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EFFECTIVENESS OF RADON CONTROL TECHNIQUES IN 15 HOMES

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ABSTRACT

Radon control systems were installed and evaluated in 14 homes in the Spokane River Valley/Rathdrum Prairie and in one home in Vancouver, WA. Subsurface ventilation (SSV) by pressurization was always more effective in these houses than SSV by depressurization in reducing indoor radon levels to below guidelines. Basement overpressurization was successfully applied in five houses with air-tight basements where practical-sized fans could develop an overpressure of 1 to 3 Pascals. Crawl space ventilation was more effective than crawl space isolation in reducing radon entry from the crawl space, but had to be used in conjunction with other mitigation techniques, since the houses also had basements. Indoor radon concentrations in two houses with air-to-air heat exchangers (AAHX) were reduced to levels inversely dependent on the new total ventilation rates and were lowered even further in one house where the air distribution system was modified. Sealing penetrations in the below-grade surfaces of substructures was relatively ineffective in controlling radon. Operation of the radon control systems (except for the AAHX's) made no measureable change in ventilation rates or concentrations of other measured pollutants. Installation costs by treated floor area ranged from approximately $\$4/m^2$ for sealing to $\$28/m^2$ for the AAHX's. Based on the low electric rates for the region, annual operating costs for the active systems were estimated to be approximately $60 to $170.

INTRODUCTION

Our studies of 172 residences in the Pacific Northwest indicate that approximately 65% of the homes located on the highly permeable soils of the Spokane River Valley/Rathdrum Prairie of eastern Washington/northern Idaho had heating season indoor radon concentrations above the Environmental Protection Agency (EPA) guideline of 148 Bq m^{-3} (4 pCi l^{-1}).[1,2,3] At the time of these studies (1983 to 1986), a popular method for reducing indoor radon concentrations was to provide additional ventilation with an air-to-air heat exchanger (AAHX). However, work by others had indicated that radon concentrations were approximately proportional to the total ventilation rate when ventilation was modified using an AAHX and that balanced ventilation provided by an AAHX generally resulted in only moderate (e.g., 50%) reductions in indoor radon levels.[4] Because of the practical limit to the amount of additional ventilation provided with an AAHX, this technique is not likely to be effective in homes with very high indoor radon levels.

As part of an effort to promote energy conservation through house-tightening weatherization, the Bonneville Power Administration (BPA) recommended that action be taken to reduce indoor radon levels above 185 Bq m^{-3} (5 pCi l^{-1}).[5] To support this program, a study was initiated to (1) develop innovative techniques that were low-cost and effective; and (2) evaluate and characterize the long-term (greater than two weeks) performance of these and other indoor radon control techniques as alternatives to the AAHX. Findings from this research are presented here. Research results related to the other objective of this study, to investigate the causes of the high indoor levels, are described separately by Turk et al.,[3] while Prill et al. discusses the long-term performance of the mitigation techniques.[6]

EXPERIMENTAL PROCEDURES

Monitoring and Instrumentation

Fifteen occupied, single-family homes with indoor radon concentrations above 185

Bq m^{-3} participated in this study of radon control systems. High indoor levels were preferred so that changes resulting from the installation or modification of the mitigation techniques could be detected easily. These homes were representative of the local house construction types and had cooperative homeowners/occupants. Fourteen homes were located in the Spokane River Valley/Rathdrum Prairie, while the other was in Vancouver of western Washington. Two of the 14 homes served as controls and remained unmitigated until completion of the project.

Continuous radon monitors (CRM) were used to measure radon concentrations in living areas on the first occupied floor above grade and were also deployed in the basement or crawl space of several homes. Radon concentrations determined with these devices have an estimated uncertainty of 10%. These data and data from other real-time instruments (indoor and outdoor temperatures, wind speed and direction, furnace blower operation and some differential pressures) were sampled every 15 seconds and recorded every 30 minutes by a data logger at each house.

Monitoring and measurements specific to selection and evaluation of the radon mitigation systems were performed at each house throughout the study. Pressure differences were measured periodically (continuously in some homes) between mid-height in the basement and the soil air approximately one meter (m) below grade at a pipe probe one to seven meters from the house. These low pressure differences are difficult to measure accurately because they are in the range of pressure fluctuations caused by door closings and wind and were not corrected for height or temperature differences in the sample tubes. They should be considered approximate indicators of the driving force for radon entry. Pressure differences under pre-mitigation winter conditions with no wind were -2 to -6 Pa, typical of the underpressure values calculated due to the thermal stack effect.[7] Pressure transducers (Setra model 261) were used to continuously monitor pressure differences to within ±0.5 Pa. Electronic liquid point gauges (Dwyer model 1430) were used to periodically measure ΔP to within ±0.5 Pa.

Flow rates of air through ducts and pipes were determined by a three-point traverse with a hot wire anemometer (Alnor Model 8500). In one house, flow rates were also measured using a tracer gas technique. The rate of injection of sulfur hexafluoride (SF_6) into the duct was varied until a target concentration, measured at a point further along in the duct, was achieved. The static pressures in the mitigation system ducts, referenced to basement air, were sensed with a pitot-static tube located at the level of the soil grade or the substructure floor using the liquid point gauge manometer. Air temperatures in the ducts of radon control systems were measured with a mercury thermometer or the hot wire anemometer when flows and pressures were measured. Temperatures were continuously monitored in the supply, return, exhaust, and fresh air ducts of the AAHX's and in the soil near subsurface ventilation pipes at one house with IC-based (AD-590) devices that are accurate to within approximately 2 °C.

Soil gas movement at possible radon entry points into the houses was detected using a chemical smoke tube. These tubes were also used to detect air movement at leakage sites between zones of a building and to the outside.

Air samples were collected in scintillation flasks from wall cavities, floor drains, wall and floor cracks, and sealed rooms and compartments. Such flasks were also used to collect soil gas samples from the soil probes outside of the building. The flasks were analyzed for radon content using a portable photomultiplier counter. The radon concentrations were then "mapped" onto a floor plan to indicate the most important areas of radon entry and to evaluate the effectiveness of the mitigation system in controlling radon entry at those points. These diagnostic techniques have subsequently been modified and expanded.[8,9]

Electrical energy consumption of mitigation system fans and blowers was measured with an induction-type watt-hour meter. Installation cost data on materials and labor effort were submitted by the subcontractors who installed the radon control systems.

The average ventilation rates were measured for periods of approximately seven days throughout the study using the passive perfluorocarbon tracer (PFT) gas technique.[10]

A detailed description of the houses and the other monitoring instrumentation and procedures that were used is found in Turk et al.[3,11,12] Instrumentation was removed from the houses in March and April 1986 and long-term follow-up monitoring with alpha track detectors was initiated.

Installation of Mitigation Systems

Most of the 15 homes were visited in the Fall of 1985 for a detailed house examination. A survey and questionnaire of house construction and probable radon entry points were completed, floor plans were sketched, the house exterior and substructure were photographed, and miscellaneous occupant information was collected. These data and those on radon sources from soil, water, and building materials were then reviewed and a radon control plan was developed for each house. Mitigation system designs reflected our finding that the major source of radon entry in these homes was convective flow of soil gas from the highly permeable local soils through openings in the substructure surfaces.[3] Following installation, system performance was evaluated. If radon levels were reduced below 185 Bq m^{-3}, then system efficiency was improved by optimizing fan speeds and the location of distribution pipes. Initially unsuccessful systems were modified or options were added until indoor radon levels were reduced below 185 Bq m^{-3}. Because indoor radon concentrations often exhibit large, short-term variations, the control systems were monitored over extended periods following installation. Some systems were cycled on and off over periods of several days to reduce the possibility that occupants and natural conditions were causing false post-mitigation radon levels. In some houses, several control techniques were examined for the purpose of comparison. As the study progressed, unsuccessful measures were abandoned and others substituted.

The five primary radon control techniques that were targeted for investigation are

described briefly below and by Scott.[13]

Sealing of Cracks and Holes.[14] To reduce the number and area of soil gas entry locations, asphaltic and mortar patch compounds were used to seal accessible wall-floor joints, floor and wall cracks, gaps around service penetrations, and holes in poorly laid slabs in the substructures of five homes. Surfaces were prepared by chipping and cleaning. The area of openings sealed at each house was different, not quantified, and depended on accessibility. Defects ranged from hairline cracks to large holes (0.4 m diameter) through slabs. In some houses (e.g., ESP111), considerable webbing, or minute cracking, was observed in the concrete slab floors, but no attempt was made to seal these surfaces.

House Ventilation with Heat Recovery.[4] Central air-to-air heat exchangers with ductwork were installed in the basements of two homes. To improve radon removal efficiency, the systems were balanced and supplied fresh air to and removed stale house air from two basement locations at each house. These systems were sized to add approximately 1.0 air change per hour (h^{-1}) of ventilation to the entire house.

One newly-constructed home (NSP204), was built according to BPA's Model Conservation Standards (MCS) that required the installation of an AAHX to compensate for construction practices that reduce the air leakage area (and natural ventilation rate). As originally installed, the AAHX (located in the crawl space) returned air from the upstairs and supplied air to only the crawl space and separate atrium. The air supply and removal locations were modified for more effective radon control.

Overpressurization of the Basement. In a technique similar to one used to reduce the entry of radioactive gases into mines,[15,16] basements in five homes were pressurized to reverse the pressure difference across the soil/substructure surfaces (Figure 1). First, cracks and openings that permit air leakage were sealed to reduce air flow to the upstairs and outside. Doors between the upstairs and the basement in each of the homes were kept closed with spring-loaded hinges. Then, using a 100 to 240 L s^{-1} fan

that pulled air from the upstairs and exhausted into the basement, the basement was pressurized with respect to the air pressure in the soil.

This technique was first tested in homes with forced-air furnaces whose blowers could be operated continuously and whose air distribution systems could be easily unbalanced to deliver more air to the basement than to the upper floors. Unfortunately, the large furnace blowers were not practically suited for this task, causing imbalanced heat distribution, excessive air movement throughout the house, noise, high electrical consumption, and extreme upper floor underpressures that resulted in backdrafting of upstairs wood stoves and fireplaces. Yet, these simple tests proved the effectiveness of the general technique.

