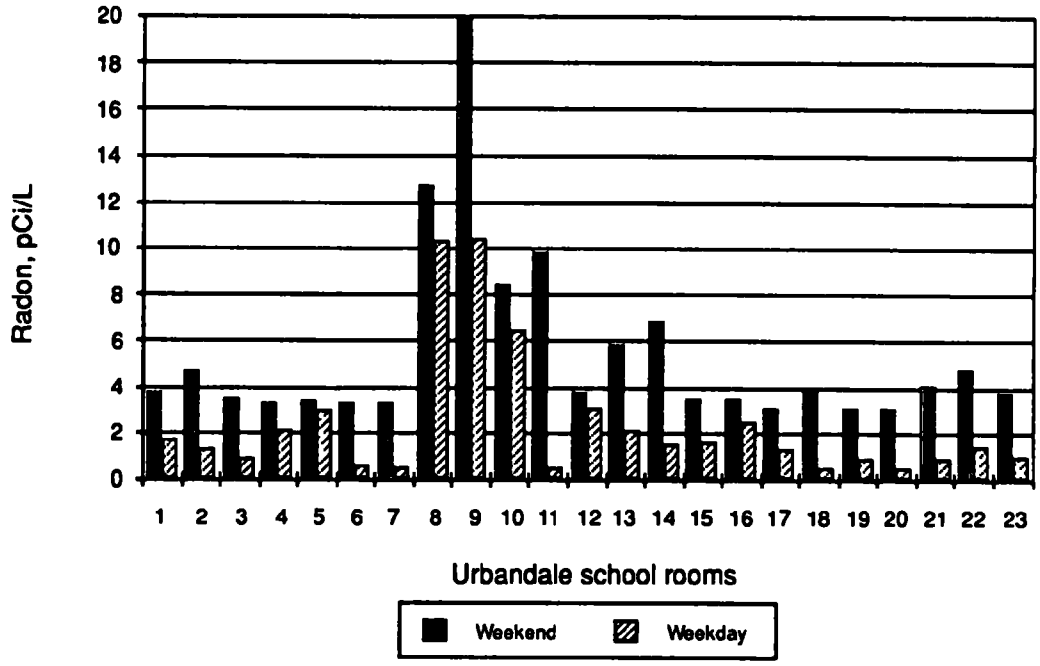
1. United States Environmental Protection Agency, Office of Radon Programs, "Radon Measurements in Schools - An Interim Report." Washington, D.C. 20460, EPA-520/1-89-010, NTIS PB89-189-419, March 1989.

2. United States Environmental Protection Agency, Office of Radiation Programs, "Indoor Radon and Radon Decay Product Measurement Protocols," Washington, DC, February 1989.



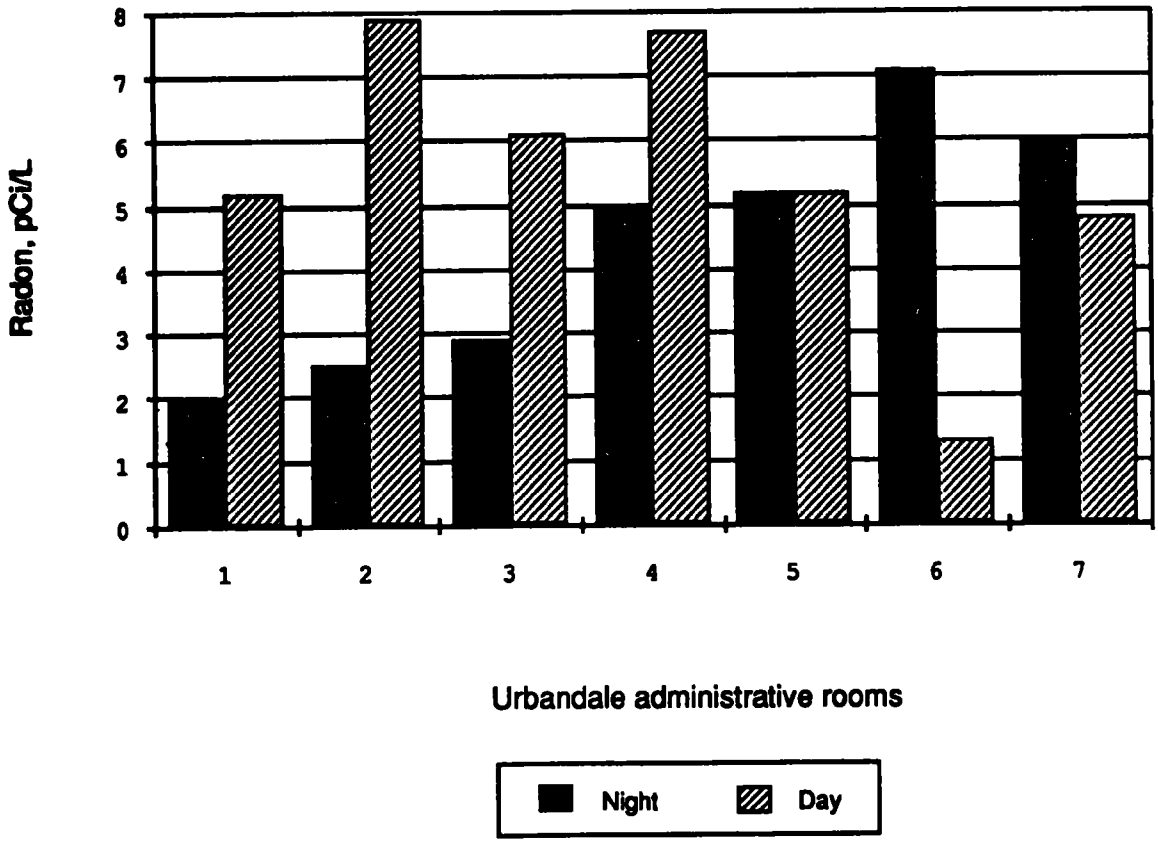
No.	Building	Room	Weekend Rn concentration pCi/L	Weekday Rn concentration pCi/L
1	Admin. Office	Account. & Pay.	3.1	5.1
2	Admin. Office	Business Man. Off.	3.6	4.6
3	Admin. Office	Dale Y.	2.7	5.5
4	Admin. Office	Lounge	1.7	3.9
5	Admin. Office	Maintenance	2.0	5 4
6	Admin. Office	Shelby Off.	1.5	3.8
7	Admin. Office	Storage Room	3.6	6 1
8	Admin. Office	Women's Bathroom	2 4	4.9
9	High School	104	4.0	7 6
10	High School	606	2.6	4 2
11	Jensen	310	2.0	9 1
12	Jensen	312	< 0.5	4.1
13	Jensen	317	< 0.5	9 2
14	Jensen	Library	0.6	8 5
15	Karen Acres	115 & 117	< 0.5	5 3
16	Rolling Green	Joyce A.	2.8	3 2

