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MONITORING AND EVALUATION OF RADON MITIGATION SYSTEMS OVER A TWO-YEAR PERIOD

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ABSTRACT

Fourteen single-family detached houses in the Spokane, Washington, and Coeur D'Alene, Idaho, area were tracked for two years following mitigation for elevated indoor concentrations of radon. Each house was monitored quarterly using mailed alpha-track radon detectors deployed in each zone of the structure. During the second heating season following mitigation, radon concentrations were monitored continuously for several weeks in seven of the houses, each house and mitigation system was inspected and selected measurements were performed in order to assess mitigation system performance. Occupants were also interviewed regarding their maintenance, operation, and subjective evaluation of the radon mitigation system(s). The quarterly alpha-track measurements showed an increase in radon levels in a majority of the homes during many of the follow-up measurement periods compared to concentrations measured immediately after mitigation. The greatest increases in radon concentrations occurred in 3 of the 4 houses equipped with basement pressurization systems where radon levels approached the pre-mitigation levels during at least one of the follow-up measurement periods. In some of the houses mitigated with subsurface ventilation, radon concentrations generally increased over the course of the follow-up periods. Factors causing decreased mitigation system performance included: (1) build up of debris on the soil at the outlet of subsurface pressurization pipes; (2) noisy and vibrating fans were turned off; (3) air-to-air heat exchanger, basement pressurization, and subsurface ventilation fans were turned off and fan speeds reduced; and (4) crawl space vents were closed or sealed.

INTRODUCTION

During recent years, the study of indoor air pollutants in residences has led to the discovery of large numbers of houses with elevated indoor radon concentrations and an increased awareness of the risks associated with exposure to radon and radon progeny. Directly associated with these events has been the rapid growth of the radon mitigation industry. Inherent in the development of an industry of this type is the initial lack of research data, practical experience, and specialized equipment and materials. Central to the goal of developing reliable and efficient radon mitigation strategies is the need for follow-up evaluations of existing radon mitigation systems. These systems must be assessed in terms of their long-term reliability and their suitability for various house designs and construction types, geographic regions (e.g., climate and soil types), and occupant-related factors. This report describes the follow-up evaluation of radon mitigation systems in 14 single family houses that received radon mitigation as part of a radon research project during the 1985-1986 heating season (Turk et al. 1987, Prill et al. 1987). These early radon mitigation systems are quite similar to many systems currently being installed by researchers and private-sector radon mitigation contractors.

METHODOLOGY

Follow-up monitoring of the radon concentrations in each level or zone of the houses was performed using mailed alpha-track detectors (Type SF manufactured by Terradex, and later in the study, detectors produced by Radtrak) which were deployed, removed and returned by the homeowners. These measurements were initiated immediately following the original mitigation study and consisted of a series of approximately quarterly measurements, followed by an annual measurement period. The homeowners were asked to record mitigation system fan on/off dates and speed settings, dates and types of maintenance performed, problems or repairs to the systems and periods when crawl space vents were closed. At the conclusion of the original study, the homeowners were advised to turn off the mitigation systems only during periods of mild weather when windows and doors were opened. Approximately two years following mitigation, the complete follow-up radon data set was compiled and evaluated and a site visit to each house was conducted. Each homeowner was interviewed by telephone to update the data files on each house and mitigation system and to discuss and schedule the visit. Furthermore, they were asked to perform no system adjustments, maintenance or repairs, in anticipation of the inspection, so that the systems could be evaluated under "normal" operating conditions.

Approximately two weeks before the visit, continuous radon monitoring (CRM) instruments with accumulator displays were installed in seven houses where radon concentrations had increased significantly. The CRMs were allowed to operate for at least two weeks following the visit. The homeowners were provided with a log sheet and instructed to record the date, time, and digital CRM display at least once daily.

The site visit at each house began with an inspection of the structure for indications of moisture damage, cracked concrete, or other damage or degradation of building materials resulting from the operation of the radon mitigation system(s). The homeowner was asked to comment on any effects of the mitigation system on thermal comfort, noise, vibrations, moisture/humidity levels, annoyance, inconvenience, and damage to the structure. Data compiled from the follow-up radon measurement periods were reviewed with the homeowner and the operation history of the radon system and house conditions during these periods were verified to the degree possible.

In houses with subsurface ventilation (SSV) systems, the fan speed setting (position of rheostat dial), the noise and vibration levels, the amount of debris on intake/exhaust screens, and the integrity of the materials and sealants were noted. Air flow rates in the SSV pipes were measured using a calibrated hot-wire anemometer. The uncertainty of these flow rate measurements is estimated to be approximately 10%. Air pressures within the pipes were measured using both a digital electromanometer (1.0 Pa sensitivity) and a micromanometer (0.25 Pa sensitivity).

Air-to-air heat exchanger (AAHX) filters and cores were inspected for dust and debris. Where possible, the ducted AAHX supply and return flow rates, and outside air intake and exhaust flow rates, were measured with the calibrated hot-wire anemometer using a three-point traverse along two axes within the ducts. The uncertainty of these flow rate measurements is estimated to be approximately 17%. Fan speed settings, and balancing-damper positions were recorded.