In homes with forced-air furnaces and ducting in the basement (ECD153, NCD077, ESP116, and NSP204), the upstairs air was supplied to a separate fan via the furnace system's return air duct. All basement return air grills were closed and a counter-weighted backdraft damper was installed in the supply air plenum. This reduced the short-circuiting of air through the basement supply ducting when only the pressurization system was operating, yet allowed conditioned air to be delivered to the basement when the furnace fan was operating. In one home without a forced-air heating system (ESP120), a hole was simply cut into the floor between the basement and upstairs and air was drawn directly from the upstairs. A section of exhaust duct one to two meters long was attached to the fan at each house to reduce noise and facilitate flow rate measurements.

Subsurface Ventilation (SSV).[17,18,19,20,21,22] Two versions of subsurface ventilation were used. Subsurface depressurization (SSD) reverses the soil/substructure pressure difference by drawing soil gas from the soil and exhausting the soil gas to outside. Subsurface pressurization (SSP) dilutes the subsurface soil gas radon concentration by forcing outside air into the soil. Subsurface pressurization was first implemented after initial use of SSD had proven only partially successful. The performance of most SSV systems was evaluated at several operating pressures.

In six homes 7.6 cm (3 inch) diameter PVC pipes were placed through the basement slab floor at one location (ECD026C, and ESP113), two locations (ESP111), and four locations (ESP101, ESP108C, and ESP120). The pipes terminated approximately 30 cm below the slab in a dry sump (60 cm in diameter) backfilled with washed pea gravel (see Figure 2). The purpose of this large sump hole was to provide a larger surface area in order to enhance propagation of the pressure field or ventilation of the soil near the house. It may not always be necessary to excavate this large hole, especially in situations where a continuous gravel layer is under the floor slab. SSV pipes were routed either singly or manifolded with other pipes to a fan, which was located either outside or in the garage, before proceeding outdoors. Flow and pressure control dampers were usually installed in each pipe that penetrated the slab or soil. Centrifugal fans (with speed controllers), capable of delivering 25 L s^{-1} air flow at a pressure of 125 Pascal (Pa), were installed on the pipes.

Two homes (ESP111 and ESP119) had similar SSV systems installed outside the structure with the pipes extending into the soil along the basement wall. The pipes and dry sump extended under the footer. At ESP111, both interior and exterior SSV systems were installed.

Crawl Space Isolation and Ventilation.[23] Various stages of sealing and isolation were implemented in five homes to reduce the migration of radon into the crawl space from the soil and from the crawl space into the house. Mechanical or natural ventilation was also added to remove radon from the crawl-space air and to decouple the house from the soil. None of the homes had a full crawl space -- they were always present in combination with a half-depth basement and/or a slab-on-grade floor. In house ESP119, mitigation was staged and included installation of an air-tight plastic membrane over the soil floor and concrete walls; sealing and isolating the crawl space from the house and insulating the house floor, kneewall, ducts and water pipes; and providing natural ventilation by adding approximately 1 m^2 of free air vents for every

100 m^2 of crawl-space floor area.

The "crawl space" in house ECD027 was in fact an unused, unheated, soil-floor basement. The first remedial action combined the removal of a wood-burning forced-air furnace from the basement and the installation of a wood stove on the first floor with sealing of all large openings between the basement and first floor. In addition, basement ceiling insulation with a Tyvek® membrane was installed to inhibit air infiltration from the basement to the upstairs yet to permit moisture to pass out of the insulation. An axial fan was used to evaluate combinations of crawl space (basement) ventilation, pressurization, and depressurization.

RESULTS AND ANALYSIS

Effectiveness of Radon Control Systems

So that comparisons can be made over heating season conditions, all data used in the analysis presented here were collected between November 1, 1985, and March 31, 1986. Indoor-outdoor temperature differences were generally greater for those test periods starting in November and December (mean temperature difference of 30 °C) and smaller for those periods starting in March (mean of 18 °C). However, even the period with the smallest temperature difference (16 °C) should experience sufficient radon entry rates to naturally elevate indoor radon levels. Additional, detailed information on the operating conditions, and modifications made to the mitigation systems can be found elsewhere.[11,12]

Sealing of Cracks and Holes. As seen in Table 1, sealing caused a significant reduction in indoor radon levels in only two homes (ESP120 and EVA604), although no corrections have been made for possible naturally-caused changes in the driving forces for radon entry and removal. No reductions were seen in the three houses where pre-sealing concentrations were above 740 Bq m^{-3}. It is possible that only small portions of the total crack and hole area were visible, accessible, and repairable and therefore small effects should be expected. If the resistance to soil gas flow through the soil is much

greater than the resistance to flow through all cracks, then sealing actions only begin to be effective once the total substructure crack resistance approaches that of the soil.[24] Work by Scott in residences in Canada and Florida shows that careful and complete sealing can significantly reduce indoor concentrations, but may have limited durability.[14,25]

The reduction at ESP120 (300 Bq m^{-3} to 150 Bq m^{-3}) occurred at a time when a separate SSD system was operating. This may imply that the sealing improved the performance of this system.[20] A later test revealed that a large amount of basement air was pulled through the substructure walls (constructed of field stone and mortar) and floor by the SSD system and indicated these surfaces were leaky even after sealing.

A summary of disadvantages of this technique include: (1) the difficulty in determining whether a surface defect penetrates the entire thickness of the floor or wall material; (2) the often poor access to the majority of the substructure defects, especially in finished basements; and (3) the unknown durability of the patch when subjected to normal aging and future substructure movement.

House Ventilation with Heat Recovery. Installation of new AAHX's resulted in reductions in average indoor radon levels from 410 to 120 Bq m^{-3} (ESP121) and 230 to 90 Bq m^{-3} (ESP109) when the units were operated at maximum air flow rates (Table 1). Intermediate reductions occurred with "medium" flow rates: to levels of 160 Bq m^{-3} for ESP121 and 110 Bq m^{-3} for ESP109.

Modification and operation of the previously-installed AAHX in NSP204 also reduced average radon levels. The first modification increased supply air to the basement and return air from the heated crawl space; radon levels fell from 970 Bq m^{-3} to 410 Bq m^{-3}. By further increasing the supply and return flow rates, levels were reduced to 290 Bq m^{-3}. The final modification, adding supply air to the upstairs, resulted in similar average concentrations of 290 Bq m^{-3}. Subsequently, a basement overpressurization mitigation system was operated in addition to the AAHX to bring levels below 185 Bq m^{-3}.

The additional ventilation (measured with the PFT system) provided by the AAHX did not meet the design objective of 1.0 h^{-1}, measuring 0.5 h^{-1} (0.3 to 0.8 h^{-1}) for ESP109 and 0.7 h^{-1} (0.3 to 0.9 h^{-1}) for ESP121. However, the reduction in radon for these two homes agreed with the reduction calculated due to the PFT-measured increase in ventilation as seen in Figure 3. The solid curves illustrate the expected response if indoor radon levels are inversely proportional to the total ventilation rate. Implicit in this relationship is the assumption that radon entry rates before and after mitigation were approximately equal. For house NSP204, the measured radon levels do not agree with the relationship because modifications to the air distribution system improved the effectiveness of the ventilation and radon removal.

The overall thermal efficiency of sensible heat exchange (heat increase of supply air minus power required by motors divided by the heat recovered from exhaust air in a 100% efficient AAHX) was calculated for the AAHX systems in ESP109 and ESP121 based on data taken over approximately three weeks in March. Large variations in the calculated efficiency (from 0.4 to 0.7) were probably due to brief periods of mild outdoor temperatures alternating with colder periods that caused the frost protection devices to operate. The mean overall efficiency for this three-week period was 0.55 for ESP121 and 0.63 for ESP109.

There are several disadvantages to the use of air-to-air heat exchangers: (1) they are limited to applications where air distribution can be improved or where initial radon levels or ventilation rates are sufficiently low so that a reasonable increase in ventilation rate will reduce radon concentrations below the target level; (2) there is a high initial cost for the installation of a ducted central unit (wall and window units with proper freeze protection may be more economical to install); and (3) they are fairly complex systems that require flow balancing, frequent changing of filters, blower lubrication in some units, and annual cleaning of the heat exchanger core.

Basement Overpressurization. By increasing pressures in the basements first to

overcome the natural depressurization due to the thermal stack effect and then by an additional average of two to three Pascals (referenced to the external soil probe), average indoor radon levels were reduced to below 185 Bq m^{-3} (Figure 4). Incremental increases in the overpressurization resulted in lower concentrations. Fan flow rates from 140 to 230 L s^{-1} were necessary to develop 1.5 to 3 Pa overpressurization.

The relationships between the amount of overpressurization and the indoor radon concentrations and radon entry rates were examined by comparing the normalized radon entry rates and basement overpressurization data from four houses in Figure 5. Entry rates were estimated using ventilation measurements from the period closest to the radon measurements, then were normalized by the pre-mitigation entry rate for that house. Increasing overpressurization tends to decrease the radon entry, with each house exhibiting a different response. One might expect that pressurization of the basement to "zero" in order to exactly offset the average natural depressurization would be sufficient to inhibit soil gas entry. However, a slight overpressurization may be necessary to overcome the periods of greater basement depressurization caused by transient environmental conditions including larger temperature differences (ΔT) and wind speeds. Increasing the overpressurization reduces the overall radon entry rate by reducing the percentage of time that the substructure is subjected to natural depressurization. It is also possible that since the measured pressure differences were referenced to mid-height in the basement, pressure differences at the basement floor may be negative more frequently, permitting radon to enter through openings at that location.

Although this experimental technique can be highly effective, it has the following possible disadvantages: (1) implementation is possible only in basements with ductwork, ceilings, and walls that can be tightly sealed; (2) overpressurization can be easily destroyed by occupants opening basement windows or doors (occupants must be thoroughly familiar with the concept of the system); (3) noise from the fans and large flows of air can be objectionable; (4) excessive upstairs depressurization can cause

backdrafting of combustion-fired appliances and cold drafts from infiltrating air; (5) unintentional heating of basements with warm upstairs air can cause additional heat loss; (6) the overall house ventilation rate may increase and lead to larger heating and cooling loads; and (7) the potential for moisture damage to house structural components in the basement from the forced exfiltration of warm, moist, indoor air is increased in cold climates.