Figure 1. Rooms from buildings in the Urbandale school system with radon concentrations greater on weekdays than weekends.



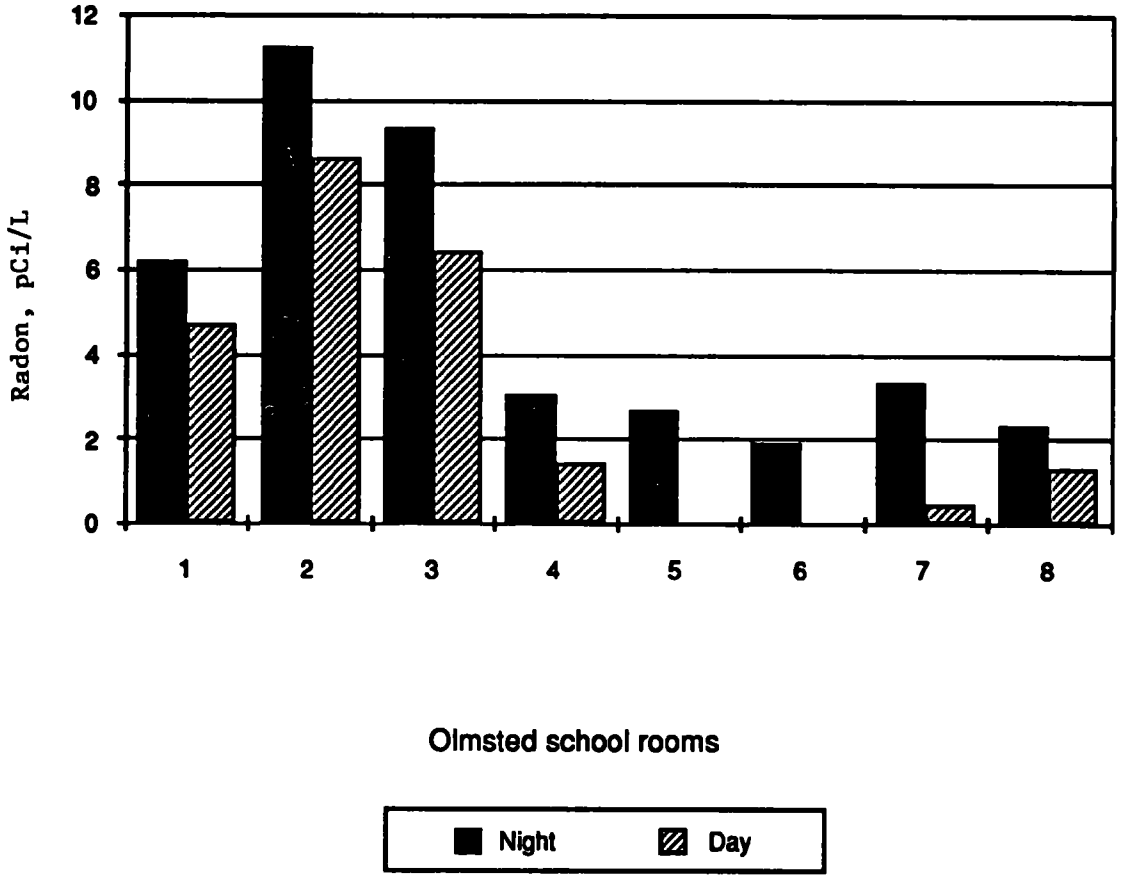
No.	Building	Room	Weekend Rn concentration pCi /L	Weekday Rn concentration pCi/L
1	High School	101	3 8	1 7
2	High School	106	4.7	1.3
3	High School	305	3.5	0 9
4	High School	602	3 3	2 1
5	High School	614	3 4	3 0
6	Middle School	Cust Break Rm	3 3	0 6
7	Middle School	Vocal Music	3 3	< 0.5
8	Olmsted	22	12 7	10 3
9	Olmsted	23	20 0	10 4
10	Olmsted	Kitchen	8 4	6 4
11	Olmsted	Lounge	9.8	< 0.5
12	Olmsted	Marion S.	3.8	3 1
13	Olmsted	Mrs K	5.8	2 1
14	Olmsted	Music	6.8	1 5
15	Rolling Green	Kitchen	3.5	1 6
16	Rolling Green	Librarian	3.5	2 5
17	Rolling Green	Lisa's Desk	3.1	1 3
18	Rolling Green	McTaggert	4 0	< 0 5
19	Rolling Green	Mrs. Ennen	3 1	0 9
20	Rolling Green	Mrs I.	3 1	< 0 5
21	Rolling Green	Mrs O.	4 1	0 9
22	Rolling Green	Mrs S.	4.8	1 4
23	Rolling Green	Music Room	3 8	1 0