In houses with basement pressurization systems, fan speed settings were recorded, and noise and vibration levels noted. Flow rates of air through the pressurization systems were measured with the hot-wire anemometer using a three-point traverse along one or two axes with an estimated uncertainty of 10%. Differential pressures across the basement slab floor and, in some cases, between zones were measured using the electromanometer and a micromanometer. The effective leakage area (ELA) of the basements, which indicates the total area of leakage pathways between the basement and other regions, was measured using the same calibrated blower door employed during the original study. Based on prior research (Dickinson and Feustel, 1986; Modera and Wilson, 1988) ELA measurements are repeatable within a range of 10% at best (i.e., when measurements are performed using surface-pressure averaging techniques, when the same equipment is used, and when seasonal and wind conditions are similar).

In order to evaluate the performance of all the systems, a complete set of "current condition" measurements were made before the systems or the houses were modified in any manner. The systems or houses were then returned to "original condition" (duplicating conditions at the end of the original mitigation study) and another complete set of measurements were performed. Where required, the systems and houses were modified to increase their performance and another set of measurements were taken for reference.

The uncertainty in the average radon concentrations measured with the CRMs is estimated to be 10% due largely to uncertainties in instrument calibration (Nazaroff et al., 1983). There are conflicting reports of the accuracy of the alpha-track measurement of radon concentrations. In chamber exposures (approximately 100 to 165 pCi-day/l) of the Terradex Type SF alpha-track detectors at the U.S. Department of Energy's Technical Measurement Center (Pearson 1987), the ratio of measured to actual radon concentration was less than 0.5 with 10% of the detectors, greater than 1.5 with 9% of the detectors, and greater than 2.0 with 3% of the detectors. If one assumes that the ratio of measured to actual concentration is normally distributed (although some of the distributions provided by Pearson do not appear normal), the coefficient of variation (standard deviation divided by the mean) of this ratio for different batches of Type SF detectors ranges from 25 to 60%. Smaller measurement uncertainties are reported by Oswald (1987). Based on data from the Environmental Protection Agency's proficiency testing of radon detectors, Oswald reports a bias of 0.91 and a coefficient of variation of approximately 15% for the type SF detectors. Thus, the CRM measurements are quite accurate and the accuracy of the alpha-track detectors is currently a controversial issue.

RESULTS AND DISCUSSION

SUBSURFACE VENTILATION SYSTEMS

Seven houses used subsurface ventilation systems (SSV) as the primary radon mitigation technique. Five of these houses were equipped with subsurface pressurization (SSP) systems that forced outdoor air (pressurized) beneath the basement slabs via interior pipes that penetrated the slabs (SSP). One house (ESP111) had a combination of interior subsurface pressurization and exterior subsurface pressurization (a pair of pipes extended to below the footing from outside), and one house (ESP119) had only an exterior subsurface depressurization system (SSD), which drew soil gas from the region beneath the footing and exhausted the soil gas to outside. All fans were located exterior to the living space and were mounted either in the garage or, most commonly, in separate enclosures attached rigidly (without a vibration isolator) to the exterior of the houses. The fans were also connected rigidly to the plastic pipes through which air was forced. The SSD system exhaust exited through a screened wall cap mounted in the gable-end of the garage, while the SSP systems had air intakes built into the fan enclosures located above snow level and were fitted with rain caps and screens, but not air filters. Centrifugal fans were used throughout, and were equipped with on/off switches and rheostats for speed control.

The results from the alpha-track measurements indicate that the SSV systems have maintained radon concentrations significantly below the original baseline, i.e., pre-mitigation, levels (see Table 1 and Figure 1). However, radon concentrations measured during this follow-up study are frequently higher than those reported at the end of the original study and are also occasionally significantly above the EPA guideline of 4.0 pCi/l. All homeowners report that they did not always operate their SSV fans during the late spring, summer, and early fall. In one house with SSP (ECD026), vents in a partial crawl space were closed during the heating seasons.

Measurements performed before modifications show that pressures in all of the SSP systems had increased (i.e., the pressures in the SSP pipes just upstream of the points where they penetrated the slabs) and flows had decreased, with the exception of one system in which the fan speed had been reduced and the pressure also decreased (see Table 2). SSP pipes that were accessible in Houses ESP108 and ESP113 were cut off near the slab and the soil surface at the pipe outlet was inspected. Substantial dust and lint-type debris was found. This was vacuumed out, the pipe reattached and the flow and pressure measurements repeated. These measurements show an increase in air flow and substantial drop in pressure after this cleaning process. Thus, the increases in radon concentrations in houses ESP101, ESP108, ESP113, and ESP120, where fan speed settings were not changed, may be caused in part by reduced subsurface ventilation due to a build up of debris on the soil at the SSP pipe outlets.