Subsurface Ventilation. As seen in Figure 6, SSV systems always reduced first floor radon concentrations below the target of 185 Bq m^{-3}, either initially or after system modification. It was also discovered that in every case where SSD and SSP were compared for these homes, SSP was more effective. For example, in house ESP111, an SSD system operating at a pressure of -430 Pa reduced average upstairs radon levels from 1800 Bq m^{-3} to 1000 Bq m^{-3}. After switching to SSP at +580 Pa, levels were further reduced to 160 Bq m^{-3} (Figure 7). Adding two exterior SSV pipes, pressurizing to approximately +500 Pa, and removing one interior SSV pipe yielded an average final concentration of 70 Bq m^{-3} upstairs.

In another example of the better performance of SSP systems, average radon levels at ESP120 were reduced from 4300 Bq m^{-3} upstairs and 5200 Bq m^{-3} in the basement to 150 and 390 Bq m^{-3}, respectively, when four SSV pipes were depressurized to -370 Pa at a total flow of 90 L s^{-1}. When the fan was reversed and the system operated as a SSP at +270 Pa, radon levels were reduced to 80 Bq m^{-3} upstairs and 100 Bq m^{-3} in the basement. The SSP proved so efficient that concentrations remained low after one SSV pipe was removed.

An explanation of the advantage of SSV overpressurization for the highly permeable, low emanation-rate soils at these study sites can be constructed, but remains speculative. It is helpful to consider subsurface depressurization as a pressure field system that reduces soil gas entry into structures, while subsurface overpressurization is a ventilation system that dilutes radon in the soil gas before it enters the structure. At equal underpressures and overpressures (and flow rates) produced by an SSV system,

similar pressure fields, represented by similar isobars, but with opposite pressures with respect to the basement, would be created near a house substructure. In the depressurization system, the negative pressures in the soil will cause air from the house to be pulled into the soil, at least until a point is reached at some distance from the pipe(s), where the underpressure has been diminished so that soil pore and house pressures are equal. Beyond that point, any crack in the substructure will allow the higher pressure, radon-bearing soil gas to enter the house. Thus, to eliminate all soil gas entry, the depressurization system must cause an underpressure at all entry points around the understructure of the house.

On the other hand, the SSV overpressure system creates a positive pressure field in the soil that always causes air to flow from the soil into the house through cracks in the substructure (almost always at greater flow rates due to the increased driving pressures). However, the positive pressure field also inhibits the transport of radon towards the house from a distance. This, together with a net flow of comparatively low radon fresh air from the SSV pipe into the soil, causes radon concentrations in the soil gas near the substructure to be diluted. The overpressure system may still be effective (where the depressurization system begins to fail) because, although air is passing into the house from the soil, it is relatively low in radon concentration. In support of this explanation, a sudden rise in indoor radon levels occurred at ESP113 after an SSD system was switched to SSP. The system initially forced high radon concentration soil gas into the house, causing the spike. As the soil gas became diluted with outside air, less radon accompanied the soil gas flowing into the house, resulting in lower concentrations. The overpressure system may fail at the point where the pressure field around the house has decreased to approximately equal the pressure of the surrounding soil. At this point, ventilation and dilution of the soil gas are no longer taking place. Stated another way, success of the overpressure system may depend on the fact that a parcel of fresh outside air from the SSV pipe that eventually re-enters the house picks up only a small amount of radon from the soil through which it passes. Therefore, a

short residence time of the air parcel in the soil (as determined by the soil path length, soil air permeability, and pressure difference) and a low soil emanating radium concentration may be necessary for the overpressure system to be effective.

Preliminary data were collected on the possibility of freezing soil and sub-slab materials when pressurizing with cold outside air. For a five-day period in early spring, temperatures were monitored near the top and bottom of the SSV sump in ESP101 when the SSP system pressurized with outside air. The outside air temperature reached a minimum of -15°C, while the sump temperatures followed the diurnal pattern, never going below +2°C. Apparently the warm interior SSV piping and material comprising the slab and the subsurface region near the pipe tempers the cold incoming air. It is not known what effect substantially colder outside temperatures would have on the sump temperatures nor what would result if those materials were to freeze.

Since most SSD system fans exhausted outdoors at the level of the basement ceiling, we measured the radon concentrations of SSD exhaust gases that could be re-entrained back into the building along with infiltrating outside air around the sill and basement windows. Concentrations in grab samples from within the SSD pipes at four houses ranged from 8900 to 17,000 Bq m^{-3} and compared with average measured and calculated[3] soil gas concentrations that ranged from 12,000 to 20,000 Bq m^{-3} and from 16,000 to 24,000 Bq m^{-3}, respectively. During a calm period at ESP120, grab samples of outdoor air were collected at 0.3 m and 0.6 m horizontal distances from the fan exhaust and had concentrations of 2400 Bq m^{-3} and 150 Bq m^{-3}, respectively as compared with grab samples of nearby, uncontaminated outdoor at less than 20 Bq m^{-3}. The exhaust pipe was temporarily extended several meters from the house, but indoor radon levels were not reduced further. Thus, we concluded that in this case SSD exhaust re-entrainment was not a significant source to the indoor air.

The various SSV systems have the potential to reduce near-house radon concentrations in the soil gas by dilution. Data collected at these houses where soil gas

radon concentrations exhibited the largest change are illustrated in Figure 8. Both SSD and SSP caused reductions although the SSP system at ESP120 had the greater effect. Soil gas radon concentrations at the control homes demonstrated less reduction for the same period. If, as we assume, the SSV systems caused the reduction in soil gas concentrations at these three homes, it implies that very large soil volumes are affected by the systems, since the soil probe pipes were up to 10 m from the nearest SSV pipe. However, the same magnitude reduction in soil gas concentrations was not observed at ESP119 and other factors, such as precipitation, might have also affected soil gas radon levels.

In an experiment designed to estimate the amount of basement air entrained into the SSD exhaust air, sulfur hexafluoride (SF6) tracer gas was mixed with the basement air at houses ESP101 and ESP120 to a concentration of approximately 50 ppm. With the SSD operating, concentrations of SF_6 were monitored in the SSV pipes and basement air. Results indicate that approximately 40% of the SSD exhaust air in ESP101 and approximately 80% in ESP120 originated in the basement. This basement air was pulled into the soil through cracks and openings in the substructure walls and floors by the depressurization in the soil surrounding the substructure. Apparently these substructure surfaces can be quite leaky and have a large effect on the flow and operation of the SSV systems.

In addition to these below grade leaks, other near-house conditions such as air gaps, gravel fill below slabs, and less tightly packed backfill material can cause high "effective" permeabilities, as seen by the SSV system. Data from a study of seven New Jersey homes indicate that the effective permeabilities were a factor of 100 greater than the air permeabilities of the surrounding, undisturbed soil.[26]

Disadvantages to the use of subsurface ventilation systems include: (1) the difficulty of identifying optimal locations for pipe penetrations; (2) the possibility of water vapor condensation on the exterior surfaces of the interior SSD pipes in the summer and the SSP pipes in the winter (perhaps becoming frost); (3) the risk of

freezing the soil, water pipes or drain pipes below the slab when using an SSP system (colder slab floors and increased heat loss through the floor and SSP pipe may also result); (4) the unknown effects (e.g., on soil moisture) of blowing/sucking large volumes of air through the soil; and (5) the possible necessity of routing SSD system exhausts away from the ground level, windows, and doors.

Crawl Space Isolation and Ventilation. Crawl space mitigation techniques were installed in stages at four of five homes, the exception being NCD077. While the data from the sealing techniques are informative, ventilation alone appears to eliminate most of the radon from crawl spaces (Figure 9). Various stages of this work are discussed, using examples from two houses: ESP119, and ECD027 that has a basement resembling a crawl space.

Sealing the soil floor of the crawl space in ESP119 reduced average first floor radon concentrations approximately 30% and average crawl-space concentrations approximately 45%. Isolating the houses from the crawl spaces by sealing the house floors, knee walls, and forced-air furnace ductwork (ESP119) reduced the crawl space air leakage area from 510 cm^2 to 150 cm^2 (71%) at ESP119 and from 9400 cm^2 to 910 cm^2 (90%) at ECD027. Adding the Tyvek® barrier to the house floor of ECD027 resulted in a further reduction of 90 cm^2. This isolation sealing work lowered average first floor radon concentrations (another 10% in ESP119, and 45% in ECD027), but raised average crawl-space concentrations (to only 22% lower than baseline conditions in ESP119, and to 250% of baseline conditions in ECD027). The addition of natural ventilation to the crawl spaces was more effective in ESP119 because more vent area was added; lowering first floor and crawl-space radon levels another 20% and 73%, respectively. In this house, an attached basement was also a source of indoor radon and required the installation of an exterior SSD to bring final indoor levels below the target concentration. Because the addition of natural ventilation to the crawl-space-like basement of ECD027 had minimal impact on first floor radon concentrations, other ventilation strategies were evaluated. Mechanical depressurization (-3.5 Pa) and

ventilation of the crawl space decreased first floor levels to approximately 10% of baseline levels, but increased crawl-space levels. When natural pressures were restored and crawl-space ventilation was boosted, average first floor concentrations were unchanged and crawl-space concentrations fell. Finally, pressurization and ventilation of the crawl space at the highest pressure (+5 to +9 Pa) reduced both first floor and crawl-space radon levels below the target concentration.

Bulk soil gas entry was dramatically demonstrated when the lightweight plastic membrane covering the floor in ESP119 was inflated until it eventually occupied one half the volume of the crawl space. Grab samples of the air from under this plastic had radon concentrations of 12,000 and 10,000 Bq m^{-3} on two separate days, verifying that soil air had inflated the membrane. During this episode, the soil gas entry rate into the membrane was estimated to be roughly 1.4 to 1.9 L s^{-1}. After the crawl-space vents were opened, the house was decoupled from the soil and the plastic membrane was deflated.

Possible disadvantages of crawl-space isolation and ventilation are freezing of exposed pipes in cold climates; and additional thermal energy losses from adjoining floors, walls, and heating/cooling delivery systems, unless thermal insulation is added.

Post-Mitigation Ventilation Rates and Indoor Air Quality

Changes in ventilation rates and the indoor concentrations of water vapor, formaldehyde, and respirable suspended particles following mitigation were reviewed. The data were not corrected for different environmental conditions between the pre- and post-mitigation periods except that outdoor concentrations of H_2O and HCHO were subtracted from the respective indoor levels.