Figure 2. Rooms from buildings in the Urbandale school system with radon concentrations greater on weekends than weekdays.



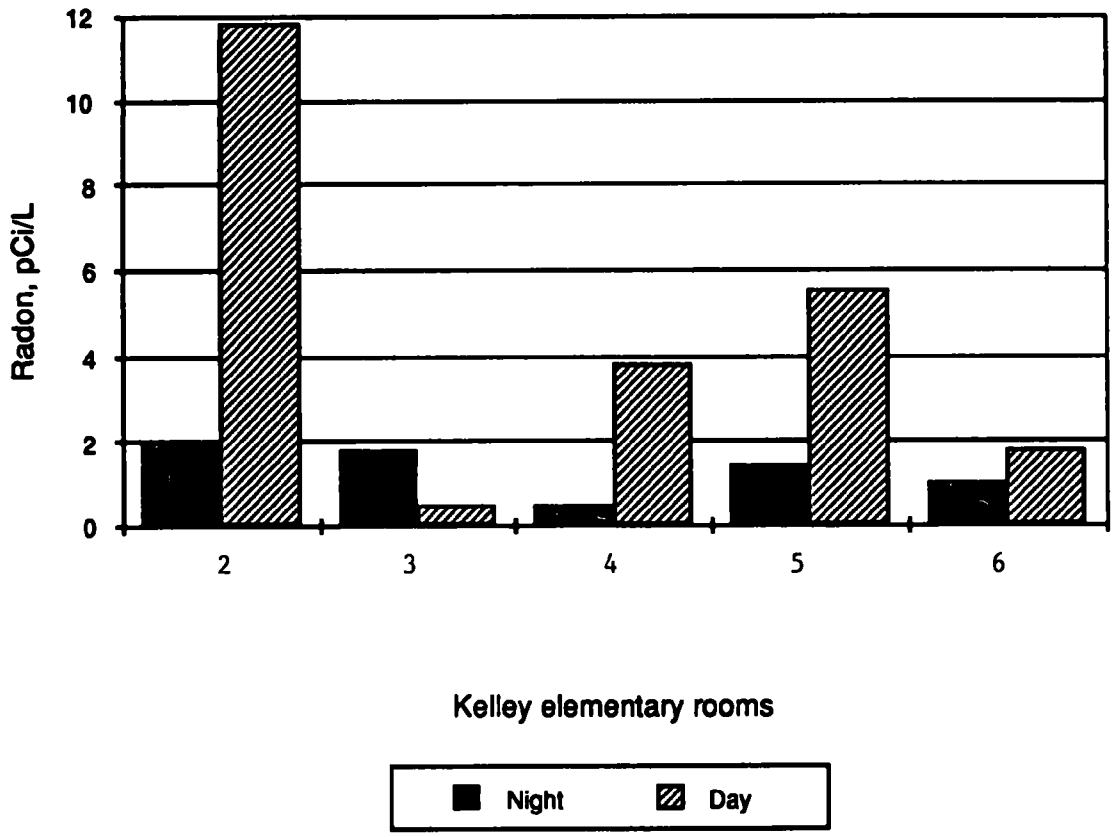
No.	Room	Nighttime Rn concentration pCi/L	Daytime Rn concentration pCi/L
1	Accounts Payable	2.0	5.2
2	Business Management Office	2.5	7.9
3	Lounge	2.9	6.1
4	Maintenance	5.0	7.7
5	Shelby's Office	5.2	5.2
6	Maintenance Office	7.1	1.3
7	Outer Maintenance Office	6.0	4.8

Figure 3. Night (unoccupied time) and day (occupied time) radon concentrations in the Urbandale school system Administration building.



