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Authors
Turk, B.H.
Prill, R.J.
Fisk, W.J.
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Radon and Remedial Action in Spokane River Valley Homes

Volume 1: Experimental Design and Data Analysis

Final Report

B.H. Turk, R.J. Prill, W.J. Fisk, D.T. Grimsrud,
B.A. Moed and R.G. Sextro

December 1987

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LBL-23430

RADON AND REMEDIAL ACTION IN SPOKANE RIVER VALLEY HOMES

FINAL REPORT

TO THE

BONNEVILLE POWER ADMINISTRATION

VOLUME 1: EXPERIMENTAL DESIGN AND DATA ANALYSIS

B.H. Turk and R.J. Prill

with

W.J. Fisk, D.T. Grimsrud, B.A. Moed, R.G. Sextro

Indoor Environment Program
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

December 1987

[Volume 2: Appendices are LBL-24638]

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ABSTRACT

Fifty-seven percent of 46 residences surveyed in the Spokane River Valley/Rathdrum Prairie region of eastern Washington/Northern Idaho had heating season indoor radon concentrations above the Bonneville Power Administration Mitigation Action level of 5 pCi/L, while 65% were above U.S. Environmental Protection Agency guideline of 4 pCi/L. Six of these measurements were greater than 20 pCi/L. Fourteen houses from this region and one house from Vancouver, Washington were selected for more intensive monitoring and testing of radon remedial action techniques. The primary radon source was pressure-driven flow of soil gas containing moderate radon concentrations (283 to 673 pCi/L) from the highly permeable (10^{-10} to 10^{-13} m^2) soils surrounding the house substructures. Radon from other sources, including potable water and building materials, was negligible. In the high radon homes, winter indoor levels averaged 12.6 times higher than summer, while a group of low radon homes averaged only 2.5 times higher. Several radon control strategies proved to be effective. Basement overpressurization of 1 to 3 pascals was successfully applied in six homes with air-tight basements, although long-term reliability was not examined here, and could be an issue. Subsurface ventilation by pressurization was always more effective than by depressurization, probably because of moderate radium concentrations and the high permeability of local soils. Ventilation of crawlspaces dramatically reduced radon entry from crawlspaces, but did not control radon below guideline levels in homes that also have basements. Air-to-air heat exchangers in two houses with low to moderate radon concentrations reduced levels to values expected for the increased ventilation rates. Sealing of cracks and holes and two other mitigation techniques were relatively ineffective. Installation costs on a treated-floor-area basis ranged from \$12.20/m^2 (basement overpressurization) to \$27.87/m^2 (air-air heat exchanger), while annual operating costs were estimated at \$62 to \$172. Experimental diagnostic procedures were useful in identifying radon entry locations and in selection of appropriate corrective measures.

EXECUTIVE SUMMARY

This study follows the work of earlier indoor air quality surveys that identified an area in eastern Washington and Northern Idaho with high indoor radon levels. Of 69 homes monitored, 46 were located in the region known as the Spokane River Valley/Rathdrum Prairie -- a region which is characterized by high soil permeabilities. Sixty-five percent of the 46 homes had indoor radon levels above the Environmental Protection Agency (EPA) evidence of 4 pCi/L, 57% were above the Bonneville Power Administration (BPA) mitigation action level of 5 pCi/L, and 44% had concentrations greater than the National Council for Radiation Protection Guideline of 8 pCi/L.

Fifteen homes were ultimately selected to participate in this study. The objectives were:

1) to examine the efficacy of various control techniques in reducing indoor radon concentrations;

2) to study the effects of these techniques on the processes of radon entry from the surrounding soil;

3) to investigate the interactions of mitigation techniques;

4) to gain information on installation and operating costs for mitigation systems;

5) to spawn innovative ideas for new mitigation techniques; and

6) to provide a long-term solution for each participating house that would reduce average heating season radon concentrations to below 5 pCi/L, the BPA mitigation action level.

Two houses served as Controls, i.e., they did not receive any mitigation measures until completion of the project so that seasonally-varying effects of the natural environment could be monitored. Only one house, with a slab-on-grade substructure was located outside of the Valley/Prairie locale in Vancouver in western Washington. The other homes provided a variety of ages, sizes, and substructure types. All homes had poured concrete foundation walls and only two homes did not use electricity as the primary heating source.

Non-soil sources of radon were not important contributors to high indoor radon levels. Outdoor air concentrations were generally $\leq$ 0.5 pCi/L. Concentrations of radon in domestic water were typically 500 pCi/L - water, which was similar to that measured in a group of 20 homes with low indoor radon levels. It was estimated that this water generally contributed less than 0.3 pCi/L in the indoor air radon levels. Likewise, building material radon emanation rates were low (0.04 to 5.53 pCi m^{-2} s^{-1}), and were, on average, comparable to those in low radon houses (0.05 to 0.08 pCi m^{-2} s^{-1}), and contributed, at most, 2.6 pCi/L to the indoor air.

Therefore, the highly permeable soils surrounding the substructure were assumed to be the main source of indoor radon. Measurements of *in-situ* permeability ranging from 10^{-10} to 10^{-13} m^2 indicated that rapid transport of radon-laden soil gas through the soil is possible. This, coupled with moderate soil gas radon concentrations and sufficient entry pathways through substructure cracks and holes, provided the necessary conditions for high indoor radon levels.

Soil gas radon concentrations, calculated from emanating radium concentrations in the soil of 0.120 to 0.238 pCi/g of soil, ranged from 420 to 833 pCi/L. Fifteen low-radon houses had a comparable geometric mean of 690 pCi/L soil gas radon concentration, indicating that house-specific factors which determine the degree of coupling between the soil and the substructure are important. Average soil gas concentrations measured prior to mitigation ranged from 283 to 673 pCi/L for the houses in this study. Estimated soil gas entry rates were very high for these homes: 0.4 to 39 m^3/hr and comprised up to 20% of the air infiltration for the total house. Soil gas radon levels measured at the two Control homes did not correlate to other parameters, such as indoor air concentrations, windspeed, and air temperatures.

Wide variations in daily and seasonal indoor radon levels for the two Control homes could not always be explained, although correlations of indoor radon with windspeed and inside-outside temperature differences (ΔT) are good for other houses. Occupant activities and complex interactions with parameters not monitored are suspected causes for some of the variation. Radon levels and ventilation rates show poor correspondence for the Control homes, but radon source strength has a better graphical correspondence with ΔT.

Winter indoor radon levels in the high radon homes averaged 12.6 times higher than summer levels, while the winter levels were only 2.5 times higher for the low radon homes, implying that seasonal variation in radon entry rates and/or removal mechanisms are different between the two groups of homes. Ratios of upper floor radon concentrations to substructure radon concentrations were always less than one and were very dependent on the leakage area between floors and the presence and operation of a forced-air heating system.

Several promising techniques for reducing excess radon concentrations in houses were identified and demonstrated. These include basement overpressurization, subsurface ventilation (SSV) by depressurization (SSD) and overpressurization (SSP), and crawlspace ventilation. All techniques, properly applied, reduced radon levels in these homes below the BPA and EPA guidelines for radon concentrations.

Basement overpressurization was installed and operated successfully in five houses with basements that had a closable door and could be tightened to reduce air leakage. The technique employed a fan pulling upstairs air at 100 - 200 L/s to pressurize the basement one to three pascals (Pa) above the outdoor air or interstitial soil pore pressure. A modification of this technique was successful in a sixth home. Incremental increases of the pressure tended to decrease radon entry. Installation and successful operation was more difficult in homes with forced-air furnaces because of leaky ductwork and the possibility of air flow from the basement to other levels through the ductwork. The system may be easily defeated by occupants violating the air-tightness of the basement and may cause discomfort due to noise and additional drafts.

Subsurface ventilation (SSV) proved to be effective in every home in which it was implemented. From one to four PVC pipes were placed through basement slab floors or along exterior foundation walls in each of six houses. Fans either depressurized the near-house soil by exhausting air to the outside (subsurface depressurization, SSD) or pressurized the soil with outside air (subsurface pressurization, SSP). Pressures of 100 to 600 Pa at the subsurface pipe opening and flows of 7 to 60 L/s were necessary. Surprisingly, in this group of homes, SSP was always more effective than SSD. This is possibly due to the moderate radium concentrations and high permeability of the local soils.

Temperatures in one gravel sump where the open end of the subsurface PVC pipe was located, dropped during SSP with outside air, but did not reach freezing temperatures for the short monitoring time. Tracer gas tests indicated that up to approximately 50% of the SSD exhaust air at one house originated in the basement. This demonstrates that there is significant leakage between the house and the soil. An effective permeability was calculated for each SSV pipe and showed that the apparent permeability seen by these mitigation systems is higher than in the undisturbed soil by a factor of 10 to 10,000. Presumably, less tightly-packed soils and gravels near the house, gaps at the substructure/soil interface, and leakage through below-grade substructure surfaces contributed to the large difference in permeabilities.

Crawlspace radon mitigation was performed in four houses and generally staged by 1) sealing a plastic membrane over crawlspace soil floors, 2) sealing between crawlspace and living spaces (isolation) and additional thermal insulation, and 3) passive or mechanical ventilation of crawlspaces. Sealing of the floors was partially effective, as was crawlspace isolation, but ventilation of the crawlspace was the most important component in reducing radon entry from the crawlspace. Ventilation was boosted with fans in some houses where natural ventilation was poor, and a slight pressurization of a crawlspace with a fan was even more effective in one house. While crawlspace ventilation is an essential method for controlling indoor radon in homes with crawlspaces, it may not control radon to below guideline levels in homes that also have basements or slabs-on-grade.

House ventilation with air-to-air heat exchangers (AAHX) was effective in homes with low initial ventilation rates and radon concentrations. For two houses, reductions in radon were inversely proportional to increases in house ventilation (65% and 75%). The sensible heat exchange efficiency was 0.55 and 0.63, respectively, for these two homes. In one other house, the air delivery system of an existing AAHX was modified and more dramatic improvements were observed, although final radon concentrations were still above the guidelines.

Sealing of cracks and holes between the substructures and the soil was generally ineffective for these homes where the technique was applied, because many openings not accessible could not be economically sealed. Other techniques, including block wall ventilation and perimeter baseboard duct ventilation, were also ineffective in the situations where they were applied in this study.

Except for the air-to-air heat exchangers, none of the radon control techniques had an observable effect on ventilation rates or on concentrations of other pollutants monitored, such as respirable suspended particles (RSP), formaldehyde (HCHO), and water vapor (H_2O). Changes in concentrations of these pollutants were more dependent on natural changes in ventilation rates and on changes in source strength.

Installation costs for the techniques varied considerably and were related to the house-specific construction, interior finish, and homeowner requests. Crack and hole sealing was the least expensive (0.62 to $9.34/m^2 - normalized by floor area of the space affected by the mitigation treatment), but also the least effective measure evaluated. SSV and basement pressurization were similar in median costs ($14.24 and $12.20/m^2 respectively), while crawlspace mitigation was unexpectedly high ($25.00/m^2), possibly because of additional costs incurred to stage the work. The average AAHX installation cost was $27.87/m^2. Operating costs for the different techniques (other than the AAHX) could only be determined within limits, since heating loads due to additional ventilation could only be estimated. Cost estimates were similar for the various mitigation measures, ranging from $62 to $172 per year.

Preliminary diagnostic procedures were developed and used for the identification of radon entry points and the selection of appropriate corrective measures. Grab samples were collected and air movement was monitored at suspected radon entry locations and then compiled on maps to assist in system design and selection. Blower door fans were used to estimate appropriate basement pressurization fan sizes. Structure leakage areas, mitigation system flows, pressures, and temperatures were periodically measured to evaluate system performance after mitigation. Alpha track detectors were then placed in the houses to monitor long-term system effectiveness and reliability.

I. INTRODUCTION

A. BACKGROUND

The deleterious health effects to miners resulting from exposure to the decay products of radon (^{222}Rn) have been known for many years NCRP (1984). However, the discovery in the middle 1970s of high radon concentrations in a significant number of residences has made it apparent that other population groups are also at risk. It was originally believed that elevated indoor radon levels resulted primarily from the lower ventilation rates in energy-efficient new houses and existing structures that had been weatherized. Because ventilation may be reduced in these buildings, it was hypothesized that certain indoor air pollutants, including radon, may reach higher concentrations. More recent evidence suggests that because pressure-driven flow of soil gas containing radon is the predominant mechanism for radon entry into most homes, the relationship between indoor radon concentrations and ventilation rate is not straightforward (Nazaroff, et al., 1985b and 1986; Nero and Nazaroff, 1984).

Since 1981, Bonneville Power Administration (BPA) has been involved in various programs to promote energy conservation through house tightening weatherization retrofits and new house construction standards in Pacific Northwest Buildings. Because of BPA's concern that these activities may adversely affect indoor air quality, a series of field surveys in the Pacific Northwest were undertaken. The general objectives of these studies, which were started in 1983, were to survey ventilation rates and the concentrations of a variety of indoor pollutants in residential and commercial structures, and to evaluate relationships between ventilation and pollutant concentrations (Turk, et al., 1987a,b, 1988).

BPA currently offers three-month passive radon monitoring to homeowners who participate in the agency's energy conservation programs. If radon concentrations above 5 pCi/L* are measured, BPA recommends that action be taken to reduce the radon concentrations to the levels before energy conservation measures were installed. The only means that it currently recommends for doing this is the installation of an air-to-air heat exchanger. These units are intended to reduce indoor radon levels by increasing the ventilation rate. BPA will partially subsidize the cost of the equipment and installation in homes that have received BPA-sponsored house tightening. Unfortunately, research by Doyle, et al., (1984) has shown that elevated indoor radon levels are usually only partially controlled through additional ventilation. This is the final report of a study that was designed to investigate and demonstrate effective low-cost indoor radon control techniques as alternatives to the air-to-air heat exchanger (Turk, et al., 1986).

The earlier indoor air quality field survey studies conducted for BPA, referred to above, included measurements of radon gas (^{222}Rn) concentrations in commercial and residential structures throughout the region. Figure 1 shows the region and the areas around the principal cities where the buildings were located. Figure 2 is a histogram of data from 103 homes in the near-coastal region of Portland and Salem, Oregon, and Vancouver, Washington. The geometric mean (GM) of the concentrations is 1.2 pCi/L. Twenty commercial and institutional buildings in Spokane - Cheney, Washington, and Kootenai County, Idaho, and 69 new and existing homes in Spokane County, Washington, and Kootenai County, Idaho were monitored. The data for these 69 homes are shown in Figure 3. Here, the GM (3.7 pCi/L) and GSD (2.9 pCi/L) are both shifted to higher values, indicating a greater occurrence of elevated indoor radon concentrations in this area. A review of the data reveals that one commercial and 46 residential buildings, all roughly located in the Spokane River Valley in Washington and the contiguous Rathdrum Prairie in Idaho, have indoor radon concentrations that are substantially

*In this report, units for radon concentrations are expressed in picocuries per liter, pCi/L, still commonly used in the U.S. The conversion to SI units is 1 pCi/L = 37 Bq/m^3.