Ventilation Rates. The PFT ventilation measurement technique provides information on the amount of outside air passing directly into a substructure, the total ventilation rate of the substructure (including air flowing from other building zones), and the total ventilation rate of the entire house. Although there were only a few homes involved in

this study, some obvious trends appear. Basement overpressurization boosted total basement ventilation by factors of approximately 1.3 to 4.5, while the entry of outside air into the basement was reduced or eliminated. Although basement overpressurization might be expected to increase the whole house (all heated zones that could be occupied) ventilation rate, only two of the six homes with this system installed had greater ventilation rates after mitigation by factors of 1.6 and 1.7. Whole house ventilation rates in the remaining homes were only 60% to 90% of the baseline ventilation rates.

The AAHX's not only increased the whole house ventilation rate significantly, but dramatically increased the supply of outside air directly to the basement of NSP204 by a factor of 4.9. Improving the local ventilation at the radon source in this house by modifying the AAHX distribution system caused the large reductions in indoor radon levels.

For crawl space mitigation techniques, sealing the floors of two houses reduced the outside air infiltration into the crawl spaces by 72% and 55%. Of course, both natural and mechanical crawl-space ventilation increased crawl-space ventilation rates. However, none of this work appears to have a large impact on the whole house ventilation rates.

Whole-house ventilation rates did not change consistently after operation of the subsurface ventilation systems. In five of the seven homes the post-mitigation ventilation rates were higher by factors of 1.3 to to 3.8, and in the remaining two ventilation rates were lower than during baseline by factors of 0.5 and 0.7.

Pollutant Concentrations. The effect of the radon control systems on indoor concentrations of H_2O, HCHO, and RSP is inconclusive, but probably minor since changes in other factors tend to be overwhelming; for example, occupant water use and environmental conditions influence indoor humidity; relative humidity and indoor temperature influence indoor formaldehyde concentrations; and tobacco smoking, woodstove and fireplace use, and outdoor particle concentrations influence indoor particle concentrations. The measured data are presented in Turk et al.[11]

Mitigation Costs

The cost of controlling radon is an important, and perhaps overriding, issue for occupants, buyers, and sellers of radon-contaminated properties. The following points should be kept in mind while reviewing the summarized data: (1) since this was a research project with many objectives, we did not always optimize installation and operation costs of the systems, (2) a wide variety of house-specific conditions and system equipment resulted in large and uncertain ranges of installation and operation costs, (3) contracted labor rates, materials cost, and overhead and profit can be considerably different than those used here, and (4) the installation costs data do not reflect the costs of designing the mitigation systems.

Installation. The sub-contractors that were hired to perform the remedial action had no previous experience in installing radon control systems, but they were experienced at general house construction and familiar with most construction techniques. The costs are summarized in Table 2. Note that labor effort also includes supervision, travel time, and gathering of materials. The large range of costs for a particular technique was due to the size of the area to be treated, complexity of the system to be installed, and the amount of finishing necessary to reduce the obtrusiveness of the system. In addition, cost reductions occurred as the contractors became more familiar and efficient in the installation of these systems. The last column in this table gives the cost per unit of treated floor area. For example, in the case of a vented crawl space, this is the area of the crawl space; for a subsurface ventilation system, it is limited to the basement floor area. The treated unit cost for the air-to-air heat exchangers was based only on the floor area of the basement to allow a comparison between techniques. For these comparisons the median values are indicative, but not necessarily representative.

Crack and hole sealing was the least expensive technique, yet it was also the least effective in controlling radon. If larger areas were treated, and more cracks and holes sealed, the cost undoubtedly would have increased considerably. The costs for

basement overpressurization include the addition of backdraft dampers to the furnaces and sealing of the floor between the basement and the superstructure. The backdraft dampers increased installation costs by approximately $200 in the four homes where they were necessary, making this technique almost equivalent in cost to that of the subsurface ventilation systems. Crawl-space sealing and ventilation was surprisingly expensive, being as high, or higher, than other techniques. This was, in large part, due to the experimental plastic membrane installed over the soil at ESP119 and ECD153, the air infiltration barrier under the first floor at ECD027, the insulation of ducts, floors and pipes at ESP119, ECD027, and NCD077, and performing the work in stages at all houses except NCD077.

Estimated Operating Costs. Table 3 summarizes estimated costs to operate three different systems. Fans were assumed to operate continuously for 12 months, while energy loss due to additional ventilation was based on a 9-month (September-May) heating season and average monthly indoor-outdoor temperature differences. We assumed that the homes were not air conditioned, therefore no costs would be associated with additional ventilation in the summer. An estimate of the additional house ventilation caused by system operation is shown in columns 5 through 7. The data are based on measured ventilation rates corrected by changes in ventilation measured in the control houses over the same period. While these corrected ventilation rate changes may be substantially in error, they serve to demonstrate the effect of a range of changes in ventilation on operating cost.

It is possible that, in some homes, basement overpressurization systems that use warm upstairs air can increase air temperatures in unoccupied basements, resulting in additional conductive heat losses through exterior basement walls and floors. We examined before and after temperatures in basements in these study houses and found no significant increase, probably because these basements were occupied and heated before the study began. All operating costs were calculated with electricity as the primary fuel and using the low regional rate of $0.03/kWh. These costs would be

approximately 2.5 times higher at the national average electricity rate.

We see that the range of total annual energy costs for the three systems are similar; $70 to $120 for basement overpressurization, $80 to $170 for SSV and $60 to $110 for AAHX. Because of the small number of homes in this comparison and the uncertainty in ventilation changes, we do not know whether system operating costs in other homes would fall within these ranges. Although the energy operating costs of AAHX's are comparable to the other techniques, the AAHX's would be unable to control the high radon concentrations that are effectively reduced by the other systems.

SUMMARY AND CONCLUSIONS

Several techniques for reducing excess radon concentrations in homes were demonstrated and evaluated. Table 4 is a summary of the effectiveness of the final mitigation configuration for each home. Subsurface ventilation by SSP was chosen as the preferred technique for the two control homes upon completion of the project on the basis of the experience gained in the five test houses. Although SSP always resulted in greater reductions of indoor levels than SSD in these homes, SSP cannot be expected to be more effective in all other homes with high indoor levels. More study of the differences between these two systems and their long-term effects on soils and materials surrounding substructures is necessary.

Basement overpressurization (or a variant thereof) was a new technique that may be competitive with SSV in homes with basements that can be sufficiently air-tightened so that a fan pulling air from upstairs can pressurize the substructure to 1 to 3 Pa above the outside pressure. Several disadvantages must be overcome before this system is widely applied. Its long-term reliability is unknown, since occupants may easily defeat the substructure overpressures.

Sealing the soil floors of crawl spaces and isolation of the crawl space from the remainder of the house were only partially successful in reducing indoor radon levels. In these houses, crawl-space ventilation alone was the single most important measure to reduce radon entry from the crawl space. Other, more recent studies indicate that an

SSD system that pulls air from below a polyethylene membrane placed on the soil floor is equally or more effective.[27,28,29] In homes that have basements in addition to crawl spaces, mitigation of crawl-space radon levels alone may not be sufficient to reduce radon levels in the house to below guideline levels.

The installation of AAHX's in homes with low ventilation rates and moderate concentrations of indoor radon may continue to be competitive. For two homes in this study, it was confirmed that indoor radon levels were approximately proportional to the reciprocal of the total ventilation rate.

Mitigation system installation costs in these homes were very dependent upon house-specific construction, interior finish, and homeowner demands, and had a large range. Regional differences in labor and materials costs could increase the range even more. In addition, operating costs were difficult to estimate due to the uncertainty in determining the amount of additional ventilation, if any, that was caused by the mitigation systems. However, the range of operating costs was similar for all of the active systems (approximately $60 to $170 per year) although it was depressed by the low rates for electricity in the region.

This study has provided further evidence that elevated radon levels in homes can be reduced to below existing guidelines with technologies that are compatible with current construction practices. In addition, through proper selection and design, the systems evaluated here appear to be affordable and have little impact on several other factors affecting the quality of the indoor environment. However, most of the successful systems make use of fans and other mechanical devices that may eventually fail in the future and will require periodic inspection to ensure their continued operation.

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Table 1. Radon reductions due to crack and hole sealing and air-air heat exchangers.

	First floor [Mean Rn Concentration (Bq m^{-3})/Std. Error - Monitoring Hours]	
Mitigation Technique/House ID	Initial Condition	After Mitigation
Crack & Hole Sealing		
ESP111	1100/25 - 322	1060/21 - 401
ESP101	1020/5 - 1133	1050/7 - 916
ESP116	750/7 - 836	860/7 -1425
EVA604	390/1 - 1637	270/2 - 484
ESP120	300/4 - 173	150/2 - 428
Air-Air Heat Exchangers		
NSP204:		
Improve distribution (#1)	970/14 - 843	410/7 - 327
Improve distribution (#2)		290/6 - 341
ESP121	410/3 - 543	120/1 - 604
ESP109	260/2 - 940	90/1 - 525

Table 2. Mitigation system installation costs.

MITIGATION TECHNIQUE	LABOR EFFORT (Man-hrs)	MATERIAL & EQUIP. ($)	TOTAL COST[a] ($)	TREATED FLOOR AREA[b] UNIT COST ($/m^2)
CRACK AND HOLE SEALING				
Median	16	26	360	4
Range	2 - 25	3 - 60	50 - 610	1 - 9
Number of Houses - 4				
AIR-TO-AIR HEAT EXCHANGER				
Median	44	1010	2160	28
Range	33 - 54	990 - 1040	1960 - 2350	26 - 30
Number of Houses - 2				
BASEMENT OVERPRESSURIZATION				
Median	22	330	840	12
Range	9 - 27	120 - 680	340 - 1400	5 - 16
Number of Houses - 5				
SUBSURFACE VENTILATION				
Median	51	400	1470	14
Range	22 - 82	300 - 600	820 - 2420	9 - 32
Number of Houses - 7				
CRAWLSPACE ISOLATION AND VENTILATION				
Median	26	320	940	25
Range	10 - 61	140 - 1010	450 - 2530	8 - 38
Number of Houses - 5				

(a) Calculated assuming average labor cost of $18/hr, 20% overhead and profit, exclusive of any sales tax

(b) Generally refers to substructure floor-type being treated (crawlspace, basement, slab-on-grade)

Table 3. Estimated mitigation system operating costs.