No.	Room	Nighttime Rn concentration pCi/L	Daytime Rn concentration pCi/L
1	22	6.2	4.7
2	23	11.2	8.6
3	Kitchen	9.3	6.4
4	Lounge	3.0	1.4
5	Marion S.	2.7	n.a.
6	Marion S.	1.9	n.a.
7	Mrs. K.	3.3	< 0.5
8	Music	2.3	1.3

Figure 4. Night (unoccupied time) and day (occupied time) radon concentrations in the Urbandale school system's Olmsted building.



No.	Room	Nighttime Rn concentration pCi/L	Daytime Rn concentration pCi/L
1	1st Grade	2.1	3.3
2	3rd Grade	2.0	11.8
3	6th Grade	1.8	< 0.5
4	Kindergarten	< 0.5	3.8
5	Library	1.4	5.5
6	S.E. room	1.0	1.8

Figure 5. Night (unoccupied time) and day (occupied time) radon concentrations in the Ballard school system's Kelley Elementary building.

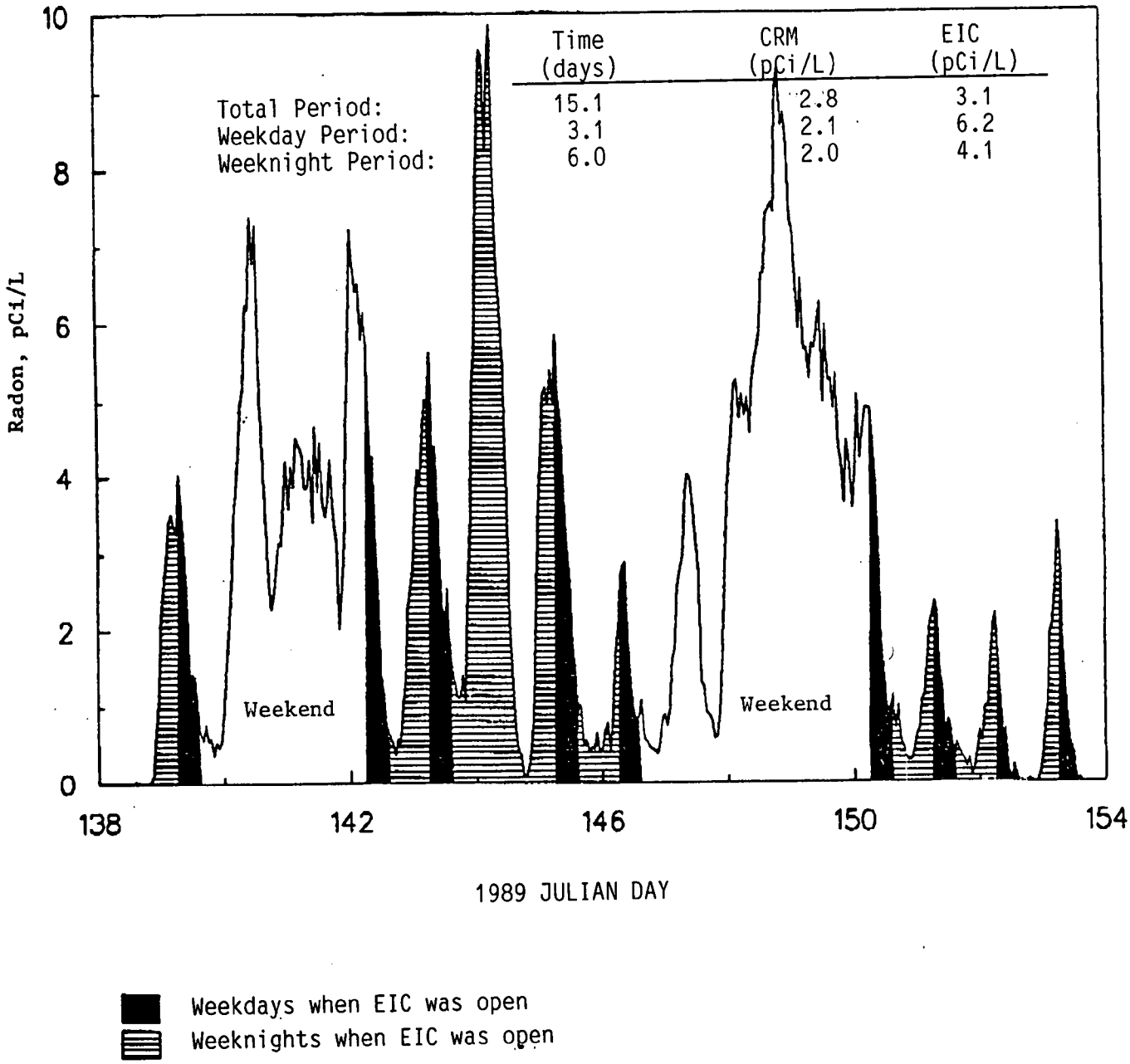
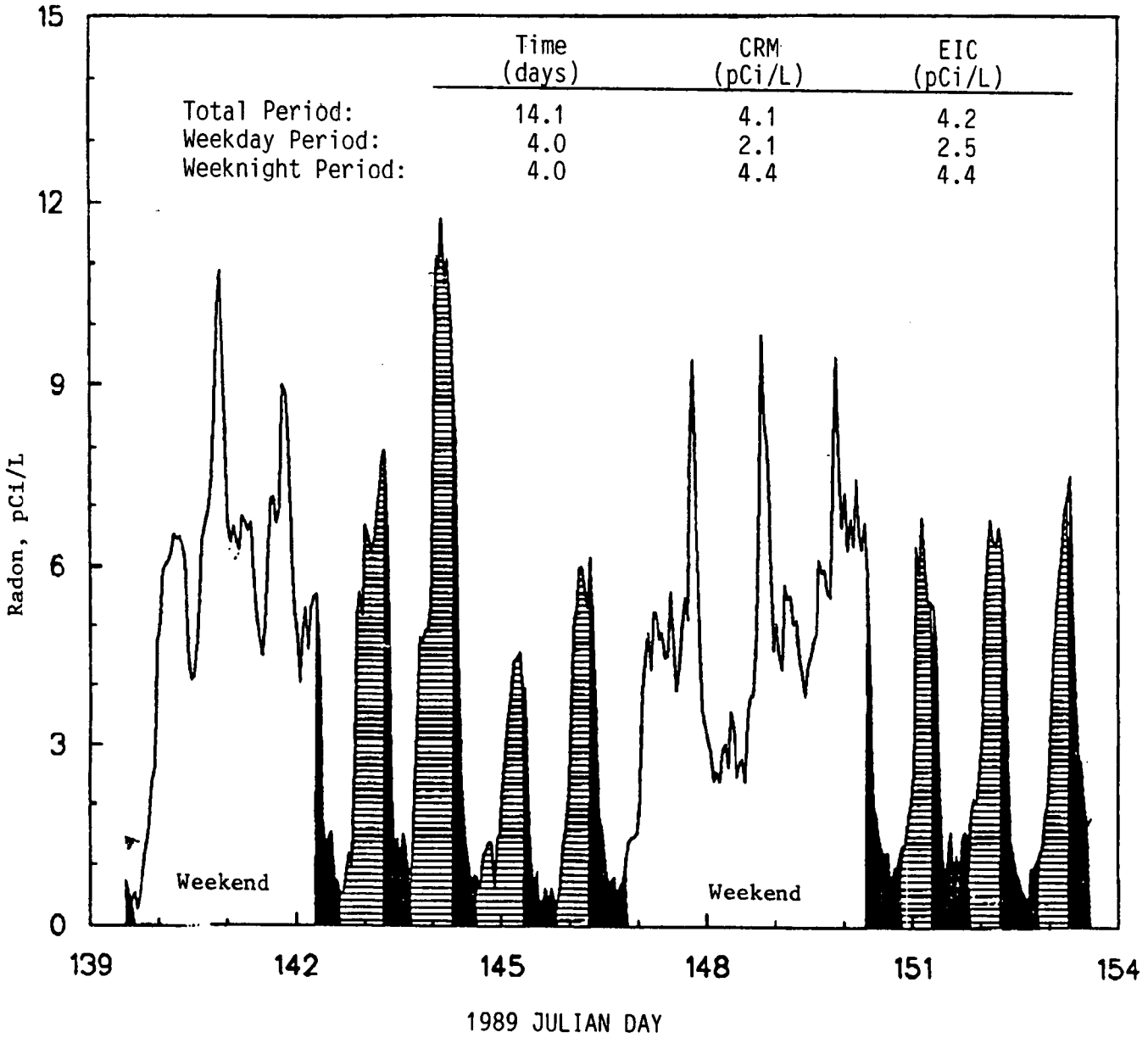


Figure 7. CRM and EIC results for Washington County school.



Weekdays when EIC was open
Weeknights when EIC was open

Figure 6. CRM and EIC results for Prince Georges County school.