Pacific Northwest General Study Locations

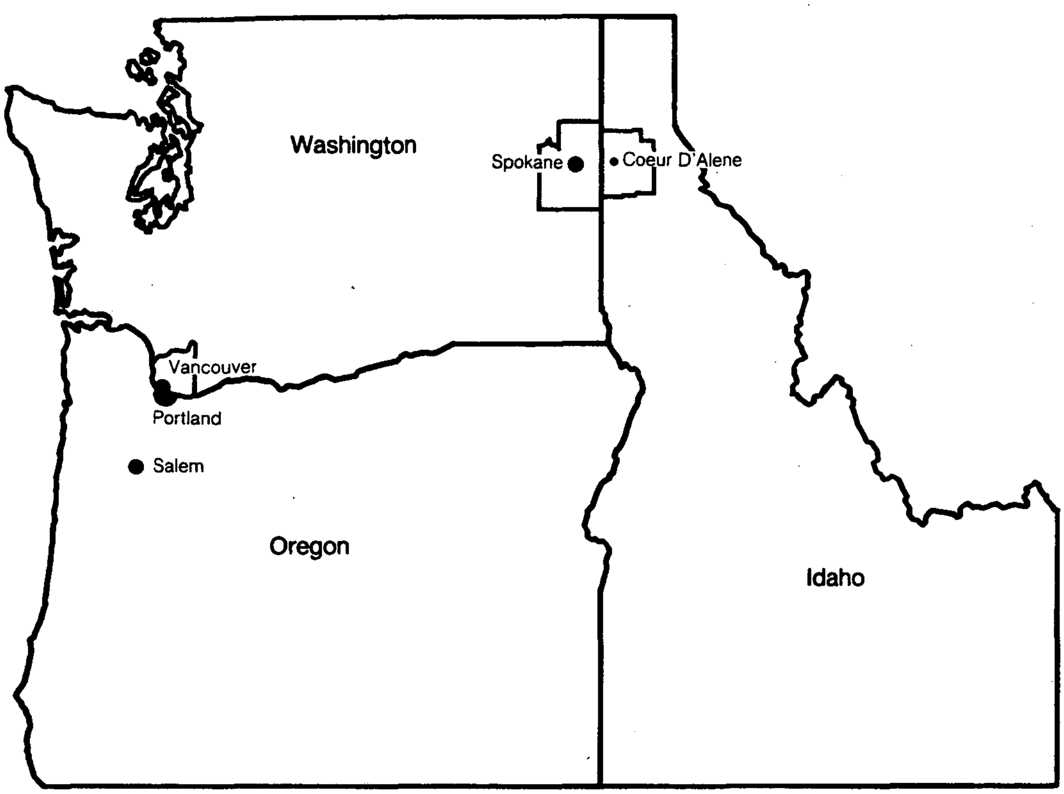

Figure 1 Pacific Northwest regions where study homes were located. Fourteen were in the Spokane/Coeur d'Alene area, while one was located in Vancouver in Western Washington.

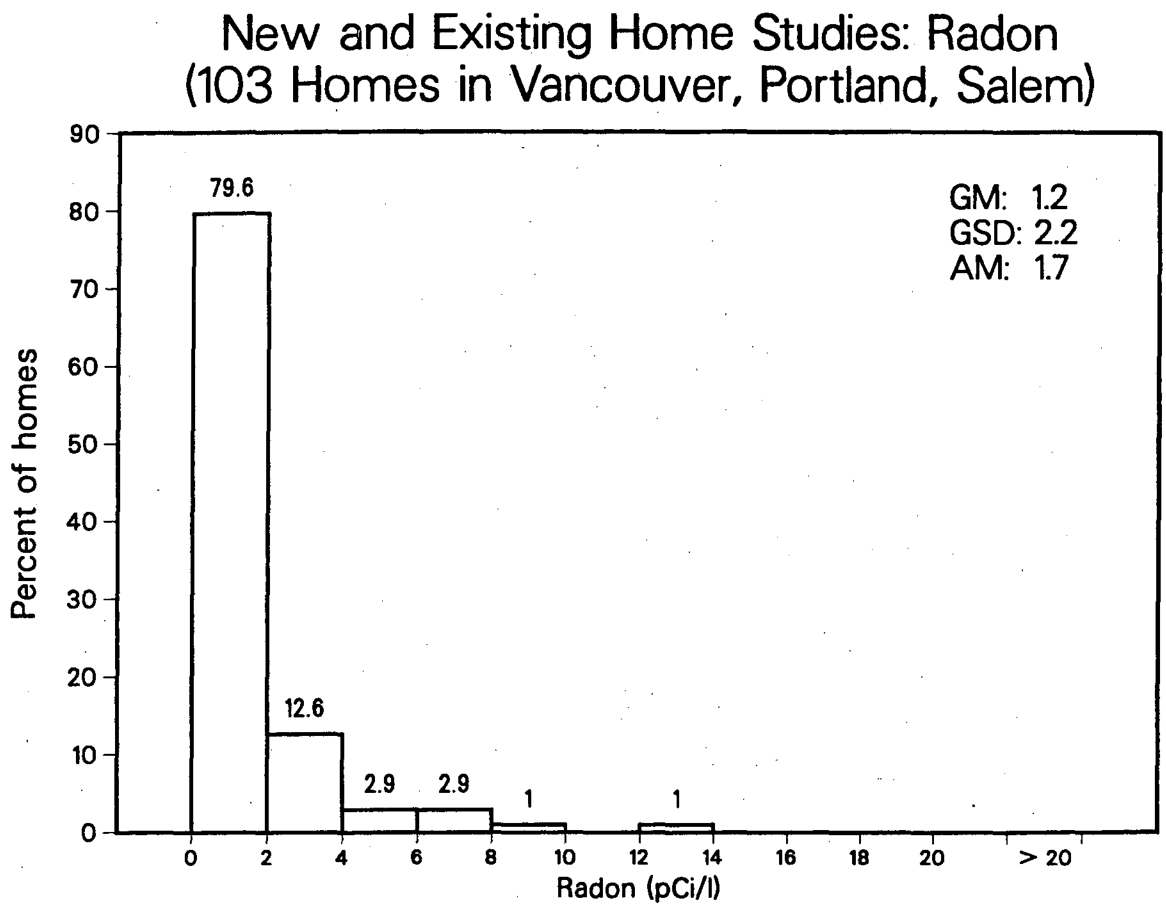

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Figure 2 Heating season indoor radon concentrations measured in 103 single-family residential structures in Vancouver, WA., and Portland, and Salem, OR. The Geometric Mean (GM) of the distribution is similar to that observed for 552 U.S. homes (Nero, et al.,1986).

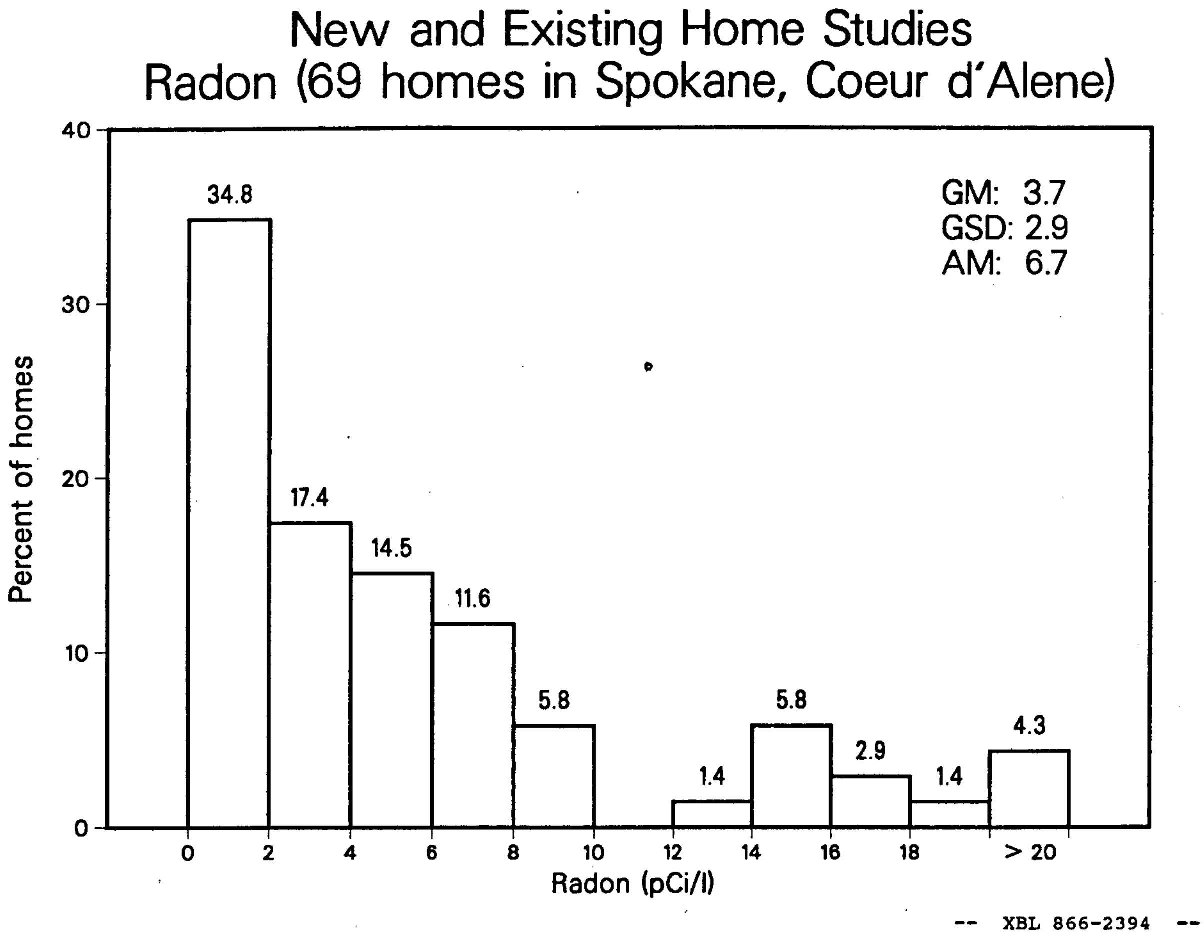


Figure 3 Heating season indoor radon concentrations for a group of 69 homes in the Spokane, WA and Coeur d'Alene, ID area. The higher GM and the larger GSD are influenced by 46 of the homes which are approximately located in the Spokane River Valley/ Rathdrum Prairie.

higher than average. The large tail in Figure 3 is in large part due to the presence of these 46 homes in our measurement sample. Figure 4 shows a histogram of data from the 46 homes. An examination of soils, domestic water supplies, and building materials strongly suggests that the high radon concentrations in homes in these areas are related to the local subsurface soil composition and structure, whereby radon entry was dominated by pressure-driven flow of radon-laden soil gas into the structures from the surrounding soil.

The average concentration for the 46 residences was 13.3 pCi/L with a median of 5.9 pCi/L and a GM of 6.6 pCi/L. The monitoring period was usually for a three to five week period during the heating season. Thirty, or 65.2% of the residences had concentrations above the U.S. Environmental Protection Agency (EPA) guideline of 4 pCi/L (EPA, 1986). Twenty-six, or 56.5%, had concentrations above the BPA action level of 5 pCi/L (BPA, 1984), and 20 residences, or 43.5%, had concentrations above 8 pCi/L, the approximate guideline of the National Council for Radiation Protection (NCRP, 1984).

These findings can be compared with those in other studies, such as a recent compilation of measurements made in 552 U.S. residences by Nero, et al., (1986), in which the data were approximated by a lognormal distribution with a GM of 1.0 pCi/L and a geometric standard deviation (GSD) of 2.8 pCi/L. These data, if assumed to apply to the U.S. housing stock, suggest that approximately 7% of all U.S. single-family houses have radon concentrations above 4 pCi/L. Six percent are above 5 pCi/L, and approximately 2% are above 8 pCi/L. In another study by Thor in 1984, of 267 BPA employee houses in the Pacific Northwest, the lognormally distributed data had a geometric mean radon concentration of 0.8 pCi/L and a GSD of 2.46. We concluded that the Spokane River Valley/Rathdrum Prairie region has conditions favorable for creating high indoor concentrations, and was therefore, a suitable area for the study of radon mitigation techniques.

B. OBJECTIVES

Specific objectives of the project were:

1. to examine the efficacy of various control techniques in reducing indoor radon concentrations;
2. to study the effects of these techniques on the processes of radon entry from the surrounding soil;
3. to investigate the interactions of mitigation techniques;
4. to gain information on installation and operating costs for mitigation systems;
5. to spawn innovative ideas for new mitigation techniques; and
6. to provide a long-term solution for each participating house that reduces average heating season radon concentrations to below 5 pCi/L.

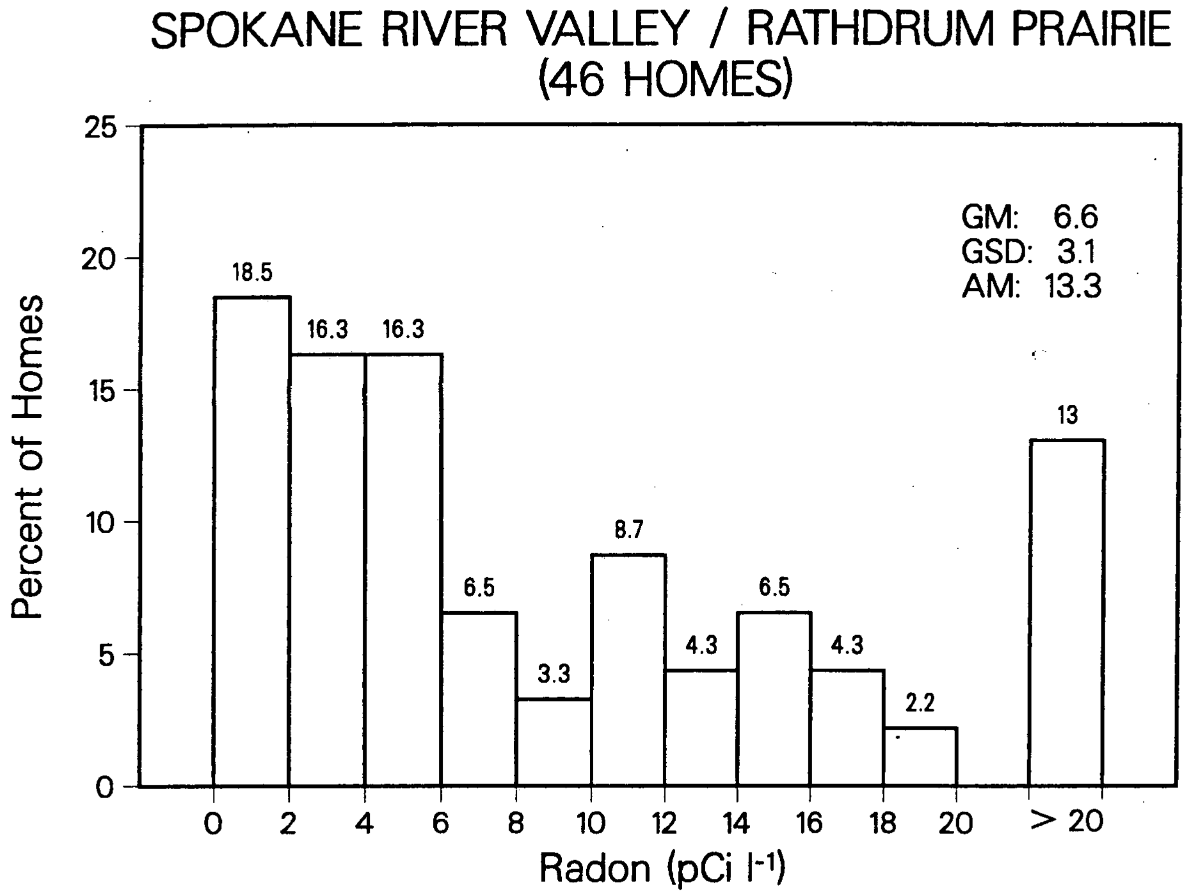


Figure 4 The subgroup of 46 Valley/Prairie Homes included in Figure 3. Twenty of the measurements in this group were greater than 8 pCi/L.