MITIGATION TECHNIQUE	SYSTEM FAN Rating (Watt)	SYSTEM FAN Annual Energy (Kwh)[a]	SYSTEM FAN Annual Oper. Cost ($)[b]	ESTIMATED ADDITIONAL VENTILATION Added Vent. h^{-1}[c]	ESTIMATED ADDITIONAL VENTILATION Annual Energy (Kwh)[d]	ESTIMATED ADDITIONAL VENTILATION Annual Cost ($)	ESTIMATED TOTAL ADDITIONAL ANNUAL ENERGY COST Energy (Kwh)	ESTIMATED TOTAL ADDITIONAL ANNUAL ENERGY COST Cost ($)
AIR-TO-AIR HEAT EXCHANGER								
Median	180	1560	50	+0.56	--	--	2800	80
Range	160 - 195	1400 - 1710	40 - 50	+0.45 to +0.67	--	--	2050[e] - 3540[f]	60 - 110
# Houses - 2								
BASEMENT OVERPRESSURIZATION								
Median	135	1200	35	+0.03	2060[g]	60[g]	3030[g]	90[g]
Range	100 - 155	870 - 1380	25 - 40	-0.05 to +0.20	1320 - 2800 [g]	40 - 80[g]	2190 - 3870[g]	70 - 120[g]
# Houses - 4								
SUBSURFACE VENTILATION								
Median	150	1330	40	+0.19	2920[g]	90[g]	4250[g]	130[g]
Range	45 - 170	390 - 1470	10 - 45	+0.10 to +0.27	1400 - 4440[g]	40 - 130[g]	2770 - 5740[g]	80 - 170[g]
# Houses - 4								

(a) System operated continuously for 12 months

(b) Electricity rates of $0.03/Kwh

(c) Based on changes in ventilation as corrected by control house data. While values may not represent actual changes, they show the effect of a range of changes

(d) Based on 9-month operation, September-May, and average monthly indoor-outdoor temperature difference

(e) Using energy exchange efficiency of 0.63

(f) Using energy exchange efficiency of 0.55

(g) Only for those two houses with increases in ventilation rates

Table 4. Summary of mitigation system effectiveness and cost

	INDOOR RADON ($Bq\ m^{-3}$)					
	Baseline		Final			
House ID	Main Flr.	Bsmt/Crwl	Main Flr.	Bsmt/Crwl	Final Mitigation Configuration	Installed Cost ($)
ECD026C	660	730	100	110	Crawlspace mechanical ventilation + 1-pipe subsurface pressurization (April - ΔP = +500 Pa)	1300
ECD027	1700	3100	20	50	Crawlspace isolation and pressurized ventilation to +5 to +9 Pa	2530
ECD153	900	ND	90	ND	Basement overpressurization to +2 to +3 Pa	840
NCD077	860	ND	120	ND	Crawlspace isolation and ventilation + basement overpressurization to +1.5 to 2.0 Pa	1710
ESP101	1000	ND	40	70	Holes sealed + 3-pipe subsurface pressurization (ΔP = +175 Pa, flow = 25 Ls^{-1})	2730
ESP108C	540	600	50	60	4-pipe subsurface pressurization (ΔP = +400 Pa, flow = 55 Ls^{-1})	1470
ESP109	260	ND	90	ND	Central AAHX in basement	2350
ESP111	1100	ND	70	120	Holes sealed + 2-pipe exterior and 1-pipe interior subsurface pressurization (ΔP = +490 Pa)	1610
ESP113	730	ND	70	ND	1-pipe subsurface pressurization (ΔP = +120 Pa, flow = 8 Ls^{-1})	960
ESP116	750	ND	130	ND	Holes sealed + basment overpressurization to +1.7 Pa	1450
ESP119	1800	4100	70	30	Crawlspace floor seal, isolation and ventilation + 3-pipe exterior subsurface depressurization (ΔP = -190 Pa, flow = 13 Ls^{-1})	2750
ESP120	4300	5200	80	100	Holes sealed + 3-pipe subsurface pressurization (ΔP = +290 Pa, flow = 95 Ls^{-1})	2680
ESP121	410	ND	120	ND	Central AAHX in basement	1960
NSP204	970	ND	110	ND	Modify existing central AAHX + basement overpressurization to +3 to +4 Pa	930
EVA604	390	ND	270	ND	18.5 m of floor cracks sealed	410

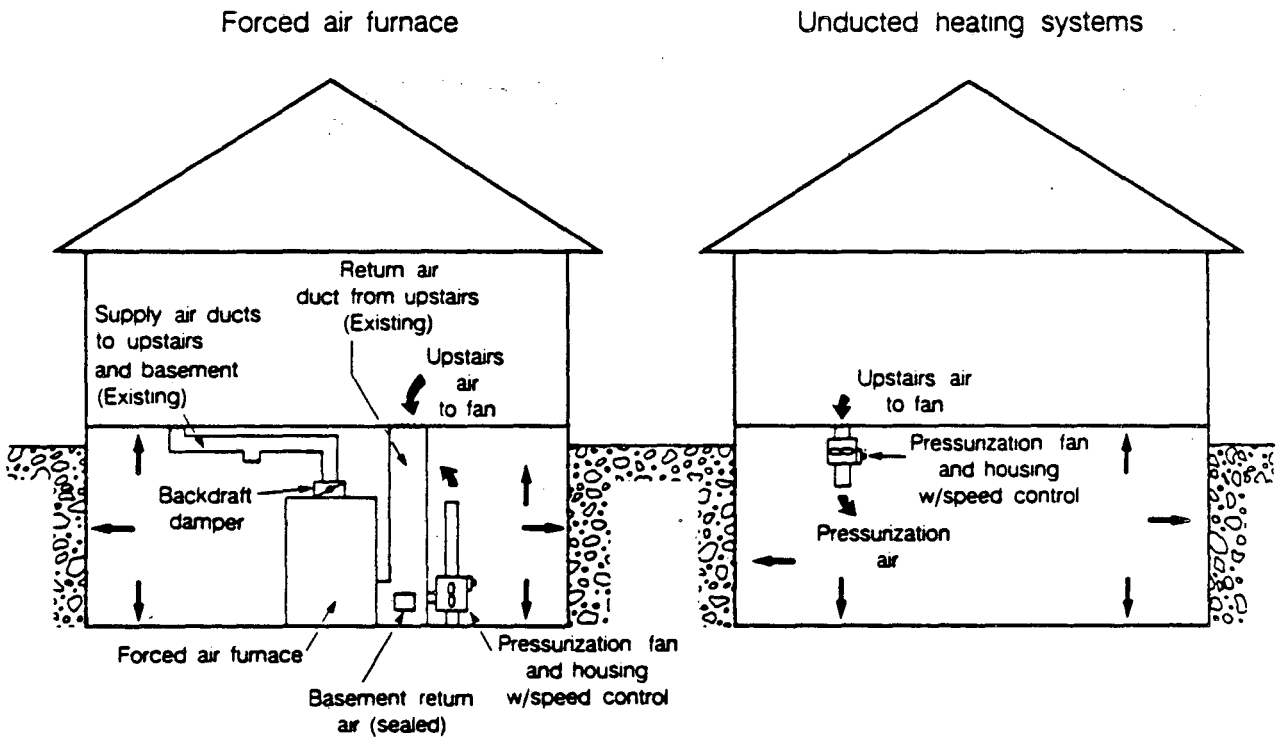
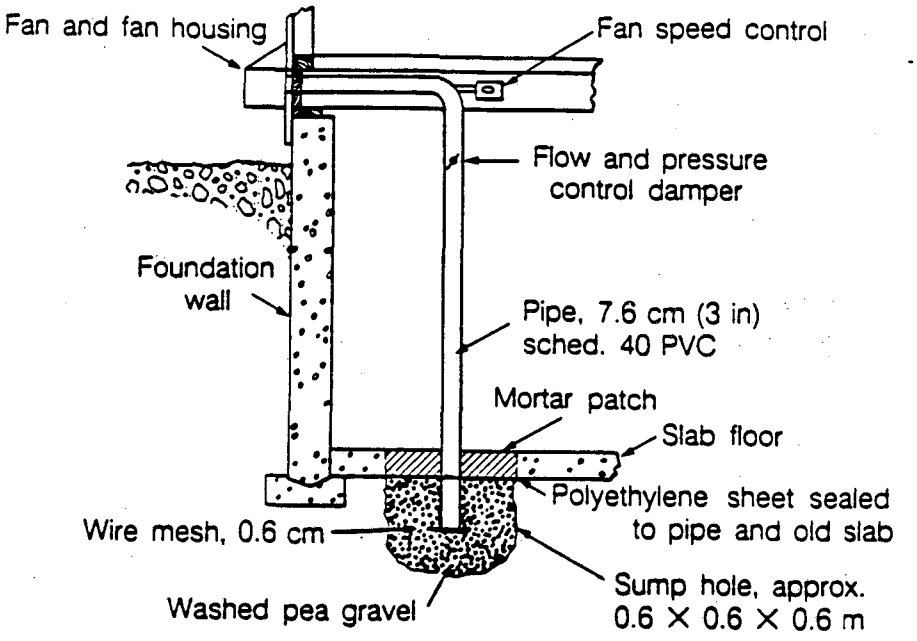


Figure 1 Typical basement pressurization systems for homes with forced-air furnaces and those with unducted heating systems. In a forced-air system, the existing return air duct from upstairs delivers air to the pressurization fan. The basement return air opening is sealed and a counter-weighted backdraft damper is installed in the supply air plenum, reducing short-circuiting of air within the basement ducting. The damper still allows delivery of conditioned air when the furnace fan operates. In both systems, sealing of air leakage paths in the basement shell may be required, so that sufficient basement pressure can be attained.