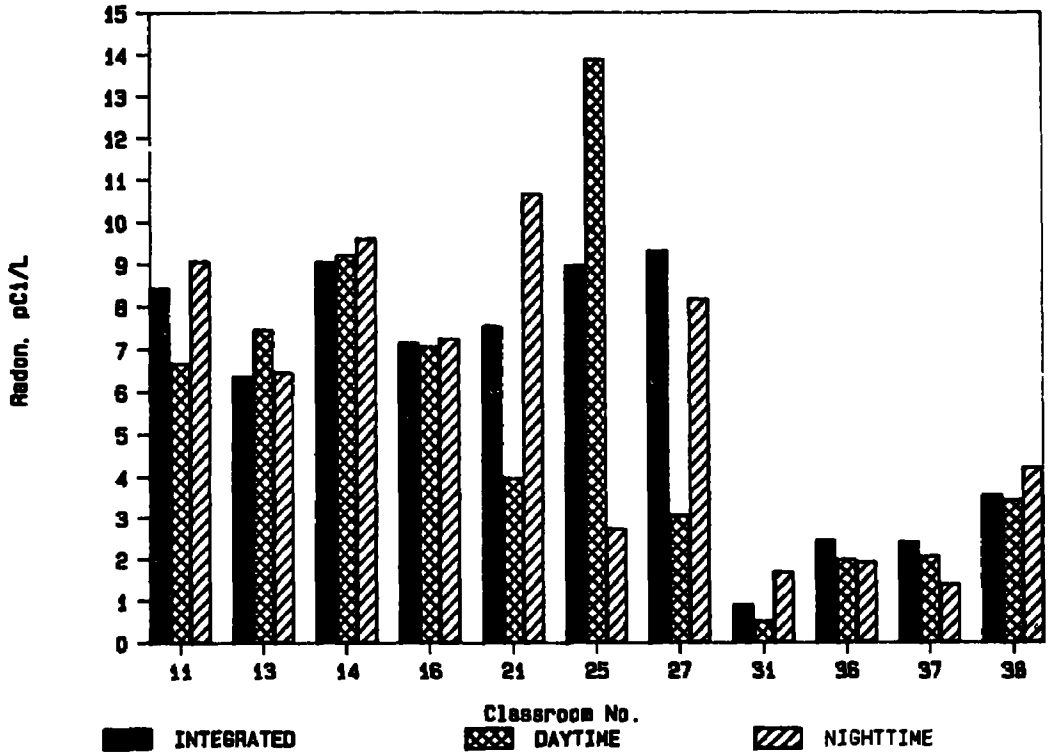


Figure 8. EIC measurements in North Carolina school under occupied and unoccupied conditions.

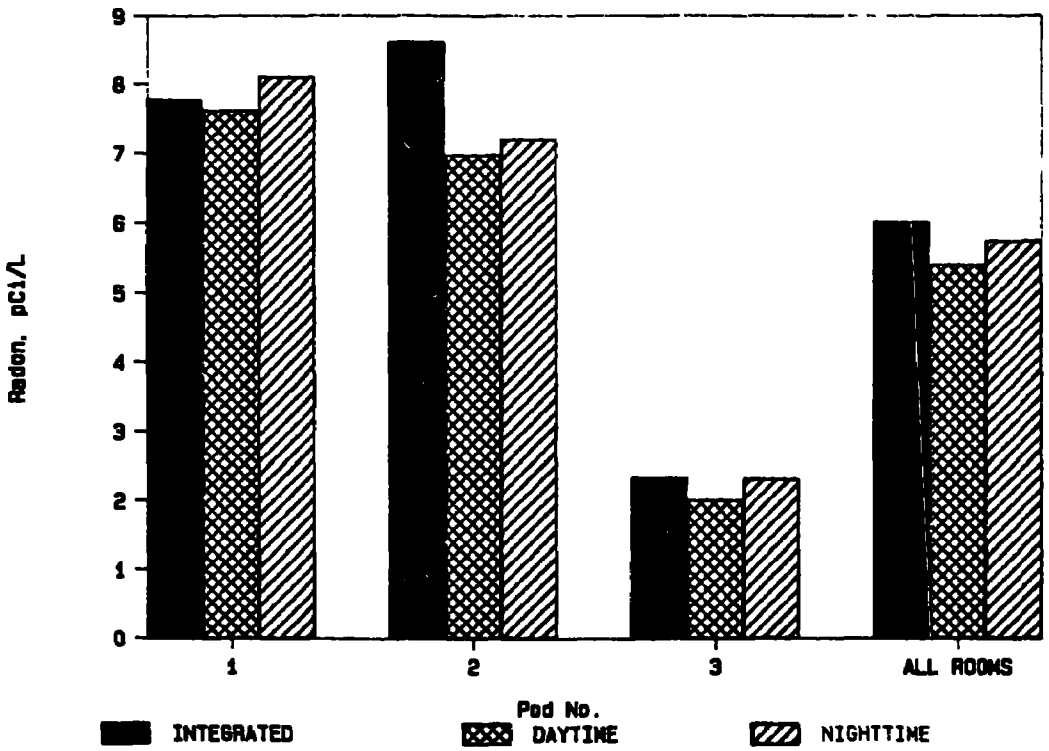


Figure 9. Summary of EIC measurements in each pod of North Carolina school.