II. EXPERIMENTAL DESIGN

A. MEASUREMENT PROCEDURES AND HOME SELECTION

It was assumed that the high indoor radon levels in these homes were due to soil-based sources. However, to eliminate the remote possibility that such other sources as the domestic water supply or building materials might make important contributions of radon, additional diagnostic measurements were conducted. A general plan was followed, shown in Figure 5, to guide the review, selection, and follow-up to the installation of mitigation systems. The first stage, Problem Diagnosis, addressed the sources of radon in the houses and characterized the building structure and radon entry points. This was important not only for selection of homes for the study, but also for selection of suitable mitigation techniques. The second stage, Selection and Implementation of Mitigation Systems, began with initial house screening and continued along with the third stage, Post-Mitigation Evaluation, in an iterative fashion throughout the remainder of the study.

Screening and Preliminary Diagnostic Techniques

Following a review of the homes monitored in the earlier studies, additional measurements were made in 33 of the 172 previously-monitored homes during the summer of 1985. These involved collecting water and soil samples, and measuring indoor air radon concentrations and radon emanation from building materials.

Non-aerated water samples were collected from an outside faucet that connected directly to the water supply of the dwelling, with no upstream conditioning or filtering. To avoid aeration of the sample, two one-liter polyethylene bottles were slowly filled with a short tube directed to the bottom of the container. The bottles were sealed, labeled, and returned to Lawrence Berkeley Laboratory (LBL) within three days of collection for analysis by gamma spectrometry. Water samples were collected from all 33 houses. Measurements of radon-in-water had been made in 16 houses during the previous winter and spring, using Terradex Type SW Track-Etch® alpha track cups placed in the bottom of a frequently-used toilet tank.

Soil samples were collected from up to four locations at each of 27 houses. Up to eight samples were gathered in total for each house. The initial protocol called for the use of a sliding hammer coring tool that collects "undisturbed" core samples 4.8 cm in diameter and 15 cm long in an aluminum sleeve. However, because much of the Valley/Prairie soil was very rocky, the coring tool could not be driven successfully into the earth to capture a core of the material. Thus, many of the soil samples from that area were collected by using a bucket auger to bring material up to the surface. Sample depths ranged from 15 cm to 1.8 m, but were typically from 0.5 to 0.8 m. These samples were sealed, labeled and returned to LBL where they were air-dried and analyzed for emanating radium* by gamma spectrometry (Moed, et al., 1984).

To measure building material radon flux rates, a shallow pan that contained activated charcoal adsorption canisters with both faces open was attached to an uncracked wall or floor surface with sealant for 24 to 48 hours. On open soil floors, the pan was placed on the soil with the pan edges below the soil surface. These canisters were returned to LBL within three days for gamma spectrometric analysis of the adsorbed radon. Typically, two wall locations and one floor location were monitored at the 11 houses where these measurements were made.

*"Emanating radium" is the radium concentration in the soil multiplied by the emanating fraction - the portion of radon generated that reaches pore spaces and is available for transport.

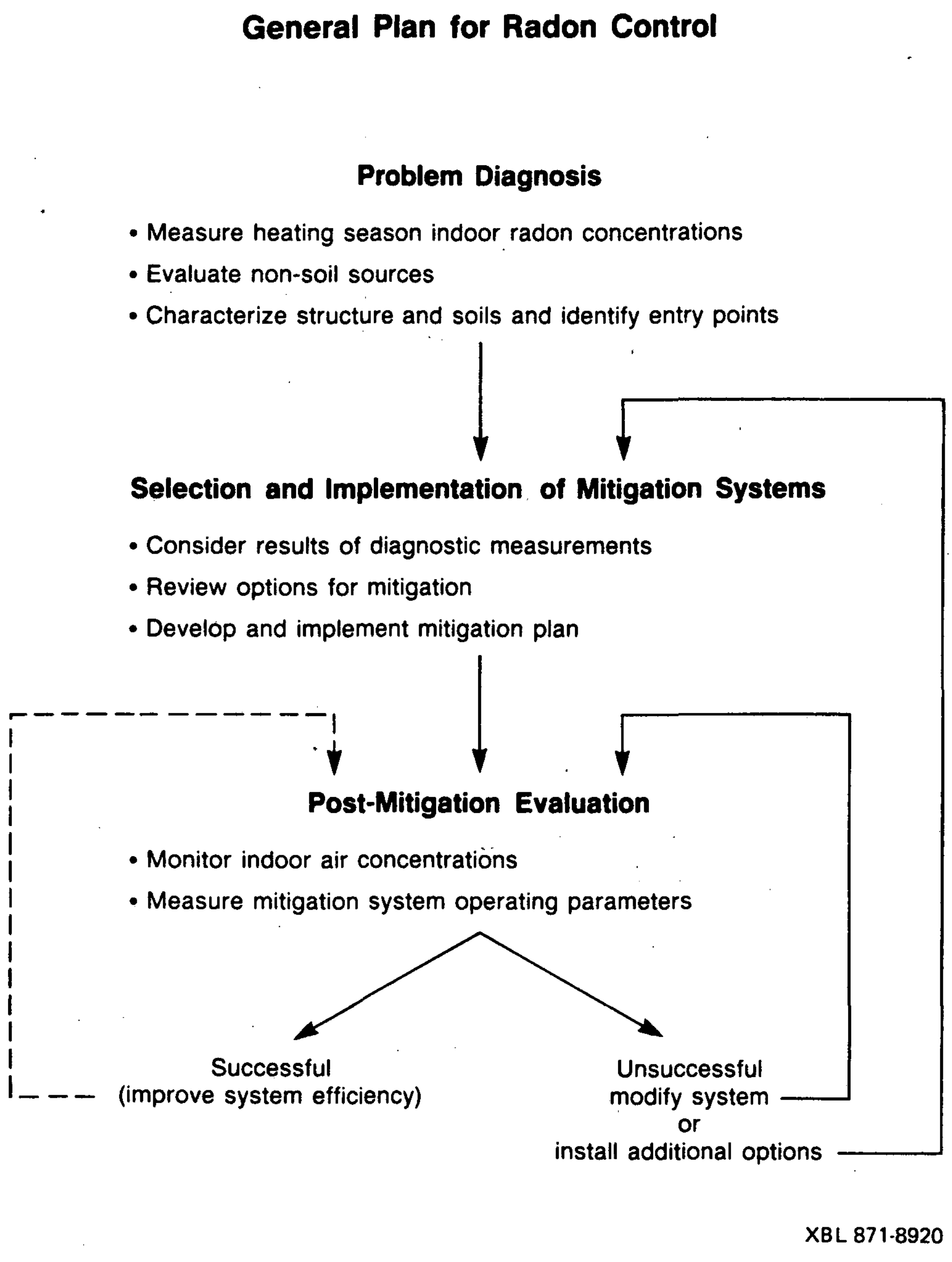


Figure 5 Plan for evaluation of radon sources, selection and implementation of mitigation systems, and follow-up evaluation of mitigation system performance.

Indoor air radon concentrations were also measured between June and September, 1985 for periods of between 65 to 115 days in 29 homes. Two Terradex Type SF Track-Etch® alpha track cups were placed side-by-side for replication in an occupied first floor space. They were deployed by technicians, but returned through the mail by the occupants.

Most of the homes selected for this study were visited in September 1985 for a detailed examination of the substructure. 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 during this visit. Data from all of the preceding measurements were then reviewed and a plan for radon control was developed for each house.

Selection of Homes

Fifteen occupied houses that had indoor radon levels above 5 pCi/L were selected for this investigation. High indoor concentrations were preferred so that changes resulting from the installation or modification of mitigation techniques could be detected easily. An attempt was made to find homes with cooperative and interested occupants and that offered a variety of construction types representative of local housing. Fourteen were from the group of 46 Valley/Prairie houses in eastern Washington and northern Idaho. The other home, in Vancouver, Washington, was the only slab-on-grade structure in the study. It was later withdrawn from the project, but not before a partially successful mitigation technique (crack sealing) was practiced on it. Figure 1 is a map of the northwest showing the regions where the study was located and Figure 6 shows sites in the Spokane River Valley - Rathdrum Prairie area.

Two of the fourteen houses were designated as "Control" structures: one in Post Falls, Idaho, approximately 15 km west of Coeur D'Alene; and the other in Veradale, Washington, approximately 15 km east of Spokane. These did not receive any remedial action until the conclusion of the project, so that seasonally-varying, natural environmental effects and indoor radon concentrations could be monitored during the course of the study. In Figure 6, general house locations are identified with large circles and the predominant Valley/Prairie soil associations are shown with hatching (Garrison-Marble-Springdale and Avonville-Garrison-McGuire). These soils are typically defined as excessively drained sandy and gravelly soils formed from the outwash of glacially-dammed Lake Missoula following the retreats of the Cordilleran ice-sheet, 18,000 to 30,000 years ago. Deposits are reported to be over 25 meters in depth. The soil associations are comprised of one or more smaller scale features of major and minor soil series that can have considerably different physical characteristics (USDA, 1968 and 1981).

Table 1 provides a brief description of the important physical characteristics of each home. The houses ranged from two to eighty-six years of age and from 79 to 330 m^2 of occupied floor area in size. Substructure types represented included: three houses with finished, full-depth basements (approximately 1.5 to 2 meters below grade); two houses with half-depth basements (approximately 1.0 to 1.5 meters below grade); two houses representing combinations of these types; five houses with a basement and an adjoining crawlspace; and three houses involving a slab-on-grade. None of the homes had only a crawlspace. Perimeter basement walls were poured concrete, except in ESP120 that had field stone and mortar walls and NSP204 that had treated wood walls.

Only two homes (ECD027, NCD077) used combustion-fueled appliances as the primary source of space heat, while four homes (ECD026C, ECD153, ESP109, ESP116) used wood stoves much of the time to augment the primary electric heating system. The woodstove was located in the basement in ECD027, although it was later moved upstairs as part of the mitigation. Ten homes had central, forced-air electric furnaces located in a basement or

Spokane River Valley-Rathdrum Prairie Map of Soil and Site Locations

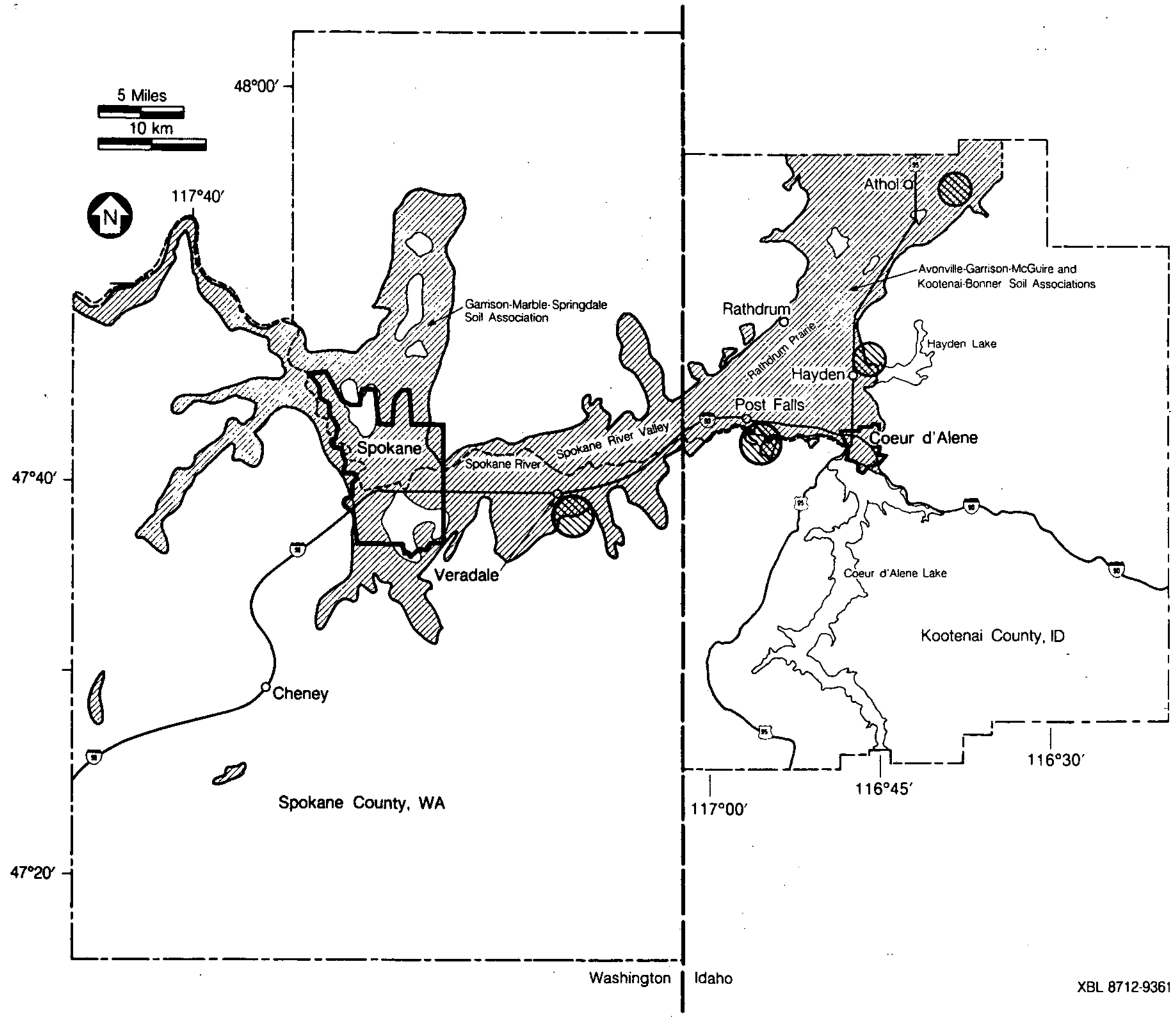


Figure 6 A detail map of Spokane County, WA and Kootenai County, ID indicating general house locations (circles) and delineation of the Spokane River Valley - Rathdrum Prairie Soil Associations. These soils are typically defined as excessively drained sandy and gravelly soils formed in glacial outwash.