(a)



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(b)

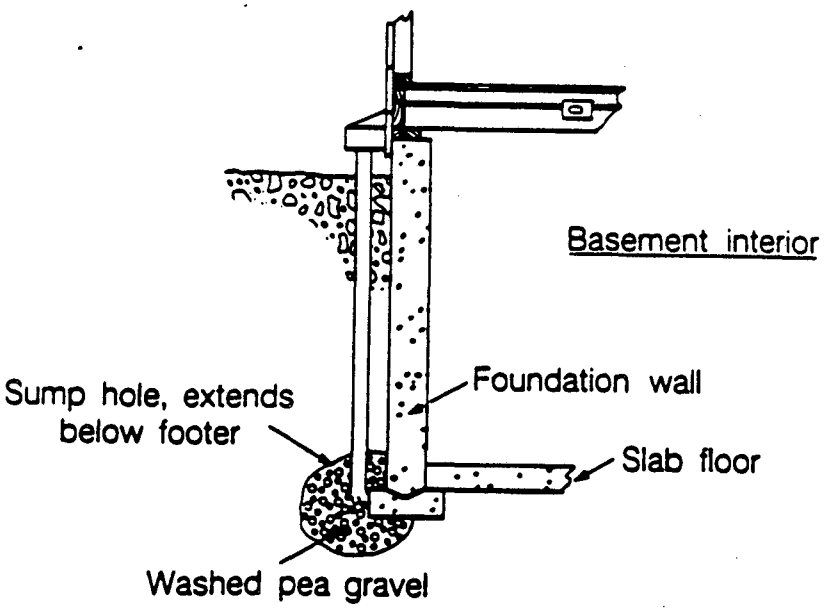

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Figure 2 Simplified schematic diagram of subsurface ventilation systems (SSV). Flows and pressures can be controlled either with the in-line damper or the fan speed control. The systems can be operated under depressurization (SSD) -- drawing soil gas from under the slab and exhausting it outdoors, or under pressurization (SSP) -- blowing outside air into the soil beneath the slab. An exterior system (b) is an alternative where an interior system (a) is impractical to install.

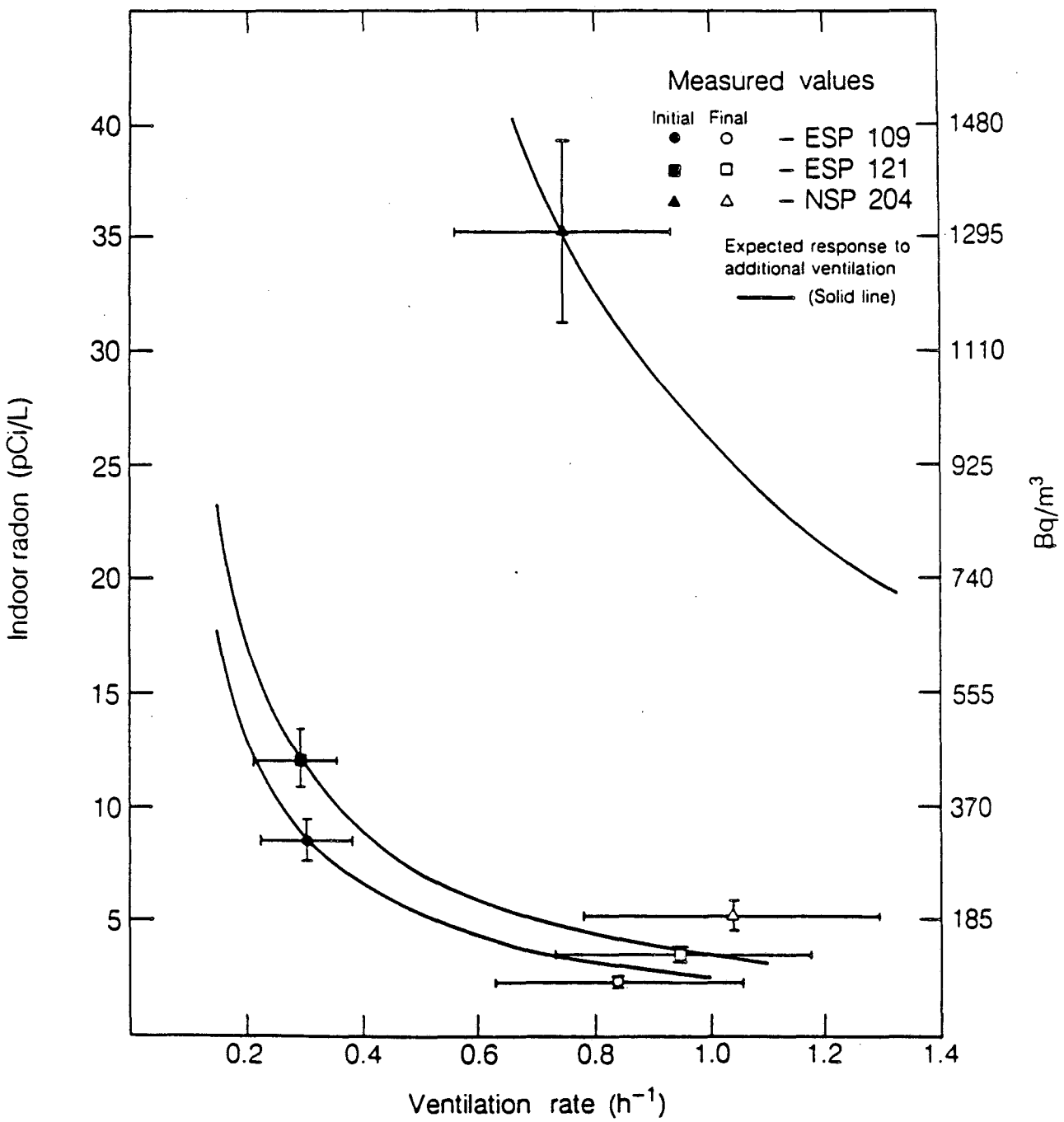

Figure 3 Comparison of the calculated effect of additional whole-house balanced ventilation on radon levels with actual measured data for the three homes with an AAHX. The solid symbols identify averages of the seven-day pre-mitigation period, open symbols the post-mitigation period. The expected response is indicated by the solid lines. The error bars for ventilation represent ±20% uncertainty, while those for radon concentration are uncertainty of CRM (±10%).

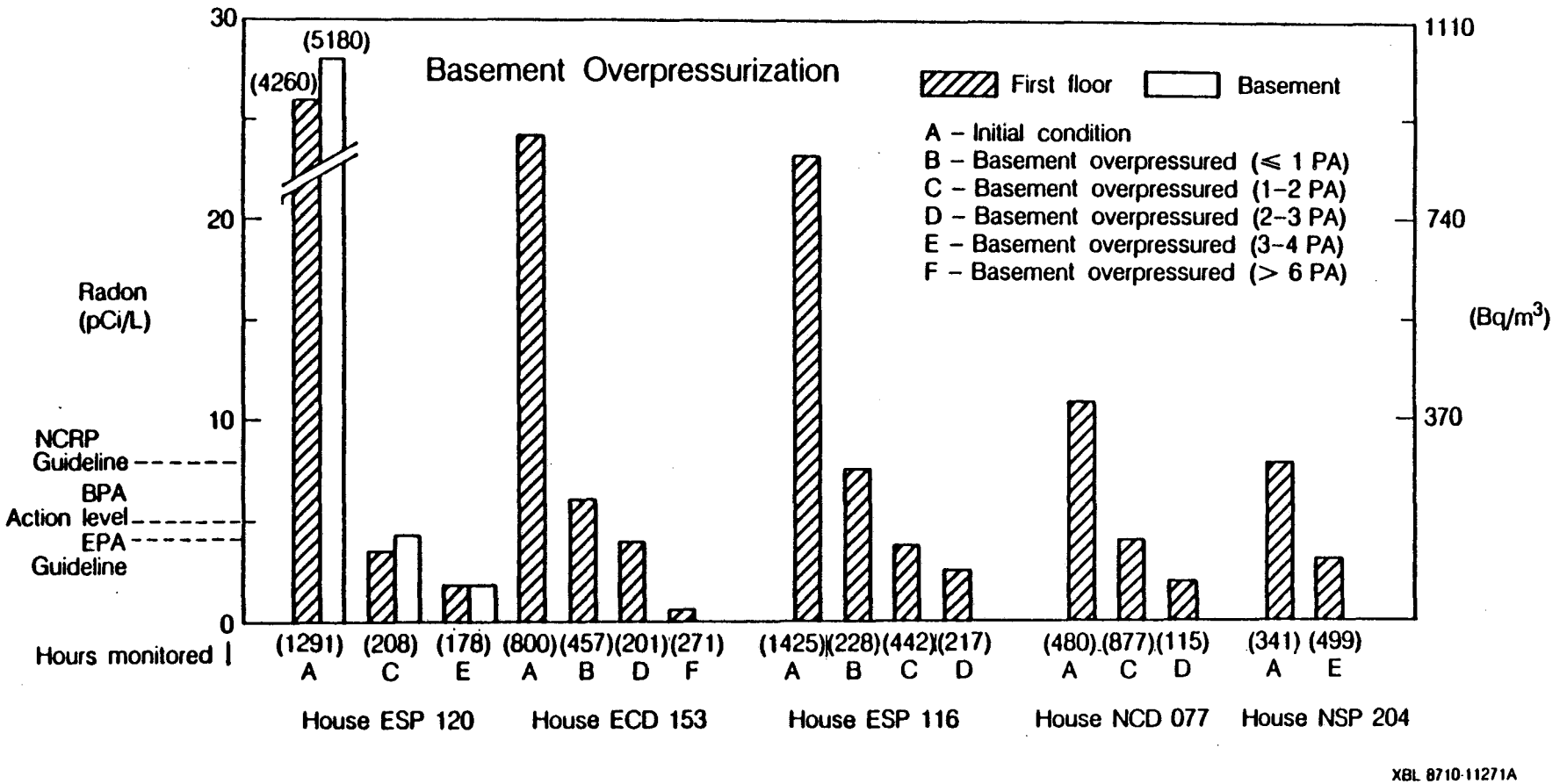

Figure 4 Reductions due to basement pressurization in five homes. Standard error of mean is much less than the instrument uncertainty (±10%) for each bar.