MEASURING RADON IN THE WORKPLACE

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ABSTRACT

The Environmental Protection Agency (EPA) has issued guidance for testing for radon in homes and interim guidance for testing in schools. Information on testing for radon in the workplace is the next initiative and this paper describes the current status of this effort. The results of measurements made in several buildings in the Washington, DC area are discussed. A discussion of preliminary guidance on radon survey design that has been offered to Federal agencies is presented .

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

INTRODUCTION

The discovery of dangerous levels of radon gas in homes in the early 1980's prompted the Environmental Protection Agency (EPA) to issue guidance for testing and mitigation of this serious health threat. Since most Americans spend a majority of their time at home, EPA decided to concentrate its resources to encourage people to test their homes for radon and to take corrective action where appropriate. In 1988, EPA was able to extend its radon program to address the hazard of radon in schools. Since children may be at higher risk from exposure to radon, this initiative was the most appropriate next step from a public health standpoint. As our understanding of the risk from indoor air pollution has grown, the predominance of radon as the most serious indoor air pollutant has become obvious. It is for this reason that EPA is now preparing guidance for testing for radon in the workplace. Congress has included radon in the workplace as an area of concern. Sections 118(k) and 403(b) of the Superfund Amendments Reauthorization Act (SARA) instruct the agency to undertake testing and research in this area.

In addition, Section 309 of the Indoor Radon Abatement Act (Public Law 100-551) requires the heads of all Federal departments and agencies that own buildings to test a representative sample of those buildings for radon and report their results to EPA's Administrator. A report to Congress on these results is then due in October, 1990. Preliminary information on the design of an effective radon survey has been provided to Federal agencies to assist them in completing this task. EPA expects that the information gained from these surveys will significantly enhance the present understanding of radon behavior in large buildings.

A study was undertaken in the winter of 1989 to perform intensive measurements in several buildings in the Washington, DC metropolitan area. Permission was obtained from the General Services Administration (GSA) to use three of their buildings for this study. The buildings were chosen to represent differing ages, construction types, and sizes. This work provided confirmation of several phenomena observed in homes including diurnal cycling of radon concentrations and dependance of radon levels on the operating parameters of the ventilation system. Information on radon movement throughout upper floors of buildings was not obtained because the observed radon concentrations were too low. The three GSA buildings, all located in downtown Washington, DC, had ground floor averages below 1 picocurie per liter (pCi/L) which made detection on upper floors impossible. This study is continuing this year.

MATERIALS AND METHOD

Federal agencies were required to submit their radon survey designs to EPA by July, 1989. The surveys are limited to radon screening measurements. Although follow-up measurements and mitigation are not addressed, these components will almost certainly be undertaken when elevated concentrations of radon are reported. Most of the agencies have chosen to perform 3-month measurements using alpha track detectors placed during the winter heating season. The next most popular device is the diffusion barrier charcoal canister which may be deployed for 2 to 7 days. Electret ion chambers and continuous monitors are also being considered by some agencies. EPA's policy is that any measurement device listed in the Indoor Radon and Radon Decay Product Measurement Protocols (EPA 520/1-89-033, March 1989) is acceptable for making screening measurements except that grab sampling may not be used alone. Grab sampling can be a useful confirmatory measurement made in conjunction with a measurement from some other approved device.

As an independent initiative, EPA is investigating radon behavior in large buildings in preparation for issuing interim guidelines for measuring radon in the workplace. This effort will include a variety of building types and sizes. The phase of this project that was completed in 1989 included initial screening measurements made with 2-day open faced charcoal canisters. Continuous radon measurements were made using continuous radon gas monitors. The data collected in the 3 GSA buildings was supplemented with the results of extensive 3-month alpha track measurements made by GSA as part of its radon program begun in 1989. Other data collected included differential pressure measurements, meteorological data, and information on the layout, type, and operation of heating, ventilation, and air conditioning (HVAC) systems.

This project is continuing this season. The prospect for locating Federal buildings with elevated radon levels is improved because of the availability of the data from GSA's radon program. It is anticipated that seasonal and annual measurements will be taken as part of this study.

RESULTS AND DISCUSSION

EXPERIMENTAL DATA

Data from the GSA buildings include charcoal canister measurements and alpha track results from all 3 buildings and continuous monitoring data from one building. A summary of the ATD results is presented in Table 1.

Table 1
ATD Results in GSA Buildings

Radon Concentration (pCi/L)	Number of Readings at Each Level		
	Bldg. 1	Bldg. 2	Bldg. 3
0 - 0.5	12	50	77
0.6 - 1.0	13	26	30
1.1 - 1.5	3	14	1
1.6 - 2.0	0	2	1

The charcoal canister results in the three buildings gave readings that were for the most part in the 0 - 0.5 pCi/L range. A few readings were obtained in the 0.6 - 2 pCi/L range with the highest of these readings being located on the lowest level of the building. One reading of 3.3 pCi/l was obtained in a crawlspace under one of the buildings, confirming the generally low source potential for radon in the GSA buildings that were tested.