TABLE 1. HOUSE DESCRIPTION

HOUSE I.D.	OCCUPIED FLOOR AREA(m^2)	HEATING SYSTEM	YEAR BUILT	FLOORS ABOVE GRADE	DESCRIPTION OF SUBSTRUCTURE[a]
NORTHERN IDAHO/RATHDRUM PRAIRIE					
ECD026 Control	167.9	Electric Forced Air, Wood Stove	1972	2	Finished half-depth[b] basement (60.4m^2); with connecting crawlspace (60.4m^2)
ECD027	249.7	Wood Stove	1900	2	Full-depth[c] open soil basement (66.2m^2); small crawlspace (21.9m^2) and utility room slab-on-grade (17.0m^2)
ECD153	201.0	Electric Forced Air, Wood Stove	1975	1	Finished half-depth basement (94.0m^2); with vented, adjoining crawlspace(17.8m^2)
NCD077	188.5	Natural Gas Forced Air	1984	1	Unfinished full-depth basement (63.1m^2) with adjoining crawlspace (61.8m^2)
EASTERN WASHINGTON/SPOKANE RIVER VALLEY					
ESP101	206.7	Baseboard Electric	1969	2	Finished full-depth basement (53.3m^2) and half-depth basement (49.4m^2)
ESP108 Control	330.0	Heat Pump Forced Air,	1955	1	Finished full-depth basement (165.0m^2)
ESP109	166.7	Electric Forced Air, Wood Stove	1978	1	Finished half-depth basement (78.4m^2)
ESP111	236.2	Electric Forced Air	1978	2	Unfinished full-depth basement (57.7m^2) and finished half-depth basement (55.6m^2)
ESP113	204.5	Baseboard Electric	1968	2	Finished half-depth basement (85.4m^2) and slab-on-grade (19.0m^2)
ESP116	169.8	Electric Forced Air, Wood Stove	1974	1	Semi-finished full-depth basement (85.7m^2)
ESP119	158.4	Electric Forced Air	1977	2	Finished half-depth basement (51.7m^2) with adjoining crawlspace (48.9m^2)
ESP120	221.3	Baseboard Electric	1920	2	Field stone and mortar walls of semi-finished full-depth basement (64.9m^2)
ESP121	168.6	Electric Forced Air	1976	1	Finished half-depth basement (76.1m^2)
NSP204	177.2	Electric Forced Air W/AAHX	1984	1	Treated wood walls of unfinished full-depth basement (56.8m^2) with adjoining crawlspace (74.6m^2)
VANCOUVER, WA					
EVA604	78.9	Baseboard Electric	1952	1	Slab-on-grade (78.9m^2)

(a) All substructure floors and walls are poured concrete unless indicated otherwise
(b) Sometimes referred to as "Daylight Basement", floor generally 1.0-1.5 meters below grade
(c) The floor of a full-depth basement is typically 2.0 meters below grade

crawlspace. Houses ESP101, ESP113, ESP120, and EVA604 had baseboard electric heating systems. One newer home, NSP204, with a forced-air furnace was constructed under BPA's energy-efficient Model Conservation Standards (MCS) program with a central air-to-air heat exchanger in the crawlspace. As far as could be determined, none of the homes had drain tile beneath or surrounding the foundation nor any evidence of water damage in the basement.

Monitoring Equipment

Monitoring equipment was installed in the first group of homes in mid-October, 1985 (Table 2). It included an EPROM data logger that, every 15 seconds, accumulated data values from wind speed and direction, indoor and outdoor temperatures, forced-air furnace fan operation, and basement-soil pressure differentials (at some homes), and recorded these data as 30-minute averages. Pulses from a continuous radon monitor (CRM) were also accumulated and reported for the same intervals. This radon monitor, which was designed and built at LBL, utilizes a pumped flow-through Lucas scintillation cell. The filtered sample air first flows through a chamber with sufficient path length for ^{220}Rn (Thoron) to decay before passing into the scintillation cell. As radon and radon progeny decay in the cell, alpha particles are emitted that impact and excite the zinc sulfide coating on its inner wall. The resulting light flashes are detected by a photomultiplier tube, producing electronic pulses that are sent to the data logger. (See Appendix A for a block diagram of CRM operation). At least one CRM was installed at each house to sample air from the first frequently occupied floor above grade. This strategy allowed comparison between houses, since all houses had a lowest-floor-above-grade that was occupied. Because of limited equipment availability, only a few homes had a second CRM placed to sample air from the basement or crawlspace. These units were periodically moved from house to house except in the two control homes. As much as possible, sample locations were chosen that were central to the space to be monitored and also were away from doors, windows, forced-air heat registers, and other disturbing influences. Indoor temperatures were monitored at a minimum of one location per floor as well as in separate substructure zones such as basements and crawlspaces.

Ventilation rates and other indoor air pollutants were measured to help in the selection of mitigation strategies. Water vapor (H_2O) and formaldehyde (HCHO) were periodically monitored, using diffusion-controlled passive samplers (Girman, et al., 1986; Geisling, et al., 1982) that provided a time-weighted average concentration for the seven-day exposure. Indoor sampling locations coincided with the temperature measurements in occupied zones. One outdoor location was also monitored. Respirable suspended particles (RSP) were also measured indoors at one location along with H_2O and HCHO and at the outdoor location using a pumped, flow-controlled system that collected particles (less than 3 μm in diameter) on a 37 mm, 0.8 μm teflon filter. The filters were later analyzed gravimetrically to provide a seven-day time-weighted average particle mass concentration. Selected RSP filters were also analyzed for one to seven higher-molecular-weight polycyclic aromatic hydrocarbons (PAH). See Table 3. These were analyzed by an outside laboratory, Clayton Environmental (formerly McKesson Environmental) using high pressure liquid chromatography (HPLC). PAH data are not presented in this report.

The passive perfluorocarbon tracer (PFT) constant injection tracer system, which was developed at Brookhaven National Laboratory (BNL) by Dietz and Cote (1982), was used to measure ventilation rates. Four distinct PFTs were available to characterize air flow within the houses (by separately labeling different house zones) as well as into and out of the buildings. These PFT sources were colocated with maximum-minimum thermometers so that corrections to the temperature sensitive permeation rates could be made. The tracer samplers were deployed for seven days alongside the pollutant samplers and, in addition, were placed in unoccupied zones including basements and crawlspaces. They were returned to BNL for analysis. Because of the considerable errors that are inherent in calculated values of inter-zonal air flows (Sherman, 1987), only whole-house and substructure ventilation rates are

TABLE 2. MEASUREMENTS AND MONITORING EQUIPMENT

MEASUREMENT	METHOD
CONTINUOUS MONITORING	
Radon in air	Continuous flow-through scintillation cell (CRM)
Indoor, outdoor soil temperature	AD-590 IC temperature sensor
Wind speed	Generator-type
Wind direction	Variable resistance potentiometer
Furnace fan	Sail switch (not at all houses)
Differential pressure	Variable capacitance transducer (not at all houses)
Data logger	17-channel, erasable programmable read only memory data storage
PERIODIC MEASUREMENTS	
House air leakage area	Calibrated-flow blower door
Soil gas radon	Scintillation-cell grab samples, portable photomultiplier tube counting station
Soil Air Permeability	Flow and pressure measurement of air injected into soil
Radon in air (Integrated)	Alpha track detector (replicated)
Water vapor	7-day average, passive sampler
Formaldehyde	7-day average, passive sampler
Respirable suspended particles (RSP)	7-day average, pumped flow-control filter, weight gain
Polycyclic aromatic hydrocarbons (PAH)	Lab-based high pressure liquid chromatography on selected RSP filters
Ventilation rates	1) 7-day average, Brookhaven National Lab PFT constant injection tracer system 2) Constant tracer injection, continuous gas chromatograph/electron capture detector analysis
Humidity	Sling psychrometer
Temperature	Mercury-filled thermometers
Occupant activities	Daily activity log
DIAGNOSTIC MEASUREMENTS	
Soil Rn emanation rate	Soil sample, lab-based gamma spectrometry
Radon in water	1) Grab sample, lab-based gamma spectrometry 2) Alpha track detector
Building material flux	Activated charcoal adsorption canisters, lab-based gamma spectrometry
Radon entry grab samples	Scintillation cell grab samples, portable photomultiplier tube counting station Liquid-filled point gauge manometer
Air flows	1) Pitot tube with manometer 2) Hot wire anemometer 3) SF_6 tracer gas with infrared analyzer
Air movement	Chemical smoke tubes
Electric usage	Induction-type watt hour meter

TABLE 3. POLYCYCLIC AROMATIC HYDROCARBONS

PAH	CHEMICAL FORMULA
Chrysene	$C_{18}H_{12}$
Benzo[b]fluoranthene	$C_{20}H_{12}$
Benzo[k]fluoranthene	$C_{20}H_{12}$
Dibenz[a,h]anthracene	$C_{22}H_{14}$
Benzo[g,h,i]perylene	$C_{22}H_{12}$
Indeno[1,2,3-cd]pyrene	$C_{22}H_{12}$

derived here. Several times during the study, house depressurization tests, using a flow-calibrated blower door, were employed to determine the air leakage area of each structure. Additional depressurization tests were also conducted on some substructures that had been air-leakage tightened as part of a mitigation technique.

Meteorological parameters, including wind speed, wind direction, and outside air temperature, were measured at a 10 meter high tower attached to each house. The towers extended approximately three meters above the roofline of each house. Independent meteorological observations for barometric pressure, precipitation, dry bulb temperature, and wind speed and direction were collected from the National Weather Service (NWS) station in Spokane, Washington. During the periods of pollutant sampling, building occupants completed logs of daily activities in or near their homes that might affect pollutant concentrations or ventilation rates.

Soil gas grab samples were periodically collected and analyzed for radon. The soil gas samples were drawn from 13 mm, 1.0 to 1.5 meter long pipes driven into the soil, following a pilot hole, at two locations at each house. Figure 7 shows the soil probe and implements used for driving the pipe. The pipes were generally within one to seven meters from the houses. To minimize sample dilution by air remaining in the sample tube and fittings, two to three sample volumes were drawn through the tube and fittings by means of a hand pump. Evacuated, 100 cm^3 Lucas alpha scintillation flasks were filled with filtered gas from the pipes, allowed to come to equilibrium with decay products for three hours, and then analyzed on a portable photomultiplier tube counting station.

An *in-situ* soil air permeability measurement was performed once at each of the 14 Spokane/Coeur d'Alene houses using the same pipe probe described above. The procedure consists of using a device suggested by DSMA (1983); a cylinder of compressed air is connected to the pipe probe via a pressure gauge and flow meter and air is forced into the soil. Permeability, K, is calculated, assuming Darcy's Law, from:

$$K = 2.5 \times 10^{-11} \frac{Q}{rP} \qquad [1]$$

where: K = permeability (m^2),

Q = flow rate (L/min),

P = pressure (Pa), and

r = inside radius of probe (m).

Detection limits for the various components on this device, restrict the range of measurable permeabilities from approximately 10^{-13} to 10^{-8} m^2.

To assist in the selection of mitigation systems and in the evaluation of the performance characteristics of these systems, a series of special diagnostic measurements of flows, pressures, air movement, and entry location grab samples were performed in each house. Minimum three-point traverses by a hot wire anemometer were used to measure flows in pipes and ducts of mitigation systems. In a technique used at one house, the amount of tracer gas (SF_6) injected into the moving air stream of a mitigation system duct was varied until a target concentration, measured at a point further along in the duct, was achieved. By measuring the injection rate, and assuming that the air and tracer are well-mixed, the air flow in the duct was calculated. The static depressurization (or pressurization) developed by various mitigation systems was sensed with a pitot tube in the duct and was measured by a liquid point-gage micromanometer with reference to basement air. Soil gas movement at possible entry points was detected using a chemical smoke tube. These tubes were also used to identify air movement at leakage sites between building zones and the outside. Scintillation flasks identical to those used to collect gas samples from the soil probe pipes were employed for taking grab samples from various building locations, including wall cavities, floor drains, wall and floor cracks, and sealed rooms and compartments. The radon concentrations in these spaces were then "mapped" on a floor plan of the house to indicate the most important areas of radon entry and to evaluate the effectiveness of a mitigation system in controlling radon entry at these points. (See Figure 46).

Temperatures were periodically measured in mitigation system ducts and pipes. They were measured continuously in the supply, return, exhaust, and fresh air ducts of the air-to-air heat exchangers in two houses and in the soil near sub-surface ventilation pipes at one other house. These diagnostic measurements have subsequently been refined and developed into a comprehensive diagnostic procedure that was used in a study of 14 New Jersey homes by Turk et al., (1987c).

Electrical consumption of the various system blowers and fans was also monitored. Spot measurements, lasting several hours to several days, were made using an induction-type watt-hour meter along with house wiring voltage. The subcontractors who were hired to install the radon control systems were required to make an accounting of the cost of materials and the cost and effort of labor to install the systems in each house. This information was then reviewed, aggregated, and tabulated by LBL.

The monitoring instrumentation was removed from the houses in March and April of 1985. At that time, four type SF TrackEtch® detectors were placed in each house as part of a long-term follow-up program. These detectors are exposed for approximately three months for the periods March-May, June-August, September-November, and December-February. Replacements are sent through the mail to homeowners or occupants, who deploy the new detectors and return the exposed ones to LBL. This follow-up is important to determine the longer term reliability and effectiveness of the different mitigation techniques, and is still in progress. These data will be presented in a subsequent report.

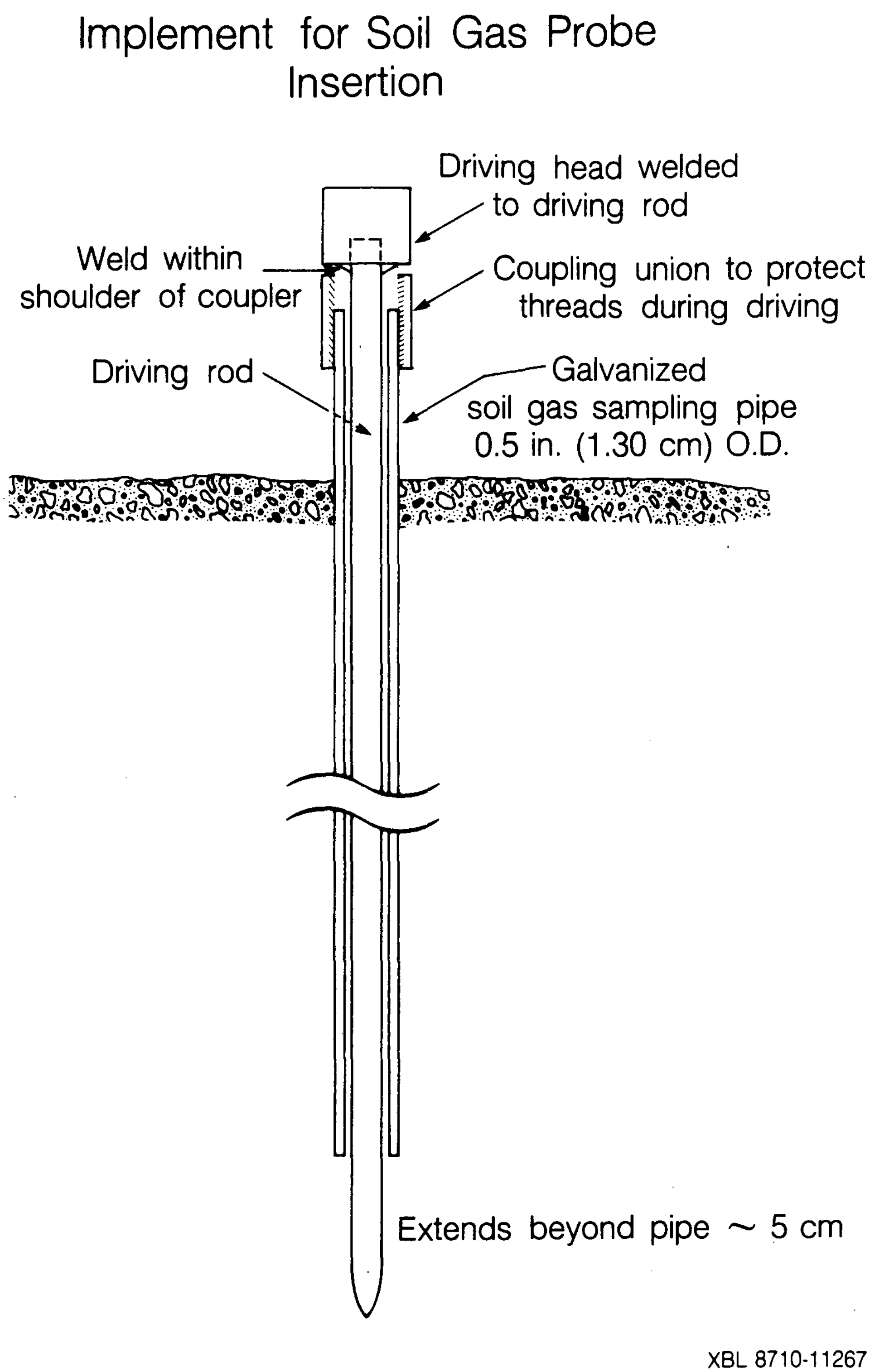


Figure 7 Sketch of the soil gas probe and method for inserting the probe into the soil (for drawing soil gas samples or measuring in-situ permeability). It involved drilling a pilot hole, that was followed by driving a 1.3 cm galvanized pipe to a depth of 1.0 to 1.5 meters. By inserting a rod into the pipe while it was driven into the soil, the pipe was strengthened, the open bottom end was kept from clogging, and the top threads were protected. This rod was then withdrawn, and a gas fitting mounted on the pipe. Probes were capped except during sampling.