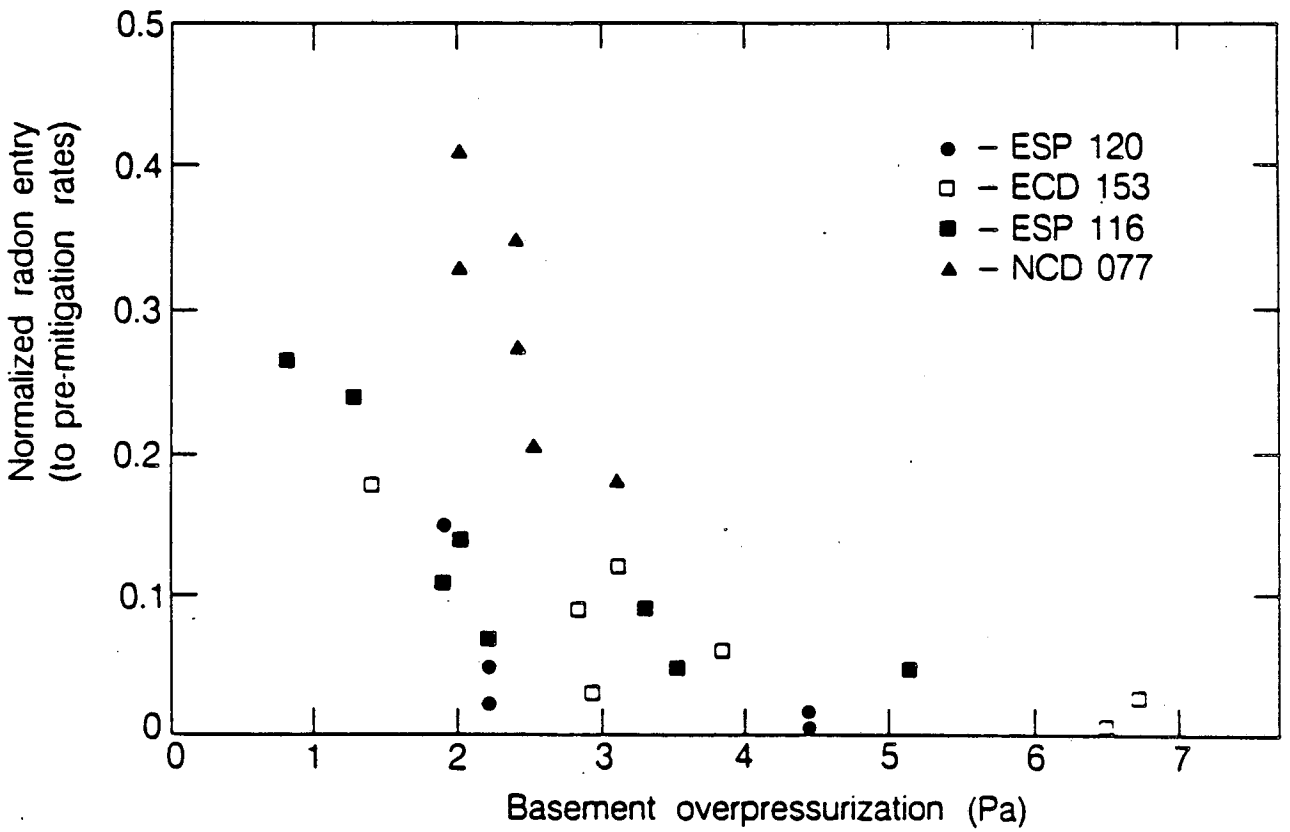

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Figure 5 Incrementally increasing basement overpressurization in four homes resulted in lower average radon entry rates. The system fan boosted basement pressures to overcome the natural depressurization and increased the pressures even more, by the values indicated. Pressure differences were measured between mid-height in the basement and the outside air (or in a nearby soil probe pipe). Measurement uncertainties for pressure are approximately ±0.5 Pa, and for entry rate approximately ±30%.

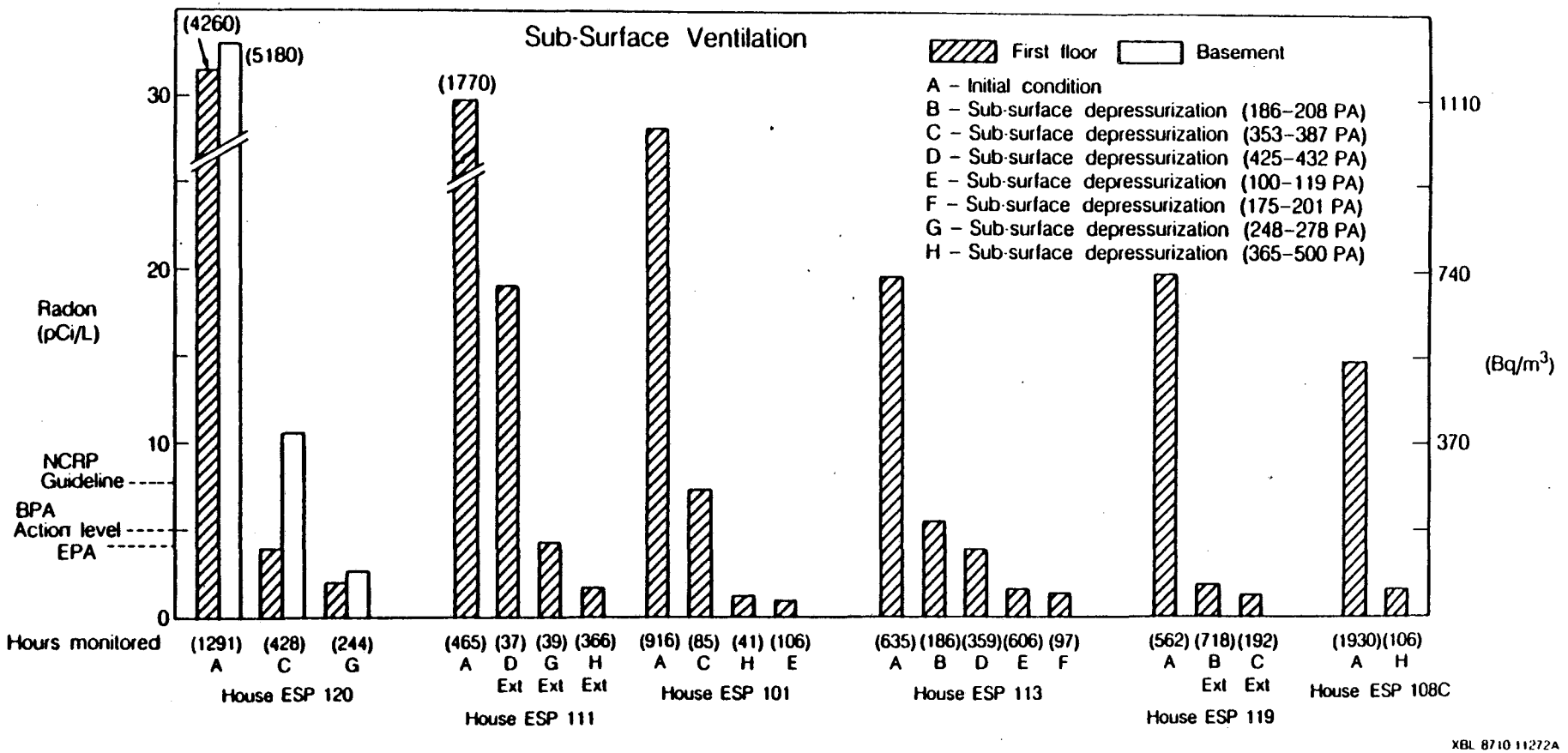

Figure 6 Radon reductions in six houses due to subsurface ventilation (SSV) by depressurization (SSD) and pressurization (SSP). Exterior SSV systems were installed in ESP111 (along with an interior SSP system) and ESP119. Data from only those homes with systems installed before March 31 are shown. Uncertainties are approximately ±10%.

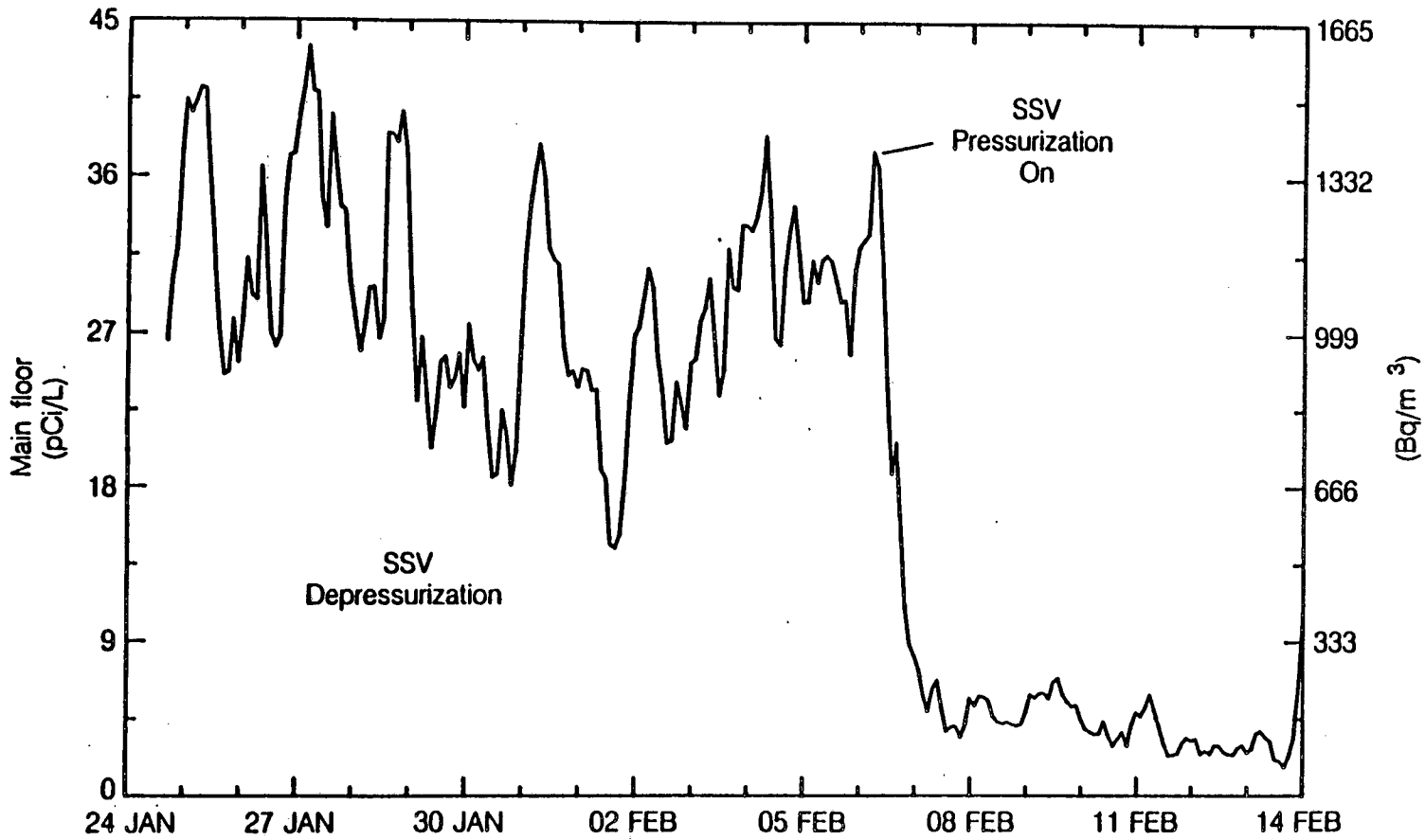

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Figure 7 Effect on indoor radon concentrations from reversing subsurface ventilation fans on February 6 from depressurization (SSD) to pressurization (SSP) in house ESP111.