In house ECD 026, increasing the fan speed to the original setting produced a significant change in the pressure and flow, with the pressure returning to the original level (see Table 2). The pre- and post-inspection alpha-track and CRM measurements for this house indicate significant drops in the radon concentrations after modifications were conducted (see Table 1). These reductions could be due to the increased flow through the SSP system and/or to the fact that the crawl space vents were opened during and subsequent to the visit.

One SSV system (ESP111) failed completely due to problems associated with the installation of the system. The homeowner turned the system off due to unacceptable fan noise and vibration. Another house (ESP120), experienced similar problems, though less severe, so that the SSP system continued to operate. Noise and vibrations associated with the SSV systems were noticeable in other houses. The inspections revealed significant air leaks at the connection of the fan to the SSP pipes in the same two houses (ESP120 and ESP111) where noise and vibrations were most pronounced. The fans and enclosures in these houses were subsequently replaced. To reduce transmission of noise and vibrations, the new fan enclosures were mounted with flexible shock mounts to a post set in concrete adjacent to the house. A highly flexible elastomeric connector was used to attach the outlet of the fans to the plastic pipes. The new enclosures contain washable air filters upstream of the fans to reduce the previously mentioned build up of debris at the surface of the soil.

Air leaks were detected at the joint between the concrete floor and the mortar patch around the SSP pipes in houses ESP108 and ESP111. These leaks were minor at the time of the inspection and it was assumed that primarily outside air was being forced out of this crack since these systems are operated in the pressurization mode. The mortar patch material was in excellent condition. However, the asphaltic sealant material used to seal the joint between the mortar patch and the concrete had failed.

Surprisingly, the inspection and interviews revealed that there were no condensation problems associated with the SSP pipes during the heating season. Condensation on the exterior surface of the SSP pipes had been anticipated since cold outside air was being blown into the pipes which pass through conditioned areas. There were also no indications of damage or problems caused from the cold air being forced beneath the concrete floors.

All homeowners stated that they were generally pleased with the SSV systems. All systems were judged to be unobtrusive, produced no thermal discomfort, required infrequent maintenance or service, and the homeowners perceived no significant increase in energy consumption due to the operation of the fans. However, some homeowners were annoyed by noise and vibrations produced by the systems.

Based on the results of this follow-up study, we suggest that SSP systems be fitted with washable/reusable and easily accessible filters upstream of the fans. We also recommend that SSV systems have pressure gauges installed at appropriate locations in the pipes so that substantial changes in pressure can be identified to allow the occupants to initiate prompt remedial action. Fans should be mounted carefully to minimize the possibility of vibration or noise transmission. High quality sealants should be used at all joints and connections to ensure permanent air tight seals. Finally, fan speed controls should be protected from casual tampering.

AIR-TO-AIR HEAT EXCHANGERS

Two of the houses have air-to-air heat exchangers (AAHX) as radon mitigation devices. The units are identical, similarly located in the basements, and ducted such that outside air is supplied, and return air exhausted from only the basement level. However, the basement of each structure is exposed to the upper levels of the houses by open stairwells and both homes have forced-air electric furnaces which supply air to, and return air from, all zones of the houses.

The alpha-track and continuous radon monitor (CRM) results show that, during all periods when the AAHX units were operated continuously, the radon concentrations were maintained below the original baseline levels (see Table 1). Some of the differences from the baseline radon concentrations measured with the alpha-track detectors may not be significant considering the uncertainty in these measurements. In house ESP109, the AAHX was operated only sporadically during both winter measurement periods and radon concentrations were approximately equal to baseline levels.

The AAHX fan speed in house ESP109 had been decreased from the original setting of maximum to a setting of "3/4" on the speed control dial. This contributed to a 25 to 30% decrease in the outside-air and exhaust-air flow rates compared to the original flow rates. The ratio of exhaust to outside air flow was essentially unchanged from the original ratio, with the supply flow rate approximately 25% lower than the exhaust flow rate. The filters were cleaned, a loose cover panel on the unit was secured, and minor damper adjustments were made to one supply and one return register so that the exhaust and outside-air flow rates were essentially equal. The mechanical ventilation provided by the AAHX for this house was approximately 0.7 house volumes/hour originally, 0.5 house volumes/hour at the time of the site visit, and 0.6 house volumes/hour after the site visit.

In house ESP121, the AAHX fan speed had been decreased from the original speed setting of maximum to a setting of "1/2" speed. This change reduced the supply and return air flow rates by 30 to 35%. After the dirty filters were replaced, the flows at "1/2" speed remained essentially unchanged. The mechanical ventilation provided by the AAHX is approximately 0.5 house volumes/hour currently compared to 0.7 house volumes/hour at the end of the original study. The fan speed control was left at the "1/2" speed position.