III. DATA AND ANALYSIS

A. RADON SOURCES

Strictly speaking, all radon in structures is derived from soil and rocks. In those houses where elevated indoor levels are due to high radon concentrations in water or natural gas, the radon originated from the strata through which the water or gas passed. If building materials are the primary radon source, then the radon-producing components of the material are a type of soil or rock. However, for purposes of treating an indoor radon problem (and to understand transport processes), it is convenient to categorize the sources according to soil or non-soil. The latter includes domestic water, natural gas for combustion appliances, outdoor air, and building materials. A general discussion of radon sources and entry is provided by Nazaroff and Nero (1988).

Although we presumed that soil was the primary source of radon for these homes, it was necessary to determine if the other sources were insignificant.

Non-Soil Sources of Radon

Outdoor Air and Natural Gas

Measurements of radon in outdoor air were made using alpha-track detectors as part of a separate study of indoor air quality in new energy-efficient homes in the region from March through June, 1985 (Turk, et al., 1987a). These data averaged approximately 0.5 pCi/L. A small number of outdoor air Lucas-cell grab samples were also collected in December 1985 near Homes ESP120 and NSP204. These concentrations were generally less than 0.5 pCi/L.

Only one of the homes in this study (NCD077) used natural gas. Previous analysis of natural gas as a source of indoor radon indicates that it is probably not an important contributor (Johnson, et al., 1973). On the basis of this data, outdoor air and natural gas were excluded as possible sources for the *high* indoor radon levels.

Water

No prior information on radon in the potable water supplies and on emanation rates from building materials was available for these homes. It is known that radon concentrations in water are generally low, particularly in water from surface and most municipal supplies. However, concentrations greater than 10,000 pCi/L (water) and up to 10^6 pCi/L have been measured at individual private wells in the U.S. - not necessarily in the BPA region (Nazaroff, et al., 1985a). At these concentrations, sufficient radon may come out of solution during indoor water use (showers, dish washing, etc.) to cause significant increases in the indoor air radon concentration. Researchers have estimated that the average ratio of potable water radon concentrations and indoor air concentrations is approximately 10,000 to 1 (Becker and Lachajczyk, 1984; Gesell and Pritchard, 1980; Nazaroff, et al., 1985a). Individual house variations in this ratio depend upon actual house ventilation rates, building volume, water usage, and the device-dependent release rate of radon from the water. Thus, radon in water concentrations greater than 10,000 pci/L may, alone or in combination with contributions from other sources, cause indoor air levels to exceed the recommended guidelines. Potable water as a source of radon is reviewed by Nazaroff, et al. (1988a).

Since four of the 15 study homes had private wells (all others were served by municipal well water supplies), water samples were collected at the 33 screened homes and alpha-track detectors were exposed at six homes. These data are presented in Table 4, which shows the highest concentration (2920 pCi/L-water) from the 13 study homes in the private well at house

TABLE 4. NON-SOIL RADON SOURCES

HOUSE ID	BUILDING MATERIAL EMANATION ($pCi/m^2/sec$)[a] Walls	BUILDING MATERIAL EMANATION ($pCi/m^2/sec$)[a] Floors	WATER SUPPLY Source[b]	WATER SUPPLY Radon Concentration (pCi/l - water) Gamma Spec.[c]	WATER SUPPLY Radon Concentration (pCi/l - water) Alpha Film[d]
ECD026C	ND	ND	W	900	187
ECD027	5.13	3.35	W	2920	ND
ECD153	0.10	0.04	W	90	5
ESP101	0.21	0.08	M	550	ND
ESP108C	ND	ND	M	630	218
ESP109	ND	ND	M	670	386
ESP111	ND	ND	M	370	ND
ESP113	ND	ND	M	570	ND
ESP116	ND	0.06	M	550	232
ESP119	ND	ND	M	460	ND
ESP120	0.23	0.14	M	500	262
ESP121	ND	ND	M	560	ND
EVA604	ND	0.05	W	610	ND
Low Concentration[e] Houses	0.05	0.08	-	524 (Max. 8050) (Min. 50)	-

(a) Maximum value of all measurements
(b) W = well, M = municipal
(c) Gamma spectrometry counting facility
(d) Track Etch, type SW detector in toilet tank
(e) Geometric mean for houses with low indoor radon levels not selected into this study:
Building materials - 5 homes
Water samples - 20 homes

ND = No Data Collected

ECD027. The data from the water samples at the other houses show relatively little variation, with the exception of ECD153 (90 pCi/L-water), even for those on the municipal system. Since the municipal well(s) probably draw water from the same aquifer as those with private wells (except for EVA604 located in Vancouver), the narrow range of values is reasonable. Assuming the 10,000 : 1 water-to-air ratio, ECD027 produces the maximum contribution from any of the water supplies - 0.3 pCi/L (see Table 8, following). In other houses, estimates of the contribution to the indoor concentrations from water were generally 0.1 pCi/L or less.

In 20 other homes with low indoor radon levels (less than 6.6 pCi/L), the geometric mean radon in water concentration is 524 pCi/L-water with a geometric standard deviation of 2.4. These concentrations are very similar to those of the high indoor radon concentration study group. One house in the low indoor radon concentration group had private well water concentrations of 8050 pCi/L-water, with indoor air heating season measurements of 1.1 pCi/L-air and summer measurements of 1.0 pCi/L-air. The radon-in-water at this house can almost entirely account for the observed indoor air concentration.

Interestingly, the concentrations as measured by the alpha-track cups in toilet tanks were generally lower than those from the gamma spectrometric analysis (average 215 pCi/L-water vs. 557 pCi/L-water). Errors in this latter analysis method are almost entirely due to mishandling of the sample when filling the bottle with water. A possible explanation for the difference in concentrations is a seasonal variation in radon in water concentrations. The alpha track detectors were exposed during the winter and spring, while the grab samples for gamma spectrometric analysis were collected in the summer. Other explanations could involve the residence time of water in the tank, allowing radon to be released; or inaccuracies in calibration factors used in calculating water concentration from alpha activity in the alpha-track cup.

Building Materials

To date, relatively few homes in the U.S. have been identified with indoor radon problems resulting from building materials contaminated with radium. The notable exceptions have occurred in areas where mine wastes or slags were used as aggregate in concrete or concrete block materials (Kahn, et al., 1979; Swedjemark, 1978). Typical emanation rates of radon from earth-based construction materials are quite low (0.02 to 0.20 pCi m^{-2} sec^{-1}; Nero and Nazaroff, 1984) and rarely cause elevated indoor air levels, although large quantities of the material (for example as thermal storage for solar heating systems) could potentially cause high levels. A more complete review of this topic can be found in Stranden (1988). Emanation rates of radon from building materials were measured in six study homes, and the data are presented in Table 4.

The maximum values for all floor and wall measurements at each house are shown. As seen, most rates fall within the range of values cited above. Only one house, ECD027, had excessively high flux rates. The maximum rate of 5.13 pCi $m^{-2}sec^{-1}$ was measured at one of two locations on the basement wall approximately one meter below grade level. This rate is many times higher than that typically seen for exhalation rates from building materials. It is only partially corroborated by the measurement at the other wall location (0.66 pCi m^{-2} sec^{-1} on the same wall materials) and may be a result of sampling error caused by a poor seal between the sampling pan and the very irregular surface of the stone and mortar basement wall. In this situation, basement air with a high radon concentration may have leaked into the sampling pan and contaminated the exposed charcoal.

However, we cannot exclude the possibilities that this basement wall of heterogeneous materials (including local stone), may contain significant radionuclide mineralization, or that the obviously old, handmade wall is very porous, permitting considerable radon from the soil to pass through the wall material. A flux of 3.35 pCi m^{-2} sec^{-1} was measured on the open soil floor.

Assuming an exposed wall area of 62.5 m^2 emanating at the lower rate of 0.66 pCi m^{-2} sec^{-1} and a floor area of 66 m^2 emanating at 3.35 pCi m^{-2} sec^{-1}, the total radon source rate would be 9.44 x 10^5 pCi/hr. Using a pre-mitigation ventilation rate measurement of 1.06 ach, a building volume of 704 m^3, and using the following steady-state concentration model for a single well-mixed zone:

$$C = \frac{S}{\lambda_v V} \; ; \qquad [2]$$

where:

C = steady state concentration (pCi/L),

λ_v = ventilation rate (hr^{-1}),

V = building volume (L), and

S = radon entry rate (pCi/hr),

the indoor air concentration is calculated to be 1.3 pCi/L. While this value approximates the concentration in summer (3.8 pCi/L), it probably grossly overestimates the actual concentrations due to these sources, since average flux rates are likely to be lower. Even if the higher (and possibly erroneous) wall exhalation rate were used for the calculation, the predicted indoor radon concentrations due to flux from these materials would still only be 2.6 pCi/L (as seen below in Table 8), considerably below the pre-mitigation heating season average of 45.0 pCi/L. In five homes with low indoor air concentrations (less than 5.4 pCi/L), the emanation rates (walls - 0.05 pCi $m^{-2}sec^{-1}$; floors - 0.08 pCi $m^{-2}sec^{-1}$) are comparable to those of the remaining five high indoor concentration study homes.

Soil as a Radon Source

The calculated contributions from building materials and water to the indoor radon levels are generally very small and are shown in columns 5 and 6 of Table 8. Since even worst case analyses do not indicate that building materials or the domestic water supply are the primary sources, we proceed with the hypothesis, based on data from studies of houses with high indoor radon concentrations, that the predominant source is the soil surrounding the building shell. Radon is then transported into the building by diffusion and by convection through the cracks, penetrations, and open areas in the substructure surfaces. Figure 8* shows the mechanisms of radon generation and movement through the soil and the primary entry paths through the building shell. Radium (^{226}Ra) in the soil has evolved from the decay of uranium (^{238}U). Enrichment of uranium or radium concentrations can occur through various

*Figure 8 also shows the decay chain for radon that has entered the structure. Radon decays into a series of reactive elements (progeny) that may adhere to other airborne particles or remain unattached. In either case, they may be inhaled where the irradiation of lung tissue by alpha particles from the decays of polonium 218 (^{218}Po) and polonium 214 (^{214}Po), in particular, can result in the development of cancers. Another radioactive gas, thoron (^{220}Rn), is frequently created in soils in similar quantities as radon. However, because of its shorter half-life (55 sec.), thoron is less able to survive long enough to enter the substructure and decay into a similar set of thoron progeny. Several attempts to measure thoron were made in this study, but because of instrument difficulties, no data were collected.

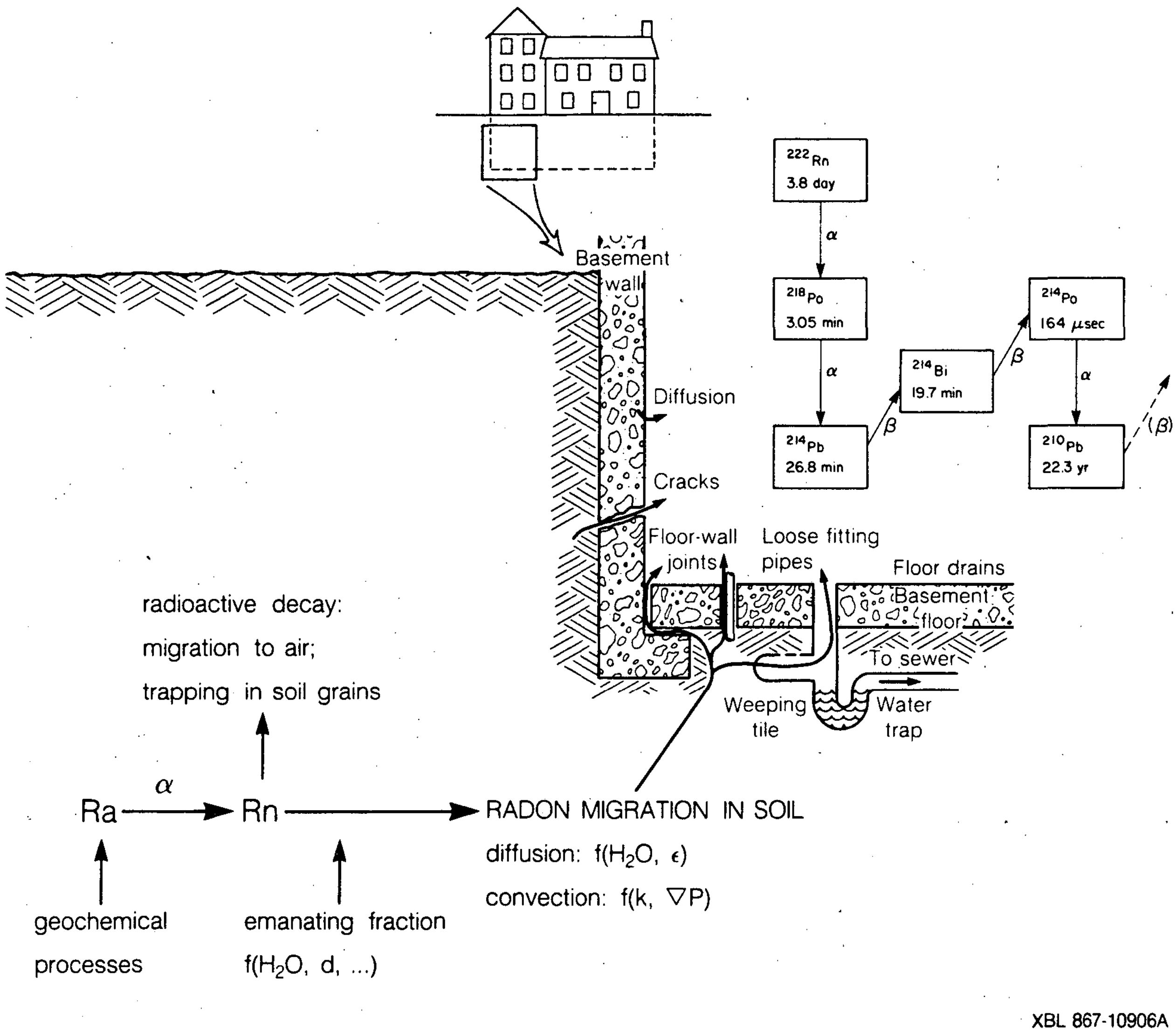


Figure 8 The transport mechanisms and decay chain of radon (^{222}Rn). Radon becomes available for transportation with soil gas following the decay of radium (^{226}Ra) in the soil or building materials. Migration is by diffusion and convection, and is dependent upon soil grain size distribution, moisture content, porosity, permeability, and the applied pressure field. It enters buildings through substructure openings or imperfections, whereupon it ultimately decays into a series of reactive decay products, some of which are responsible for the development of cancer in lung tissue. Thoron (^{220}Rn) follows similar processes and pathways, although its shorter half-life results in smaller quantities actually entering the structure.

geochemical processes. Radium subsequently decays, creating radon (^{222}Rn). The amount of radon that is available for transport in the soil (emanating fraction) depends on soil moisture and the size distribution of soil grains. Once in the soil pore space, radon can move by diffusion, which is influenced by soil porosity, moisture content, and the diffusion gradient; and by convection of soil gas, which depends on soil air permeability and the applied pressure field. These factors are, in turn, affected by other environmental parameters including precipitation, soil and air temperatures, and wind speed; and by house operating parameters such as indoor air temperature and structural parameters such as leakage area of the shell between the house and soil.