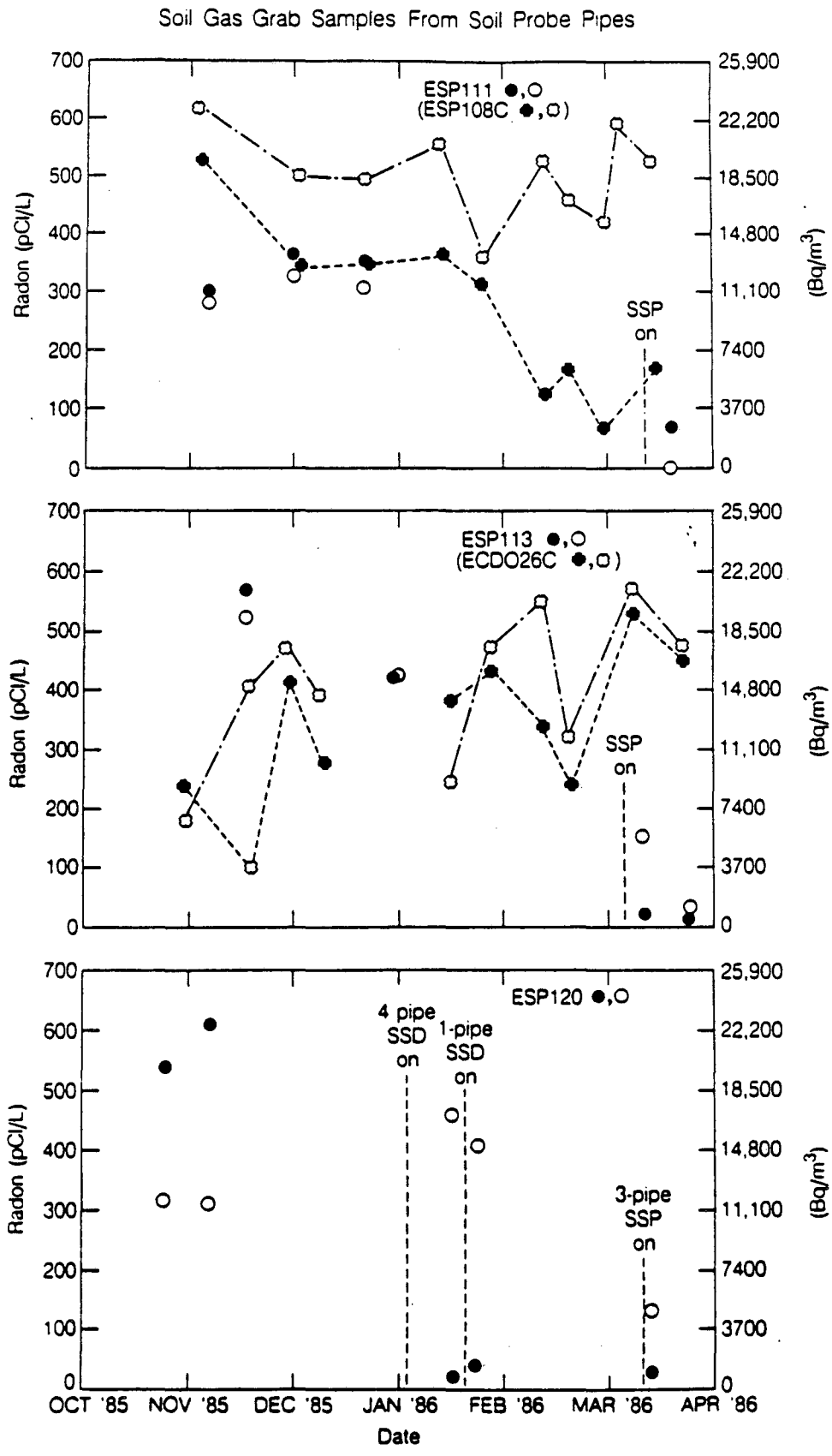

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Figure 8 Soil gas radon concentrations before and after operation of SSV systems at two soil probe pipes exterior to each of three homes are shown (solid and open circles). Data for two control homes (ECD026C and ESP108C) are shown for comparison (x and + symbols connected by dotted lines). Grab samples were collected periodically throughout the study at each of two probe pipes. The estimated uncertainty for these measurements is ±20%. Some probe pipes were more than 10 m from the nearest SSV pipe.

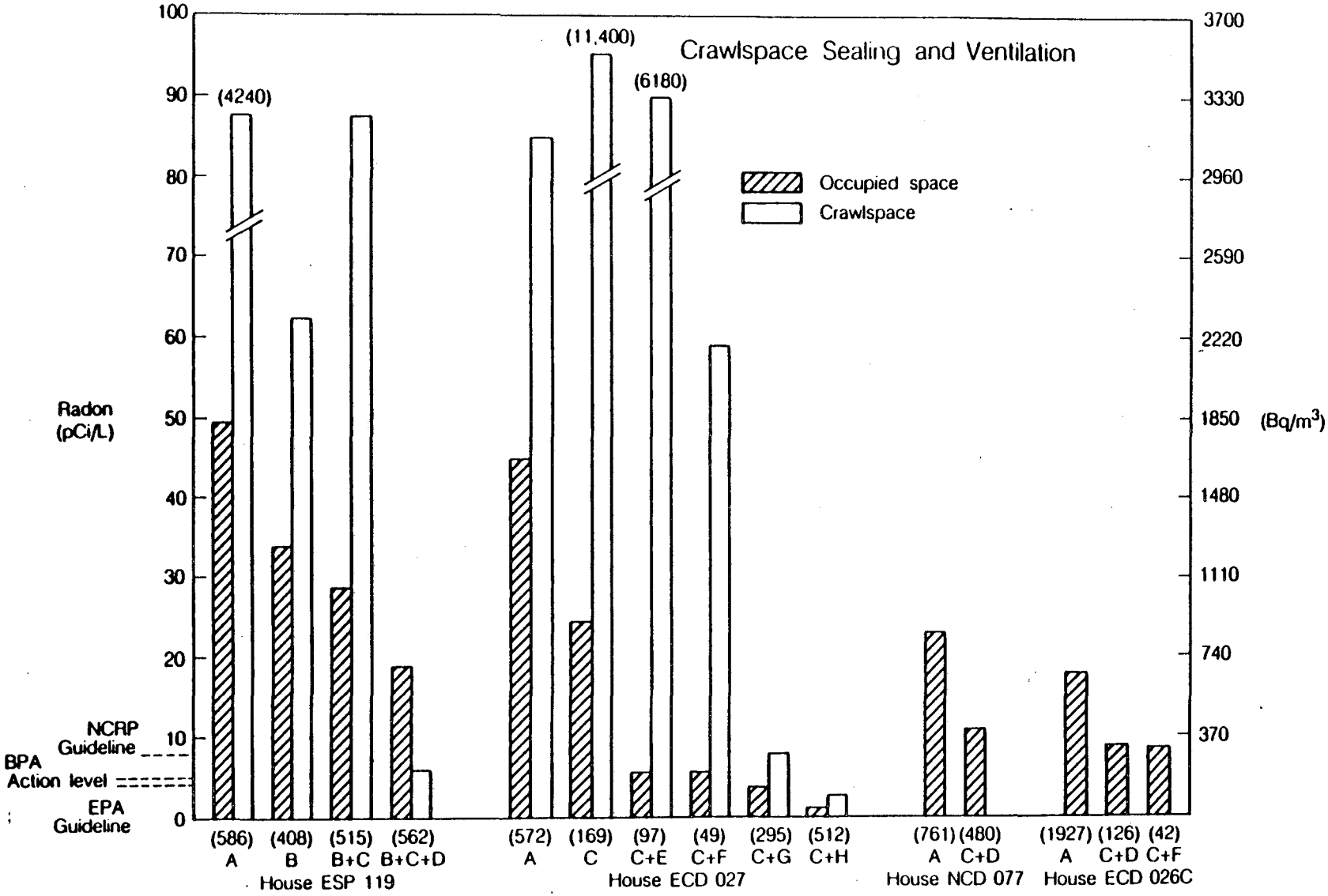

Figure 9 Radon reductions in four of five homes due to various phases of crawlspace sealing and ventilation. Codes for phases: A - initial condition; B - plastic barrier on soil floor; C - seal between crawl space and house; D - crawl-space natural ventilation; E - crawl-space mechanical exhaust ventilation (underpressure ~3.5 Pa); F - crawl-space mechanical exhaust ventilation (neutral pressure); G - crawl-space mechanical supply ventilation (overpressure ~ 2.5 Pa); H - crawl-space-boosted mechanical supply ventilation (overpressure ~10 Pa). All homes had adjoining substructures, with those in ESP119, NCD077 and ECD026C, contributing approximately half to the indoor radon levels. The instrument uncertainty (±10%) is larger than standard error of mean.

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