Although the AAHX units were installed in very similar houses and were located and configured similarly, the two sets of occupants had very different evaluations of the units. In house ESP109, the husband thought the unit created cold drafts, caused the furnace to operate more frequently which increased their space heating expenses, and complained that the supply air contained unacceptable levels of wood smoke. The wife disagreed somewhat with her husband's evaluation and appreciated the radon removal capability of the unit. Consequently, the unit is often operated during the day when the husband is away and is often off in the evening and at night when he is present. The other household is extremely satisfied with their unit which is operated 24 hours/day, and stated specifically that the unit had relieved their daughter's allergic reactions, reduced the amount of dust in the house, helped reduce the smell of wood smoke indoors and created no uncomfortable drafts or increased space heating expenses. Both households praised the units for quiet and vibration-free operation.

Aside from some loose fiberglass duct insulation in one house and a loose cover panel on one of the units, the installations were satisfactory. Based on this follow-up study, AAHX units used for radon mitigation should have a conveniently located fan on/off switch but speed controls should have an optional provision to protect them from casual adjustment.

BASEMENT PRESSURIZATION

Four of the houses have occupied basements which are pressurized, relative to the pressure within the soil surrounding the substructure, with main-level air using an auxiliary fan system. This technique of basement pressurization had not been used prior to the original mitigation study. All four houses have electric forced-air furnaces as the primary heating system and all but one of these houses has a partial crawl space. Two of the homes had occupant changes during the follow-up period.

These systems have maintained the main level radon concentrations substantially below the baseline values despite periods when some systems were not operated continuously (see Table 1 and Figure 2). However, the radon concentrations in the basements approached pre-mitigation levels in all of the homes during at least one of the alpha track follow-up measurement periods and many of the measured radon concentrations are above both the original post-mitigation concentrations and the EPA guideline. Some of these increases in radon can be explained. For example, during the winter 1986-1987 the system in house ESP153 was turned off at the discretion of the homeowners, while the system in house NCD077 was not operated because the new occupants had not been appraised of the purpose or operation of the system. Also, the crawl-space vents in these homes were closed during these measurement periods. In all of these houses, increased radon concentrations during the summer may be due to the fact that the systems were not operated and adequate natural ventilation may not have been provided. Some of the fall, spring and even the annual measurements may be skewed since the systems were frequently not operated for the entire measurement period. The increased radon concentrations in houses NSP204 and ESP116 during the winter periods 1986-1987 and 1987-1988 are more difficult to explain since the systems were reportedly operated continuously during the entire measurement periods.

The flow rates through the basement pressurization systems had decreased in all of these systems by 20 to 25%. The effective leakage areas (ELA) of all the basements were essentially unchanged from the original basement ELAs. The amount of air required to maintain a positive pressure in the basement is proportional to the effective leakage area of the basement.

Before fan speeds were changed or other modifications were made to the systems, the basement pressure minus the pressure directly beneath the basement slab floor at a central location ranged from -2 Pa in house ESP116, neutral in house NSP204, and between neutral to +2 Pa in house ESP153 (unmodified measurements were not made in NCD077). After sealing obvious air leaks and by-passes in the basement shell, and increasing fan speeds to the original settings of maximum (except NCD077 which was originally set at 1/2 speed), the pressures increased to neutral in ESP116, and ranged from +1 Pa to +3 Pa in NCD077, +1 Pa to +4 Pa in ESP153, and to +3 Pa to +6 Pa in house NSP204. With both the basement pressurization fan and forced-air furnace blower turned off, the pressures ranged from -1 Pa to -2 Pa in NSP204, -3 Pa to -5 Pa in ESP116, -5 Pa in ECD153, and -5 Pa to -7 Pa in house NCD077. These measurements were performed during heating season conditions with outdoor temperatures between 3 to 10 °C. These data indicate that the basement pressurization systems reduced, but did not always reverse, the pressure differences that drive radon entry.

The inspection revealed no serious degradation of the systems nor any indication of structural or material damage from the pressurization of these basements. The systems themselves were in satisfactory condition with the exception of one fan which was vibrating due to a bent fan wheel shaft. We noticed that basement clothes dryer vent door flaps were often either missing, stuck open or were being forced open by the pressure in the basement. Vents with weighted door flaps were installed. Air leaks or bypasses from the basement to the exterior were found to be much more significant than air leaks to the main level in terms of compromising the pressurization of the basement. The original air-sealing of the basements was judged to be incomplete.

Immediately following the inspection and modifications, the quarterly alpha-track detectors in house NSP077 were replaced with new "post-modification" detectors while in house NSP204 "post-modification" detectors were simply added. These measurements indicate a substantial decrease in the radon concentration of the crawl space in NCD077 (opened during and subsequent to the visit); however, changes in the main level and basement concentrations are not significant, considering our estimates of measurement uncertainty. No changes were seen in the NSP204 post-modification radon levels compared to the entire quarterly measurement (see Table 1). CRM measurements were made in the lowest occupied zones in three of the basement pressurization homes for a period of at least 2 weeks immediately before and 2 weeks immediately following the visit. Radon concentrations decreased 40% to 80% in these lowest occupied zones after the modifications or adjustments.