Of the two migration processes, convective flow of radon-bearing soil gas has been found to be the most important entry mechanism for the majority of houses with elevated radon levels (DSMA, 1985; Nazaroff, et al., 1985b, 1986a, 1986b), and is reviewed by Nero and Nazaroff (1984) and Nazaroff, et al. (1988b). One of the houses in this study (ESP120), was intensively studied by Sextro, et al. (1987a). The surrounding soil was found to have very high soil gas migration rates (greater than 1 m h^{-1} at 30 Pa depressurization in the basement), certainly an important contributor to the high levels observed in this house. The soil gas with radon is drawn into houses by the negative pressures that occur in substructures during the heating season. These negative pressures are created when indoor temperatures are higher than outdoor temperatures causing a "stack effect" that "pumps" air (and soil gas) into the lower levels of the house and exhausts it near the top. Aggravating this depressurization are forced-air furnace supply and return flows (leaky return ducts and plenums in basements and crawlspaces), vented combustion devices (fireplaces), and wind interacting with the complex distribution of structural leakage area.

To characterize the soil, samples were collected, *in situ* air permeability measurements were made, and soil gas samples were periodically collected and analyzed for radon. Visual inspection indicates that the soil is loosely packed and likely to be highly permeable. Permeability measurements made on-site at each one of the Spokane/Coeur d'Alene homes were in the range of 10^{-10} to 10^{-13} m^2 (See Table 5). Figure 9 displays these data graphically and exhibits an interesting relationship between increasing pressure and permeability. While it is possible that under test conditions, permeability could be decreased as applied pressure is increased (due to repacking of soil grains near the open end of the pipe probe) another explanation is the natural differences in the soil at different house locations. The measurement technique required that higher pressures be applied to less permeable soils so that the flow rate of air into the soil was above the measurement minimum of the flow monitoring devices. A second set of data of different applied pressures for the same probe (ESP120) shows the permeability to be relatively constant at $\sim 1.5 \times 10^{-10}$ m^2 over 60 to 1400 PA. These data can be compared with a range of possible soil permeabilities from Tuma and Abdel-Hady (1973) in Table 6, indicating that the soil around the study homes is within the appropriate range for gravelley soil.

The emanating radium concentrations of the soil samples collected at each of the sites are shown in Table 7. The data are within the range of typical values for other soils (~0.25 pCi/g) reported by Nazaroff (1988b), but are somewhat lower than those measured by Moed, et al. (1984) for other soils in the Spokane area (0.2 to 1.5 pCi/g). We might expect concentrations to be modestly higher if the measurements were made on the samples under more moist field conditions. Concentrations are fairly uniform between houses, including EVA604 in Vancouver. The maximum concentration of radon in soil gas, C_∞, at depths typical of basement floors can be calculated from:

$$C_\infty = \rho e / \varepsilon$$

where ρ, soil density was taken to be 1.4 g/cm^3; e, emanating radium concentration from local

TABLE 5. SOIL AIR PERMEABILITY MEASUREMENTS
SPOKANE RIVER VALLEY / RATHDRUM PRAIRIE

HOUSE ID	SOIL PIPE LOCATION	PERMEABILITY (K) (m^2)	APPLIED PRESSURE (Pa)
ECD 026C	1	1.4×10^{-10}	11
	2	1.4×10^{-10}	11
ECD 027C	1	1.4×10^{-10}	11
	2	7.6×10^{-13}	200
ECD 153	2	2.6×10^{-10}	7
ESP 101	1	2.6×10^{-10}	7
ESP 108C	1	2.2×10^{-10}	8
	2	1.9×10^{-11}	70
ESP 109	1	1.8×10^{-10}	10
	2	1.7×10^{-11}	72
ESP 111	1	1.3×10^{-10}	12
	2	1.4×10^{-10}	11
ESP 113	1	4.3×10^{-11}	35
ESP 116	1	5.9×10^{-11}	26
	2	2.6×10^{-10}	7
ESP 119	1	1.8×10^{-10}	10
	2	1.4×10^{-10}	11
ESP 120	1	1.6×10^{-11}	62
	2	4.3×10^{-11}	30
ESP 121	1	4.4×10^{-11}	34
	2	5.0×10^{-12}	140
NCD 077	1	1.8×10^{-10}	10
NSP 204	1	1.0×10^{-11}	100
	2	3.0×10^{-12}	150

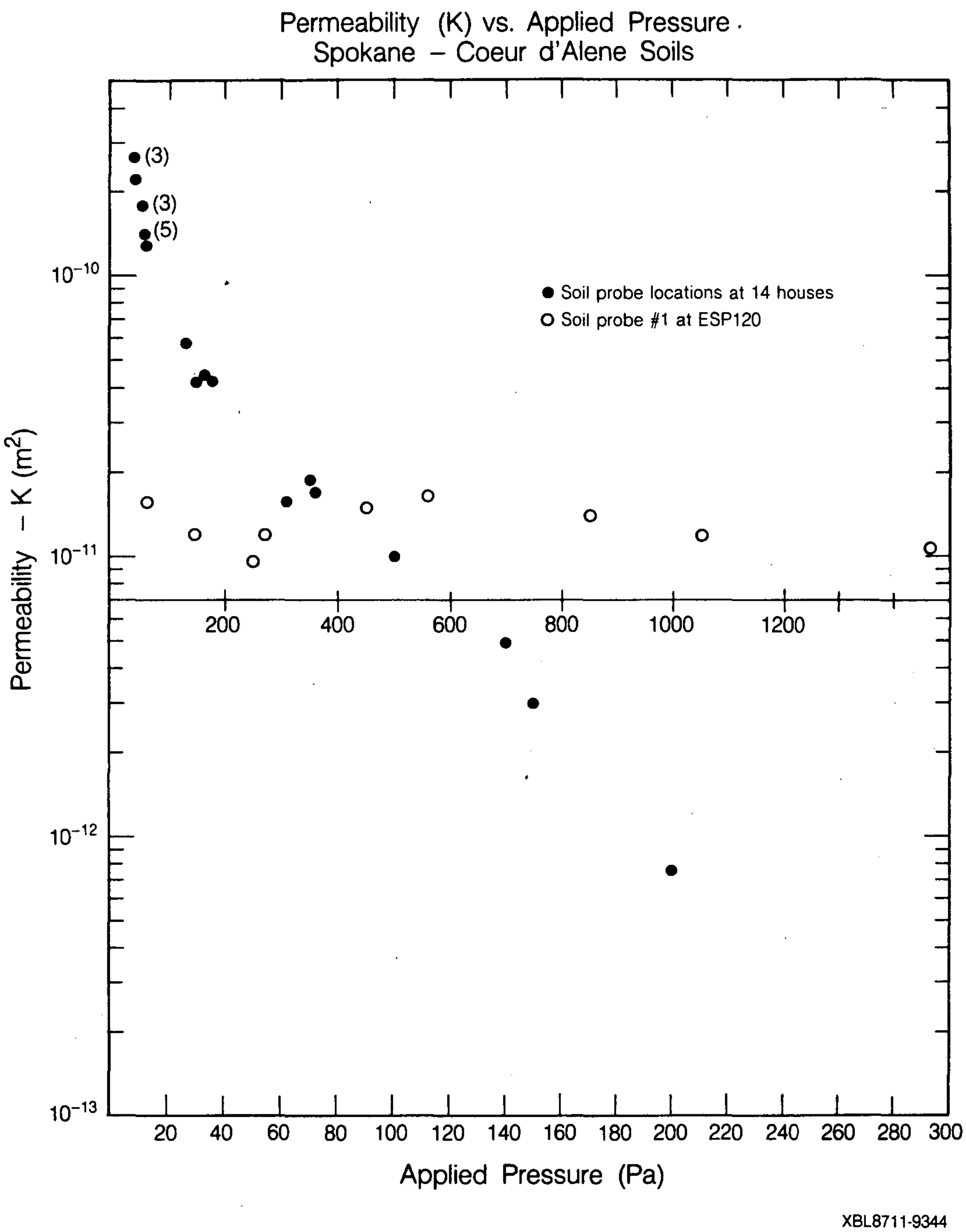


Figure 9 A log-linear plot of in-situ soil air permeability, K (m^2), from the 14 Spokane/Coeur d'Alene houses. The solid points refer to the bottom abscissa. The apparent relationship between increasing applied pressure and decreasing K is probably an artifact of the measurement technique that requires higher pressures in less permeable soils to maintain a flow rate above the detection limit. The data shown by the open circles refers to the middle abscissa and represents K calculated for a range of pressures at one soil probe. Here, K changes very little.

TABLE 6. RANGE OF SOIL PERMEABILITIES

SOIL TYPE	PERMEABILITY (m^2)
Clay	10^{-16}
Sandy Clay	5×10^{-15}
Silt	5×10^{-14}
Sandy Silt and Gravel	5×10^{-13}
Fine Sand	5×10^{-12}
Medium Sand	5×10^{-10}
Gravel	10^{-8}

samples, and; ε, soil porosity was assumed to be 0.4 cm^3 (air) per cm^3 (soil). These data are shown in column 3 of Table 7 with concentrations ranging from 420 pCi/L to 833 pCi/L.

Another interesting finding summarized in Table 7, is the soil gas concentration, C_∞, calculated for low indoor radon concentration homes. For these 15 homes, the geometric mean C_∞ was 690 pCi/L, which is within the range of measured and calculated values for the high indoor radon concentration homes. This supports the argument (discussed below) that the other factors: 1) house coupling to the soil, and 2) soil air permeability, are also important in governing the amount of radon entering a structure.

Grab samples of soil gas from soil probes at the houses were collected prior to installation of mitigation systems and were analyzed for radon concentrations. These concentrations are shown in the last three columns of Table 7. They tend to agree within 50% of the calculated maximum, C_∞, and also show a relatively small range, 283 to 673 pci/L from house-to-house. Measured concentrations may be different than C_∞ because 1.) soil gas at the probe depth (1.0 - 1.5m) near the house is depleted due to diffusion to the soil surface and the "pumping" action of the house, or 2.) of poor assumptions for porosity and soil density used in calculating C_∞. Detailed information on date, location, and concentrations of the soil gas samples is available in Appendix B. In Figures 10 and 11, we show soil gas grab-sample concentrations that were measured in the Control homes over the course of the study. With the exception of the last four measurements made at ESP108C, samples from each of the two pipes at each of the houses, tend to correspond with one another. Hoping to explain the observed variations in soil and house concentrations, the data are compared with other parameters. Since it was anticipated that indoor levels would follow changes in soil gas concentrations, indoor radon concentrations were measured on the first floor and based on a two-hour average after collection of the soil gases. The two environmental parameters, outside temperature and wind speed, are based on data averaged from measurements taken in the two hours before collection of the soil gas samples. If lower outdoor temperatures (larger indoor-outdoor temperature differences) increased the substructure depressurization, then soil gas radon concentrations might be expected to be lowered (depleted) by the higher flow rate of soil gas. We were also looking for a relationship between lower soil gas concentrations and higher wind speeds, which might tend to ventilate the soil. There was no observable relationship between

TABLE 7. SOIL AS RADON SOURCE

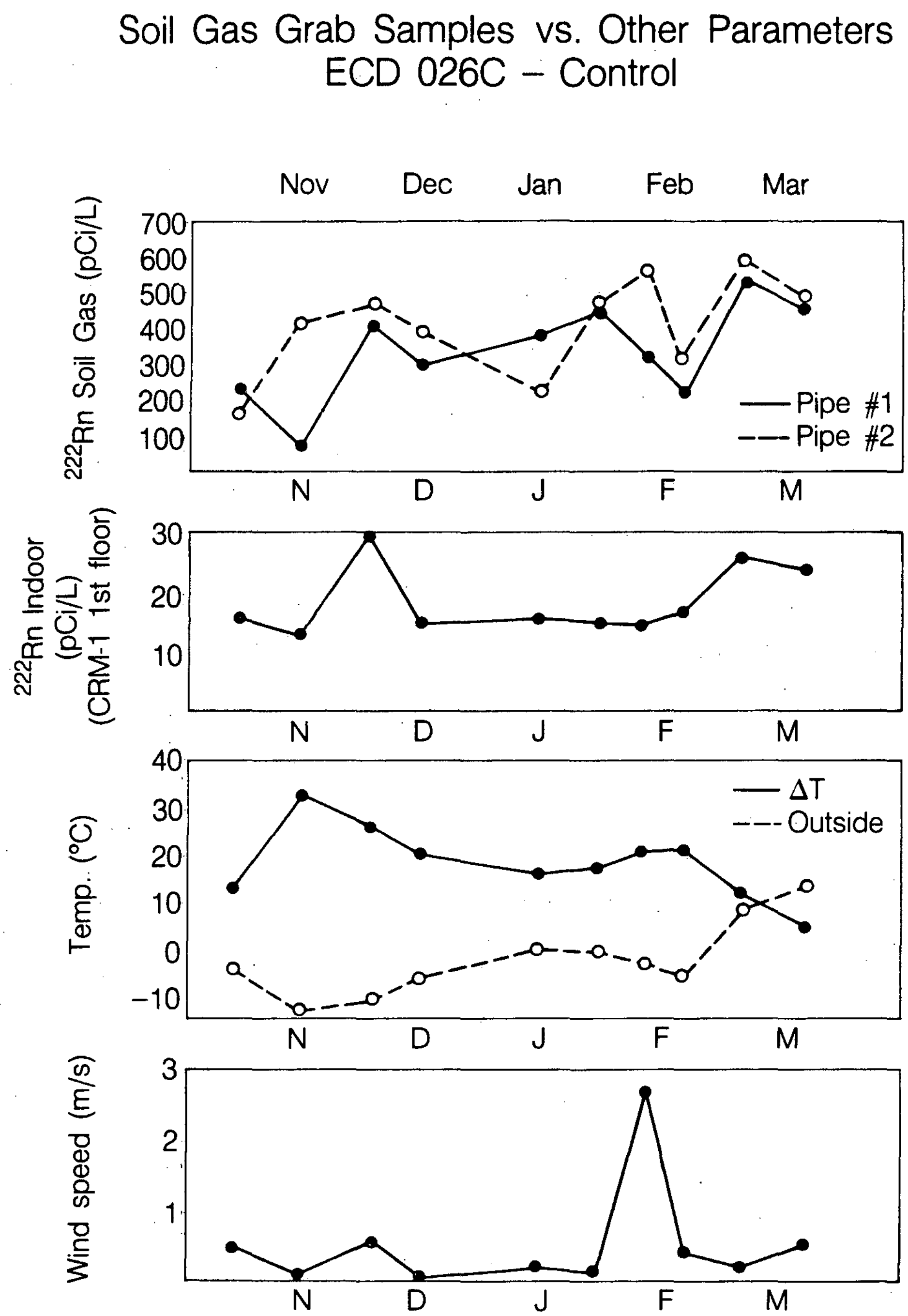
HOUSE ID	SOIL EMANATING RADIUM CONCENTRATION (pCi/g soil)[a]	SOIL GAS, C_∞ CALCULATED (pCi/l)[b]	SOIL GAS RADON MEASURED (pCi/l)[c]		
			Mean	Range	No.
ECD026C	0.150	525	1) 295	97-422	8
			2) 376	189-567	8
ECD027	0.233	816	1) 419	--	1
			2) 338	--	1
ECD153	0.165	578	1) 673	--	1
			2) 639	--	1
NCD077	ND	ND	1) 546	--	1
			2) 568	--	1
			3) 474	--	1
ESP101	0.160	560	1) 314	--	1
ESP108C	ND	ND	1) 283	68-532	8
			2) 489	420-629	8
ESP109	0.150	525	ND		
ESP111	0.120	420	1) 306	284-328	2
			2) 333	300-365	2
ESP113	0.170	595	1) 571	--	--
			2) 525	--	--
ESP116	0.133	466	ND		
ESP119	0.170	595	1) 446	--	--
			2) 442	--	--
ESP120	0.188	658	1) 314	311-316	2
			2) 574	537-610	2
ESP121	0.160	560	ND		
NSP204	ND	ND	407	--	--
EVA604	0.238	833	1) 632	620-644	2
			2) 617	608-626	2
Low concentration[d] houses	0.197	690	ND		

(a) Average of all samples at house - air dry conditions

(b) $C_\infty = \rho e/\varepsilon$; where soil density, ρ, is 1.4 g/cm^3; soil porosity, ε, is 0.4 cm^3 (air)/cm^3 (soil); and e is soil emanating radium concentration

(c) grab sample values obtained during all pre-mitigation measurement periods from each of several locations at a depth of 1.0 - 1.5 meters

(d) geometric mean for 15 houses with low indoor radon levels not selected into this study



Note: 1) Indoor radon concentration based on 2-hour average after collection of soil gas sample.
2) Temperatures and windspeed based on 2-hour average before collection of soil gas sample.