Continuous monitoring of radon in Building 3 exhibited a diurnal pattern of radon concentrations. During the weekdays, a rise in radon concentration was noted beginning around 6 pm. By 2 am, the radon concentration was at its maximum where it remained at this plateau or oscillated until 6 am. At 6 am on weekdays, the radon concentration dropped rapidly to under 1 pCi/L by 10 am where it remained until 6 pm. This pattern is explained by the operation of the HVAC system. The air handlers in the area under study are turned on at 6 am and shut off at 6 pm on weekdays. In spite of a slight negative pressure created by running the system, the air handlers are responsible for decreasing radon concentration because of fresh air dilution and mixing. On the weekends, when the HVAC system is not operating, the peak concentration remains relatively stable until Monday morning when the system is restarted.

FEDERAL GUIDANCE

Based on the preliminary results of this study and input from technical experts, information was distributed to Federal agencies to assist them in preparing their radon survey designs for complying with the Indoor Radon Abatement Act. It was decided to recommend that all ground-contact occupiable rooms be tested. In addition, it was suggested that a few detectors be placed on upper levels in stairwells, near elevators, and beside service shafts and ductwork. Radon is principally a soil gas problem and testing ground contact rooms should indicate the highest radon concentrations in the building. Movement of radon throughout a building should be indicated by the upper level locations that were specified. Private water supplies are also required to be tested which increases our confidence that we can identify a radon problem if one exists.

Federal agencies were advised to perform screening measurements during the winter heating season. In warm climates where there is no heating season, it is recommended that testing be done during the period of minimal outside air intake to minimize dilution flow. For colder climates, the stack effect is assumed to be the principal driving force for radon entry. The stack effect occurs during the colder months when the effect of rising warm air creates a negative pressure in the lowest levels of a building relative to the air outside the building. This negative pressure causes radon-rich soil gas to be sucked into the building. In commercial buildings, large negative pressures can also result from unbalanced HVAC systems. The assumption that winter is the time to test is being investigated as part of EPA's ongoing research efforts.

The suggested time to test is during the work week under normal building conditions. The HVAC system should be operated normally. While screening conditions are chosen to produce results higher than the annual average, there is no benefit to testing under conditions or during periods that do not reflect conditions present when the building is occupied.

In the situation where an agency decides not to test all of its buildings, EPA's recommendation is to test fewer buildings according to the above guidelines rather than to test more buildings with only a few detectors per building. While the latter option may produce a statistically valid estimate of the percentage of Federal buildings with elevated levels of radon, it cannot certify that any individual building is safe. Experience has shown that even adjacent rooms can have dramatically different radon levels.

Finally, all Federal departments and agencies were strongly advised to put in place a quality assurance program with a strong

quality control component. For radon measurements made with passive detectors, a good quality control program will include an appropriate number of duplicate and blank detectors as well as a few spiked detectors. Duplicate detectors are collocated and provide an indication of the precision of the analytical laboratory. Blank detectors serve as a check on the background of the detectors. Spiked detectors, those exposed to a known concentration of radon, provide an indication of accuracy or bias.

CONCLUSIONS

Ongoing research has tended to support assumptions about the importance of building conditions to the potential for radon entry. Research to confirm that winter testing will yield maximum values is continuing. Experience has shown us that a balanced HVAC system, particularly one that contributes to a slightly positive differential pressure in rooms in ground contact, will minimize or eliminate radon entry.

Yet to be determined is the extent of radon movement vertically within large buildings. Testing has been encouraged in stairwells, near elevators, and near service shafts. It is hoped that the extent to which radon may be a problem on upper levels of buildings can be determined from the current phase of EPA's work in this area.

Because the Congress required Federal agencies to sample a representative number of their buildings this year, EPA will have a large amount of data to assist in confirming the preliminary guidance for testing in the workplace. Interim guidelines for measuring radon in the workplace will likely be available by the end of this year.

THE SCHOOL EVALUATION PROGRAM

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ABSTRACT

A pilot program to provide classroom and field training to school facility operators was implemented by the U. S. Environmental Protection Agency's Office of Radiation Programs in 1989. This program consisted of two phases. The first phase developed and delivered a three day workshop in Nashville, Tennessee. As a result of the workshop, a second phase was initiated. The second phase investigated several school buildings with elevated indoor radon levels in the Western United States. Radon entry mechanisms were identified. Measurements to evaluate soil depressurization as a radon control method were made and HVAC systems were characterized. Measurements were made to evaluate HVAC modification as a radon control method. Building shell tightness measurements were made and information was collected to judge the suitability of potential sites for additional EPA sponsored "hands on" school training. Physical and institutional problem areas were identified.

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