All of the homeowners described the basement pressurization systems as inconvenient and obtrusive since they were required to keep the basement tightly closed. More annoying, and potentially dangerous, is the fact that the system reportedly contributed to back-drafting of a main level wood-burning fireplace insert in house ESP116, during periods when the fire was low (weak draft). In spite of these evaluations, most of the homeowners thought the technique was a better choice than "having plastic pipes running through the basement" (SSV). Originally, ESP120 had both types of systems installed (both were effective in spite of approximately 140 pCi/l initial radon levels), but the occupants decided to use the SSV system after having lived with both techniques.

Based on these findings, future installations of these systems should be made in houses without combustion appliances that might back-draft, with basements or substructures which can be tightened (air-sealed) with a reasonable amount of effort, and fans should be over-sized to provide a margin of performance in case the basement becomes leakier or fan performance decreases. Fans should be mounted in a manner that reduces noise and vibrations and speed controls should be protected from casual adjustment.

BASEMENT VENTILATION WITH PRESSURIZATION

Radon in one of the study houses was reduced by mechanical ventilation which also provided a slight positive pressure in the basement which was unoccupied, unconditioned, and had a dirt floor. The main level floor above the basement was first sealed against air leakage, insulated, and the pipes wrapped with thermostatically controlled heat tape and insulated. Vents for natural ventilation were difficult to install such that adequate cross flow could be achieved, so a fan was installed which forced outdoor air into the space and provided approximately 10 Pa positive pressure relative to outside air at soil level. Air exited the basement through relatively small vents spaced along two sides of the house.

The alpha-track results illustrate the continued effectiveness of the technique (see Table 1). The elevated annual average radon concentration in the basement was probably due to the fact that the occupants kept the basement door open during a period of remodeling, which probably increased the ventilation rate, but decreased the pressurization. The radon levels in the living space, however, have continued to remain far below the baseline values.

The fan installation does not allow accurate flow rate measurements to be made. The ΔP between the basement relative to both the outside and the main level during the original study was +10 Pa. Before modification, the ΔP was +6 Pa in the basement relative to both the main level and the outside. After modification (the fan safety screen was cleaned of debris), the pressure differences increased to +10 Pa. The fan was equipped only with an on/off switch with no speed control and was operated continuously on an annual basis.

The inspection revealed no indications of damage or degradation to building materials or the structure resulting from the system operation. There were no instances of frozen water pipes, cold floors on the main level over the basement or other related problems. The fan safety screen was beginning to occlude with lint-type debris which reduced the rate of basement ventilation.

The homeowners described the mitigation strategy as excellent. The only negative aspect reported was the loss of the basement space for vegetable storage during the winter, but this was more than offset by the fact that the home was judged to be thermally more comfortable and more economical to heat (the floor had not been insulated previously).

CRAWL SPACE VENTILATION

All crawl spaces were ventilated during the original mitigation study but this technique alone was not effective in reducing radon concentrations to below guideline levels. None of these homes had a complete crawl space, so that the substructures consisted of a partial crawl space in combination with either a full or half-depth basement.

Alpha-track follow-up measurements in the crawl spaces clearly illustrate the effectiveness of ventilation. During periods when the crawl space vents were closed, the radon concentrations increased. When the vents were subsequently opened the levels were reduced as seen in houses ECD026 and NCD077 after the site visit (see Table 1).

The inspections revealed no problems related to the actual crawl space ventilation. The floor, duct, and pipe insulation, and crawl space access door weatherstrip and knee-wall sealants were in excellent condition, as was the membrane that was installed over the soil in two of the crawl spaces.

The homeowners' comments ranged from complete satisfaction to continued concerns about freezing water pipes during severe winter conditions. The crawl space vents were closed in house ECD026 due to the concern about pipe freezing in spite of the fact that the homeowner was aware of the thermostatically controlled heat tape installed beneath the pipe insulation. The new homeowner in house NCD077 was not aware of the purpose of the crawl space vents and, thus, simply closed them in preparation for winter. Two small fans which had been installed in the crawl space in house ECD026 to provide increased ventilation were turned off permanently during the 1986 winter period due to vibration. The safety screens on the intake side of the fans in ECD026 were moderately occluded with debris. The crawl space vent screens were clean in all of the other houses.

SUMMARY AND RECOMMENDATIONS

It is clear that continued follow-up of radon mitigation systems is an important element in increasing our understanding of radon control. The active radon mitigation systems used in the houses in this study have generally maintained average indoor radon concentrations substantially below the initial pre-mitigation concentrations. However, in all of these houses main level radon concentrations were found to have increased above 4.0 pCi/l during at least one of the quarterly follow-up measurement periods.

In the majority of the subsurface ventilation (SSV) systems that operated in the pressurization mode, we observed increased pressures and decreased air flows due to a two-year build up of debris at the SSV pipe outlet where air was forced into the soil. The reduced flows may have caused the increases in radon concentrations in these houses over the course of the follow-up measurement periods. Most of the homeowners were pleased with the subsurface ventilation systems.