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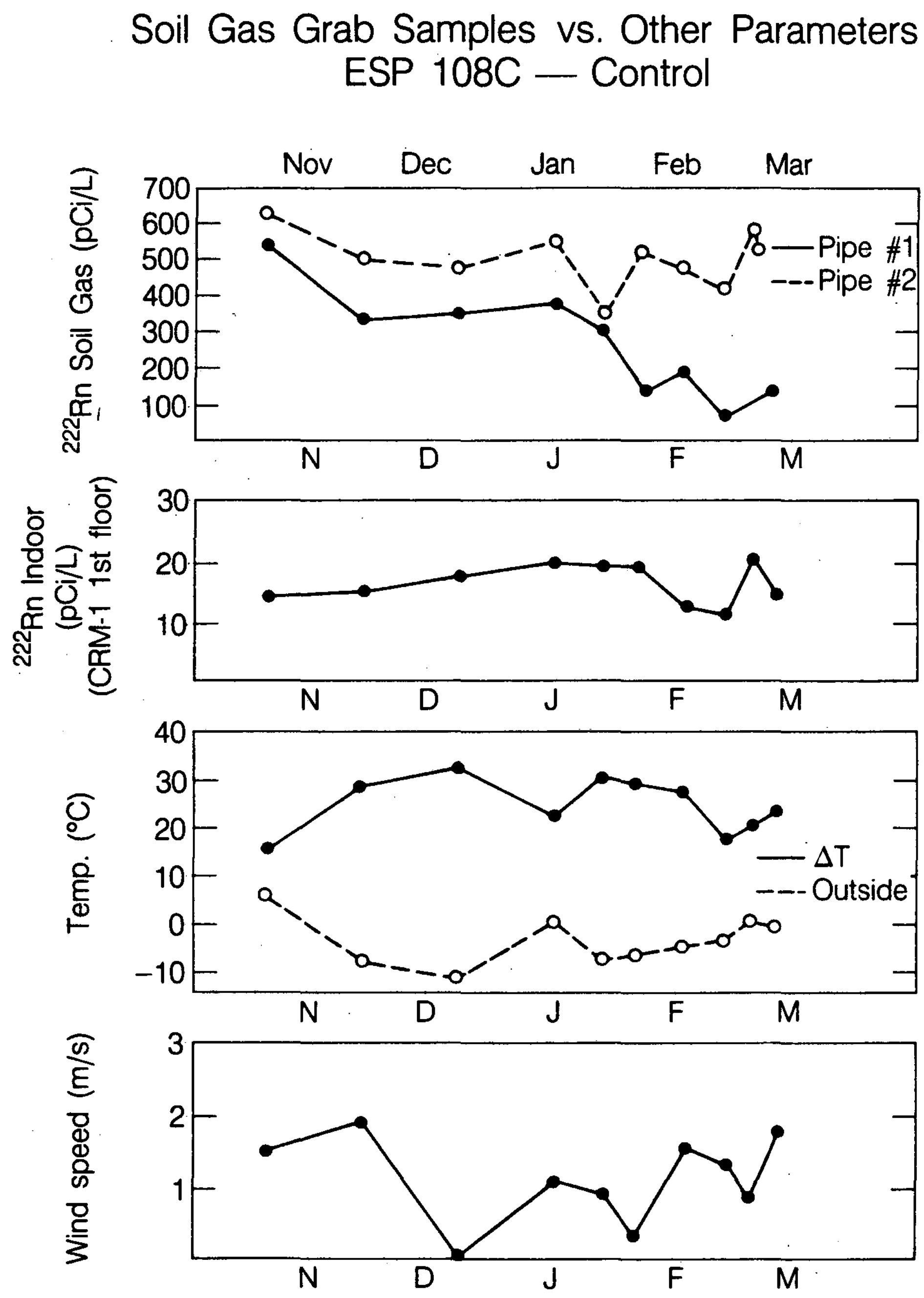
Figure 10 Periodic data from soil gas radon grab samples and other parameters for Control home ECD026C. Radon concentrations generally correspond well between soil probes at the same house, but display no observable relationship to the other factors.



Note: 1) Indoor radon concentration based on 2-hour average after collection of soil gas sample.
2) Temperatures and windspeed based on 2-hour average before collection of soil gas sample.

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Figure 11 Same as figure 10, but for Control home ESP108C.

the environmental parameters and the soil gas concentrations, or the soil gas concentrations and the indoor radon levels. More detailed continuous monitoring of these variables and soil moisture content may be necessary to demonstrate relationships. These do provide examples of the type of seasonal variation in soil gas radon concentrations that one might expect.

In order to account for the observed indoor concentrations resulting from convective flow of soil gas into the structure, a sizable quantity of soil gas must be entering these buildings. This is only possible when the observed soil gas concentrations are combined with high soil air permeability and adequate house leakage area below the soil line for coupling. A dramatic demonstration of soil gas movement occurred at ESP111. On several occasions with low outdoor air temperatures, vapor was seen to be rising out of soil near to the foundation wall. Using chemical smoke many variable-sized soil openings were located, some next to the foundation wall surface, some up to 1.0 to 1.5 m from the house. The vapor developed when the comparatively warm, moist soil gas condensed in the cold above-ground atmosphere. This escaping vapor also formed hoar frost on the cold grass, and foundation and siding surfaces near the soil openings. Flow rates were not measured, but were sufficient to cause movement of grass blades and leaves. Radon concentrations of 302 pCi/L and 317 pCi/L were measured in grab samples of air venting from one hole adjacent to the foundation. The mechanism causing this soil gas movement was never determined.

A calculation of the quantity of soil gas that must be entering the building to account for the observed winter season indoor radon concentrations was made for each of the study houses. The results are tabulated in the last column of Table 8. The soil gas entry rates are calculated from:

$$Q = \frac{C_W \ \lambda_v \ I}{C_\infty} \qquad [4]$$

where:

Q = soil gas entry rate (m^3/hr),

C_W = winter season indoor air concentration (pCi/L),

C_∞ = maximum calculated concentration of radon in soil gas (pCi/L),

V = building volume (L), and

λ_v = ventilation rate (hr^{-1}).

These calculations indicate that soil gas entry may be a significant portion of the infiltrating air. For example, in house ESP120, with a ventilation rate of 0.2 ach and a volume of 487 m^3, the soil gas entry rate is approximately 20 m^3/hr or almost 20% of the infiltrating air. In another house with lower indoor concentrations, (ESP111) and an indoor volume of 571 m^3, an estimated 7%, or 12 m^3/hr, of its infiltrating air would be soil gas. These values are similar to those predicted by Fisk and Mowris (1987) for permeable soil, but considerably higher than the 1 m^3/hr typically calculated by other researchers (DSMA, 1983; Nazaroff, et al., 1985b).

An examination of the "estimated contributions" from various sources in Table 8 clearly shows that radon entry due to water or building materials is negligible compared to convective flow of radon from the soil. Therefore, the mitigation systems selected for this project were not designed to control sources such as building materials or domestic water supplies, but rather were designed to control indoor radon concentrations resulting from high rates of soil gas entry.

TABLE 8. ESTIMATED CONTRIBUTION TO INDOOR RADON FROM VARIOUS RADON SOURCES.

HOUSE ID	MEASURED INDOOR AIR RADON (pCi/L) Winter Season 84-86[a]	MEASURED INDOOR AIR RADON (pCi/L) Summer 85[b]	PRE-MITIGATION WINTER VENTILATION RATE (ACH)[c]	ESTIMATED CONTRIBUTION Building Materials (pCi/L)[d]	ESTIMATED CONTRIBUTION Water Supply (pCi/L)[e]	ESTIMATED CONTRIBUTION Soil Gas Entry m^3/Hr[g]
ECD026C	17.4	1.1	0.45(15)	ND	0.1	7
ECD027	45.0	3.8	1.06(1)	2.6	0.3	39
ECD153	24.2	1.0	0.25(1)	0.3	<0.1	5
NCD077	23.3	ND	0.46(1)	ND	ND	11
ESP101	27.6	3.5	0.16(1)	1.1	0.1	4
ESP108C	15.5	4.3	0.35(15)	ND	0.1	9
ESP109	6.9	1.8	0.31(1)	ND	0.1	2
ESP111	29.6	0.9	0.31(1)	ND	<0.1	12
ESP113	19.8	3.7	ND	ND	0.1	3
ESP116	20.2	ND	0.45(1)	0.2[f]	0.1	8
ESP119	49.4	ND	0.47(1)	ND	<0.1	17
ESP120	140.8	11.9	0.20(1)	1.0	0.1	20
ESP121	11.2	1.2	0.29(1)	ND	0.1	2
NSP204	26.3	ND	0.74(1)	ND	ND	23
EVA604	10.4	0.9	0.18(2)	0.4	0.1	0.4

(a) Average for intermittent non-mitigation continuous monitoring throughout the months November - March

(b) Alpha track monitors

(c) PFT-measured average for all pre-mitigation 7-day monitoring periods November 85 - March 86. () is number of periods

(d) Calculated from $C = \frac{\text{Emanation} * \text{material area}}{\text{Ventilation rate} * \text{building volume}}$

(e) Estimated by applying indoor air to water ratio of 10^{-4} to Table 1 gamma spectroscopy data

(f) Using only emanation rate from floors for entire wall and floor area

(g) Quantity of soil gas entry calculated from $Q = \frac{\text{Winter season indoor air concentration} * \text{building volume} * \text{ventilation rate}}{\text{Calculated soil gas concentration } (C_\infty)}$

B. SPATIAL AND TEMPORAL VARIATIONS IN INDOOR RADON

A better knowledge of the variations of indoor radon concentrations, that depend on location in a structure and the time of year or time of day, is important in establishing methods and procedures for properly monitoring radon and assessing exposure (Ronca-Battista, et al., 1986), and in understanding the relationships among the many factors affecting radon entry and accumulation in buildings. While this study was not designed or instrumented to address these issues, some of the data collected, particularly from the unmitigated Control homes, provide a unique opportunity to briefly examine the response of indoor radon to several factors.

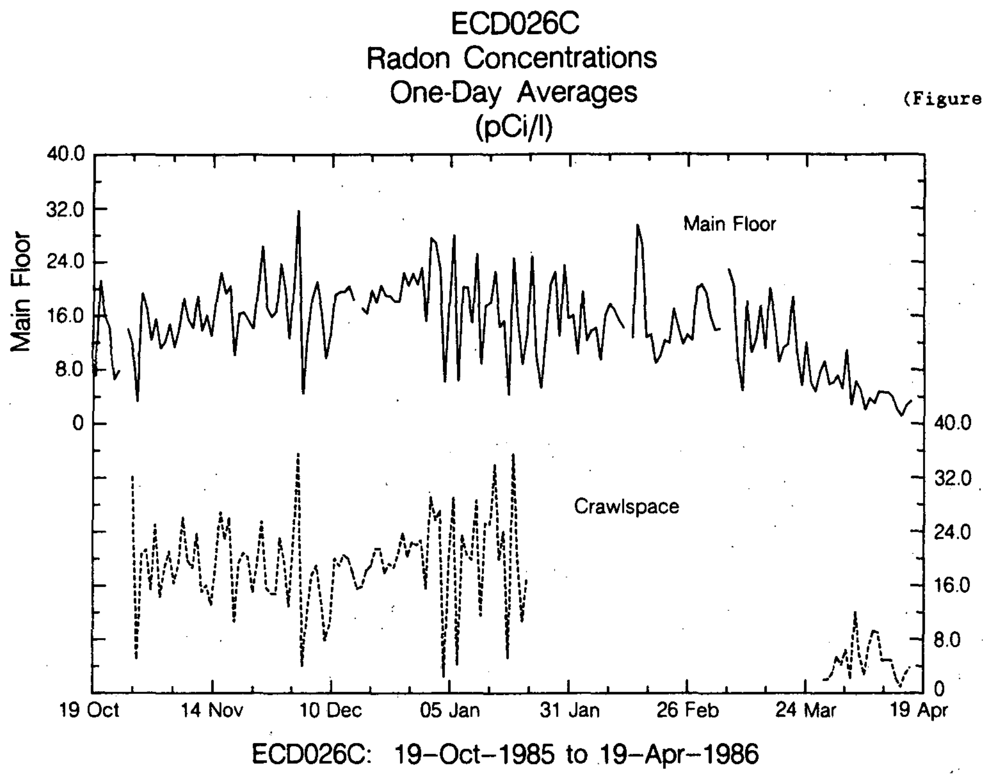
A comparison of winter or heating season indoor radon concentrations with those measured during the summer is shown on Table 8. Radon concentrations measured during the summer were lower than those measured during the winter in all homes. The average winter/summer ratio for these homes was 12.6 (standard deviation = 8.97), ranging from a ratio of 3.6 to one of 32.9. For 18 homes with low indoor concentrations during the winter (the maximum indoor concentration was 5.7 pCi/L), the average winter/summer ratio was 2.5 with a standard deviation of 1.4. This indicates that the winter/summer ratio is dramatically higher in those homes in this area that have high heating season concentrations and implies that seasonal variations in radon entry rates (due to soil conditions and soil-substructure coupling) and/or removal mechanisms are different between the two groups of homes. This may also imply that modified operation of radon control systems during the summer months when indoor radon levels are naturally lower is possible.

Figures 12 and 13 show approximately 20 weeks of continuous, one-day averaged, main floor and substructure radon data for Control Homes, ECD026C (half-depth basement with a crawlspace) and ESP108C (full-depth basement). Mitigation was not begun in these homes until the second week of March. Since both homes had forced-air furnaces which tend to mix the air within a building, it is not surprising to see average substructure and main floor radon levels as approximately equal, although substructure levels were always higher. A gradual increase in radon levels is observed in both homes from the start of monitoring in October through January. At that time, concentrations appear to level off, but also exhibit large fluctuations sometimes enduring for several days. Some of the variation may result from occupant activities, such as house cleaning or weekends when the houses were unoccupied. Both houses experienced a brief period of relatively low concentrations in mid-January, possibly due to meteorological phenomena. A thorough attempt at explaining these variations has not been made. Similar plots for each of the other study houses along with a chronicle of mitigation activities are contained in Appendix C.