The basement pressurization systems continued to reduce indoor radon concentrations when operated, although concentrations were not maintained at the original low post-mitigation levels. Based on measurements of the pressure difference across basement slab floors, these systems did not always maintain positive pressures in the basements. Homeowners generally considered the basement pressurization systems to be obtrusive.

In two houses equipped with AAHX units, the radon concentrations have generally continued to be moderately below the initial pre-mitigation levels, except during periods of intermittent operation, although measurement uncertainties prevent firm conclusions. Homeowners had decreased the unit fan speeds and thus the rates of air flow through the AAHX units and the homeowners' evaluations of the units were variable.

Recommendations for future mitigation system installations, include the use of air filters on subsurface pressurization systems, shielding of fan speed controls to prevent casual adjustment, careful mounting of fans to prevent noise and vibration transmission, and the display of notices, on or near the mitigation equipment, describing the mitigation system and the correct operation of the fan and other components.

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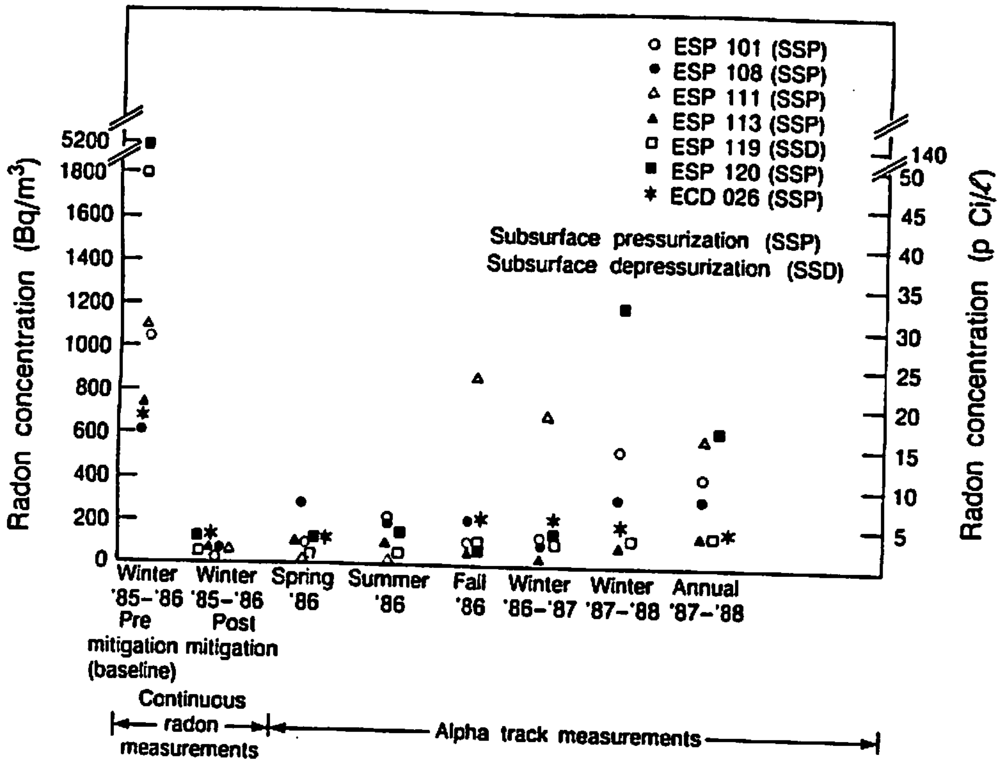

Figure 1. Radon concentrations in the main occupied level of seven houses with subsurface ventilation systems.

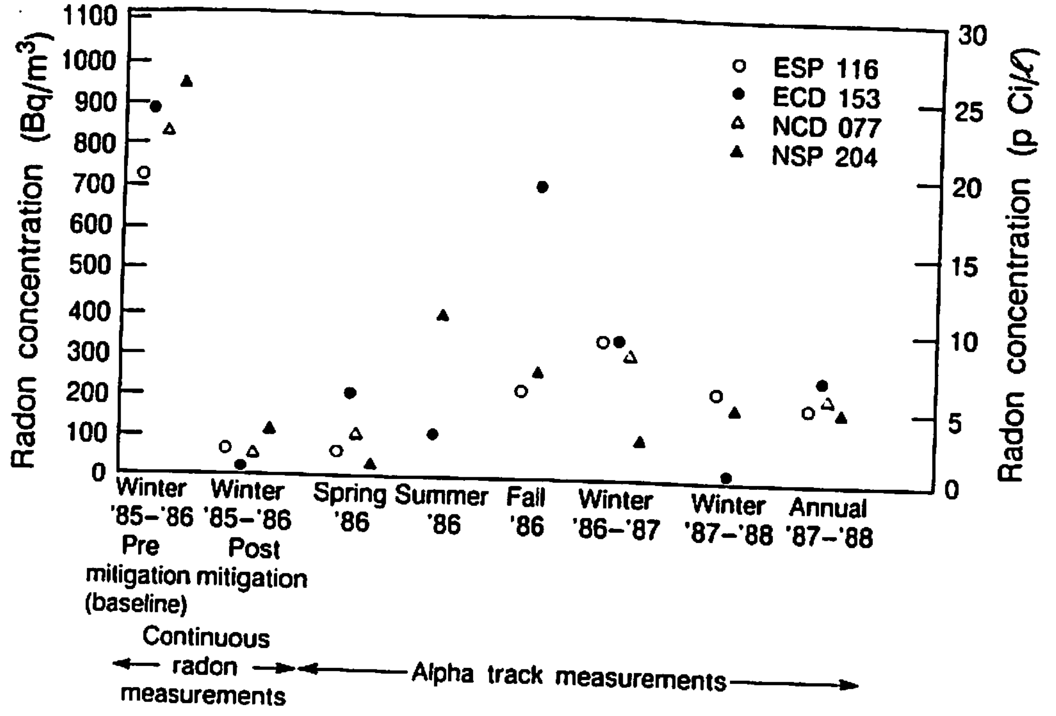

Figure 2. Radon concentrations in the main occupied level of houses with basement pressurization systems.

TABLE 1. SUMMARY OF RADON MEASUREMENTS (pCi/l)

Sample Location	Alpha Track Summer '85	Continuous Radon Monitor Original Study Pre Mit Winter 85-86	Continuous Radon Monitor Original Study Post Mit Winter 85-86	Alpha Track Spring 3/86-6/86	Alpha Track Summer 6/86-9/86	Alpha Track Fall 9/86-12/86	Alpha Track Winter 12/86-4/87	Alpha Track Winter 12/87-5/88	Alpha Track Annual 4/87-4/88	Alpha Track Follow-up Visit Pre Winter 87-88	Alpha Track Follow-up Visit Post Winter 87-88	Continuous Radon Monitor Follow-up Visit Pre Winter 87-88	Continuous Radon Monitor Follow-up Visit Post Winter 87-88
SUB SURFACE VENTILATION PRESSURIZATION MODE													
HOUSE ESP101													
Lvl 1 F.B.			2	7	13	4	3	21	17				
Lvl 2 Hd.B.				6	12	3	3	18	16				
Lvl 3 Main	3	28	1	3	7	3	2	15	11				
Lvl 4 Top				5	5	2	3	14	10				
HOUSE ESP108													
Lvl 1 F.B.			1	11	10	9	2	10	11				
Lvl 2 Main	4	15	1	8	6	6	2	8	8				
HOUSE ESP111													
Lvl 1 F.B.			3	1	4	39[b]	28[b]	---	15	---	4	---	---
Lvl 2 Hd.B.				1	7	37[b]	20[b]	---	18	---	4	40[b]	6
Lvl 3 Main	1	30	2	1	6	23[b]	18[b]	---	15	---	3	---	---
Lvl 4 Top				1	4	25[b]	16[b]	---	18	---	3	---	---
HOUSE ESP113													
Lvl 1 Hd.B.				6	5	4	2	4	8				
Lvl 2 Main				3	3	4	2	3	6				
Lvl 3 Top	4	20	1	3	3	2	2	3	4				
HOUSE ESP120													
Lvl 1 F.B.			3	17	15	4	3	39	20				
Lvl 2 Main	12	140	2	3	4	2	4	33	15				
Lvl 3 Top				4	3	3	3	26	13				
HOUSE ECD026													
Crwl				6	---	4[a]	11[c]	---	3	7[c]	3	---	---
Lvl 1 Hd.B.			3	4	---	8	9[c]	---	3	6[c]	3	6[c]	3
Lvl 2 Main	1	17	3	4	---	7	6[c]	5[c]	3	---	---	---	---
Lvl 3 Top				4	---	16[a]	7[c]	6[c]	3	---	---	---	---
DEPRESSURIZATION MODE													
HOUSE ESP119													
Crwl	---			1	1	1	1	1	1				
Lvl 1 Hd.B.				2	2	4	4	5	5				
Lvl 2 Main		49	1	2	1	3	3	4	3				
Lvl 3 Top				3	4	3	2	4	4				

<u>KEY</u>:

Lvl	= Level
Pre Mit	= Pre-mitigation
Post Mit	= Post-mitigation
F.B.	= Full Basement
Hd.B.	= 1/2 Depth Basement
Crwl	= Crawlspace
Main	= Typically Ground Floor
---	= No Data
a	= Suspect Mislabeled Detector Locations
b	= System Fan Off
c	= Crawlspace Vents Closed

TABLE 1 (continued). SUMMARY OF RADON MEASUREMENTS (pCi/l)

Sample Location	Alpha Track Summer '85	Continuous Radon Monitor Original Study Pre Mit Winter 85-86	Continuous Radon Monitor Original Study Post Mit Winter 85-86	Alpha Track Spring 3/86-6/86	Alpha Track Summer 6/86-9/86	Alpha Track Fall 9/86-12/86	Alpha Track Winter 12/86-4/87	Alpha Track Winter 12/87-5/88	Alpha Track Annual 4/87-4/88	Alpha Track Follow-up Visit Pre Winter 87-88	Alpha Track Follow-up Visit Post Winter 87-88	Continuous Radon Monitor Follow-up Visit Pre Winter 87-88	Continuous Radon Monitor Follow-up Visit Post Winter 87-88
BASEMENT OVERPRESSURIZATION													
HOUSE ESP116													
Lvl 1 F.B.				9	5	---	16	9	21			8	5
Lvl 2 Main	---	20	2	2	---	6	9	6	5			---	---
HOUSE ECD153													
Crwl				5	3	11[bc]	7[bc]	3	4				
Lvl 1 Hd.B.				13	5	19[bc]	14[bc]	3	8				
Lvl 2 Top	1	24	1	6	3	19[bc]	9[bc]	1	7				
HOUSE NCD077													
Crwl				1	--- 3[c]	---	4[bc]	---	5	12[bc]	5	---	---
Lvl 1 F.B.				1	--- 5[c]	---	19[bc]	---	12	15[bc]	13	23[bc]	5
Lvl 2 Main	---	23	2	3	--- 9[c]	---	8[bc]	---	6	10[bc]	6	---	---
HOUSE NSP204													
Crwl				5	11	14	5	7	10	---	---	---	---
Lvl 1 F.B.				2	3	13	18	5	9	---	6	21	4
Lvl 2 Main	---	26	3	1	11	7	3	5	5	---	5	---	---
AIR-AIR HEAT EXCHANGERS													
HOUSE ESP109													
Lvl 1 F.B.				2	2	4	10	---	4			7	5
Lvl 2 Main	2	7	2	2	2	3	7	---	4			---	---
HOUSE ESP121													
Lvl 1 Hd.B.				6	3	5	---	4	6				
Lvl 2 Main	1	11	3	3	1	4	---	5	4				
BASEMENT VENTILATION WITH PRESSURIZATION													
HOUSE ECD027													
Lvl 1 F.B.			1	1	3	3	2	1	18				
Lvl 2 Main	4	45	1	1	2	2	1	2	5				
Lvl 3 Top				1	2	1	1	1	5				

<u>KEY</u>

Lvl = Level
Pre Mit = Pre-mitigation
Post Mit = Post-mitigation
F.B. = Full Basement
Hd.B. = 1/2 Depth Basement
Crwl = Crawlspace
Main = Typically Ground Floor
--- = No Data
a = Suspect Mislabeled Detector Locations
b = System Fan Off
c = Crawlspace Vents Closed

TABLE 2. FLOW RATES AND PRESSURES IN SUBSURFACE VENTILATION SYSTEMS

	PIPE 1		PIPE 2		PIPE 3		PIPE 4		
House I.D.	Flow (l/s)	ΔP(Pa)	Flow (l/s)	ΔP(Pa)	Flow (l/s)	ΔP(Pa)	Flow (l/s)	ΔP(Pa)	Configuration/Modifications:
<u>ESP 101</u>	(MANIFOLD @ FAN)								
A Original:	25	175	---	---	---	---			
B Unmodified:	15	312	---	---	---	---			B Fan speed and dampers same as original
<u>ESP 108</u>	(WORKROOM)		(STORAGE)		(OFFICE)		(BEDROOM)		
A Original:	17	437	14	412	12	375	12	375	
B Unmodified:	8	500	8	460	7	438	8	445	B Fan speed and dampers same as original
C Modified:	12	413	--	--	--	---	---	---	C Cleaned soil at pipe outlet (workroom pipe only)
<u>ESP 111</u>	(INTERIOR)		(EXTERIOR)						
A Original:	24	472	---	505					B Speed same as original
B Unmodified:	17	505	17	495					
<u>ESP 113</u>	(SINGLE PIPE)								
A Original:	8	121							
B Unmodified:	7	283							B Speed same as original
C Modified:	9	205							C Cleaned soil at pipe outlet
<u>ESP 119</u>	(SINGLE PIPE)								
A Original:	14	-192							A Original fan speed = "11:30" on rheostat dial
B Unmodified:	13	-233							B Speed lower at ~1:00" on rheostat dial
C Modified:	13	-244							C Speed at original speed at ~ "11:30" on rheostat dial
<u>ESP 120</u>	(N/E)		(S/E)		(S/W)				
A Original:	16	375	21	375	48	---			
B Unmodified:	1	515	4	520	20	150			B Fan speeds and dampers same as original
C Modified:	1	520	---	---	20	150			C S/W = Fan screen cleaned N/E = Air leak sealed @ S/E pipe
<u>ECD 026</u>	(SINGLE PIPE)								
A Original:	---	500							A Original fan speed ~maximum
B Unmodified:	6	404							B Speed at "minimum"
C Modified:	6	412							C Speed at "minimum" and cleaned intake screen
D Modified:	7	502							D Speed at maximum