Figure 14 is a plot of windspeed, indoor-outdoor temperature difference (ΔT), and indoor radon for a three-week period before mitigation at ESP111. This house exhibited dramatic decreases in indoor radon levels closely associated with increases in wind speed (Pearson correlation coefficient of approximately -0.8). Since the house did not have excessive specific air leakage area* (approximately 4 cm^2/m^2), we believe the factor of ten reduction was not due to increased ventilation. Instead, the increased wind speed appears to directly affect the radon entry rate, possibly by ventilating the soil surrounding the house (DSMA, 1983, 1985). This process could occur because the dynamic wind pressure interacts with the house profile to create a positive pressure region on the windward side of the house, and a negative pressure on leeward sides forcing a flow of outside air through the soil surrounding the house. During calm periods, the figure suggests that radon levels respond to changes in ΔT in the expected fashion, i.e. they increase as indoor-outdoor temperature difference increase.

*Specific leakage area (SLA) is defined as the leakage area (cm^2) normalized by the floor area (m^2).

(Figure 12)



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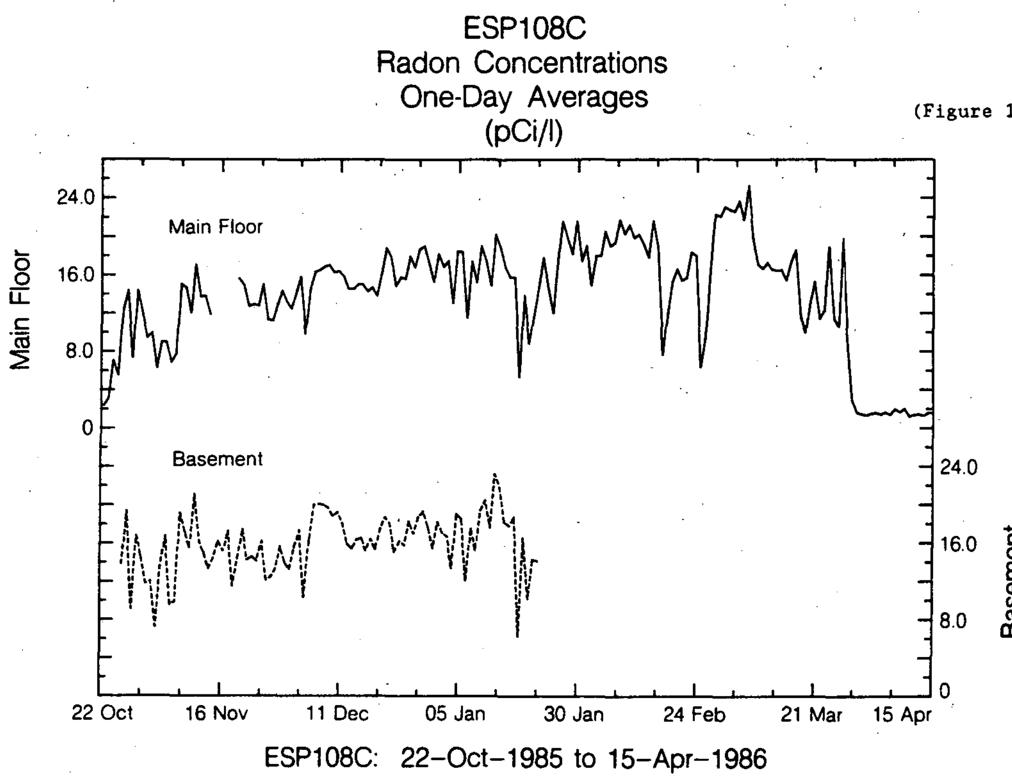
(Figure 13)



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Figures 12 & 13 **Continuous radon data for the main floor and sub-structure of the two Control homes during the heating season. The data are one-day averages. Mitigation did not begin until the second week of March.**

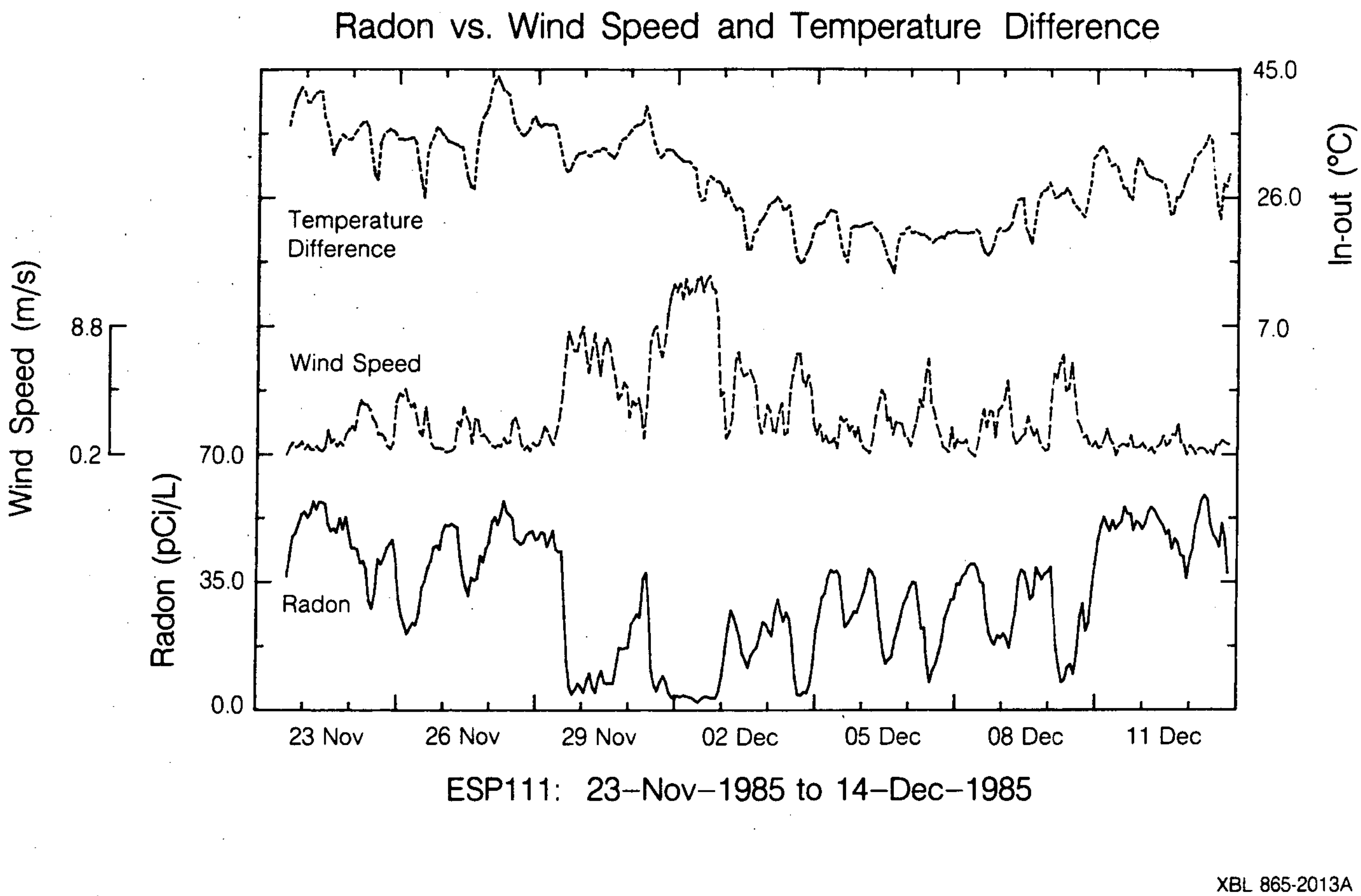

Figure 14 Continuous radon, windspeed, and indoor-outdoor temperature difference data for a three-week period before successful mitigation. Data suggests that the soil surrounding the structure is being ventilated with outside air during windy periods.

Partly in an attempt to explain some of the variations in radon levels, the five to nine-day ventilation rates determined with PFTs were plotted with the average radon concentrations for the same period in the two Control homes (Figure 15). It is obvious that any analysis of these data will be complex. We observe periods in both house where radon levels change in opposition to changes in ventilation, as expected. However, we also find a smaller number of periods in both houses where radon levels appear to positively track changes in ventilation. The test periods for both Controls do not exactly overlap, but are, at most, only one to two days offset so that environmental conditions should be similar. Therefore, it is somewhat surprising to note that ventilation rate changes do not track between the two houses, although local wind shielding may be different. Once again, individual structural and occupant usage characteristics probably account for some of the disparity. To determine if radon entry rates could be related to the primary driving potential or "stack effect", radon source strengths were calculated for each period using:

$$S = \frac{C \ \lambda_V}{V} \qquad [5]$$

The results shown on Figure 16 are compared with the average ΔT for that period. If we compare Figures 15 and 16, we see that changes in source strength are dominated by changes in ventilation rates, which may in turn act as a surrogate for changes in ΔT. Indeed, with a few exceptions, source strength does correspond with changes in ΔT. Radon source strengths were calculated for the other homes during baseline conditions. Values ranged from 3.14×10^5 pCi/hr (EVA604) to 344.7×10^5 pCi/hr (ECD027). Since Control home source strengths can vary by a factor of two, these data for all homes should be used carefully.

Recent models incorporating parameters describing soils, the building structure, operating conditions, ventilation, and environmental conditions have been developed to account for the radon variations observed in houses (DSMA, 1985; Nazaroff, 1988b; Avela and Winqvist, 1986; Louriero, 1987; Mowris, 1987; Revzan, et al., 1987). Two investigations, in particular, have applied models to data collected on the Control homes in this study. Mowris (1986) used a simplified analytical model on ESP108C to predict ventilation rates, basement depressurization, soil gas and radon entry rates, and indoor radon concentrations from ΔT, windspeed, and house characteristics. Predicted and measured radon concentrations generally differ by less than 25%. He concludes that agreement between model predictions and measured concentrations would be improved by better handling of substructure gap and crack geometries and through validation of model assumptions. In Turk, et al., (1988), Revzan creates a parametric model of radon levels for ECD026C and ESP108C for evaluating the effects of house weatherization. This partially successful model would be improved if data were available for the other important variables (soil moisture, permeability, radon gas concentration, and substructure and subslab pressures).

Figure 17 shows the average time-of-day variations in radon concentrations within ESP108C for approximately 120 days before mitigation. The standard deviation for the data points for the main floor was approximately 5.0 pCi/L and for the basement, approximately 3.5 to 4.5 pCi/L. The diurnal swing in basement radon may be attributable to the diurnal temperature changes; however, for this house it is at least partly affected by operation of the forced-air furnace. Comparing the two curves of the figure, we notice that basement concentrations begin to fall as main floor concentrations begin to increase, at about 7:30 AM. The set-back thermostat requests higher house temperatures at this time causing the furnace (and blower) to operate a larger percentage of the time. Thus, air throughout the house is well-mixed and radon levels are nearly equal between floors. Once the desired temperature is reached, furnace activity decreases and basement concentrations begin to climb again. In the evening, falling outdoor temperatures and greater occupancy rates put a larger demand on the furnace which again mixes house air until night, when the thermostat reduces house temperature and furnace operation.

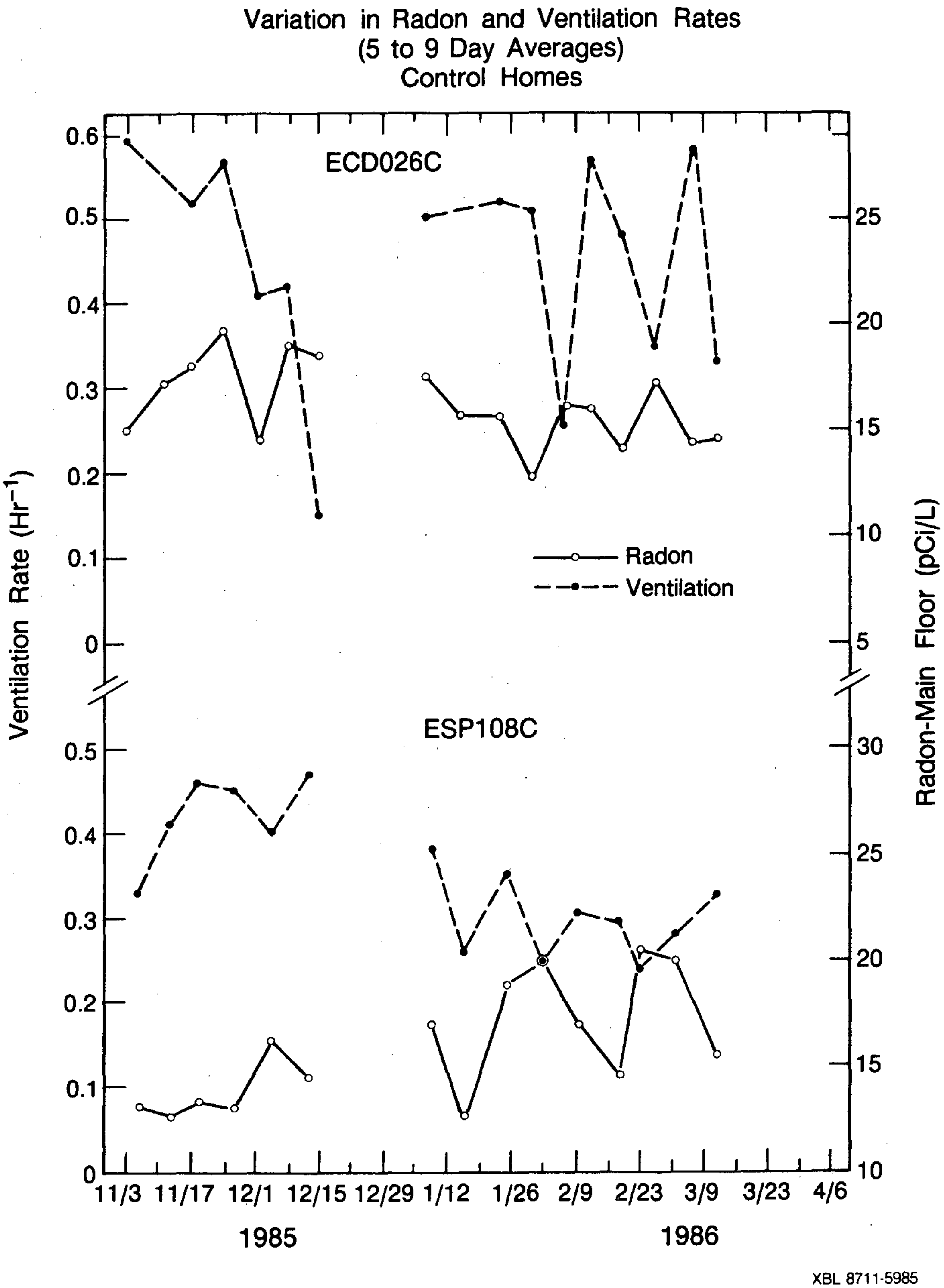

Figure 15 Five to nine-day average radon and ventilation rates for the two Control Houses. Correlation is poor. There is also poor correspondence for ventilation rates of the two houses for the same monitoring period.

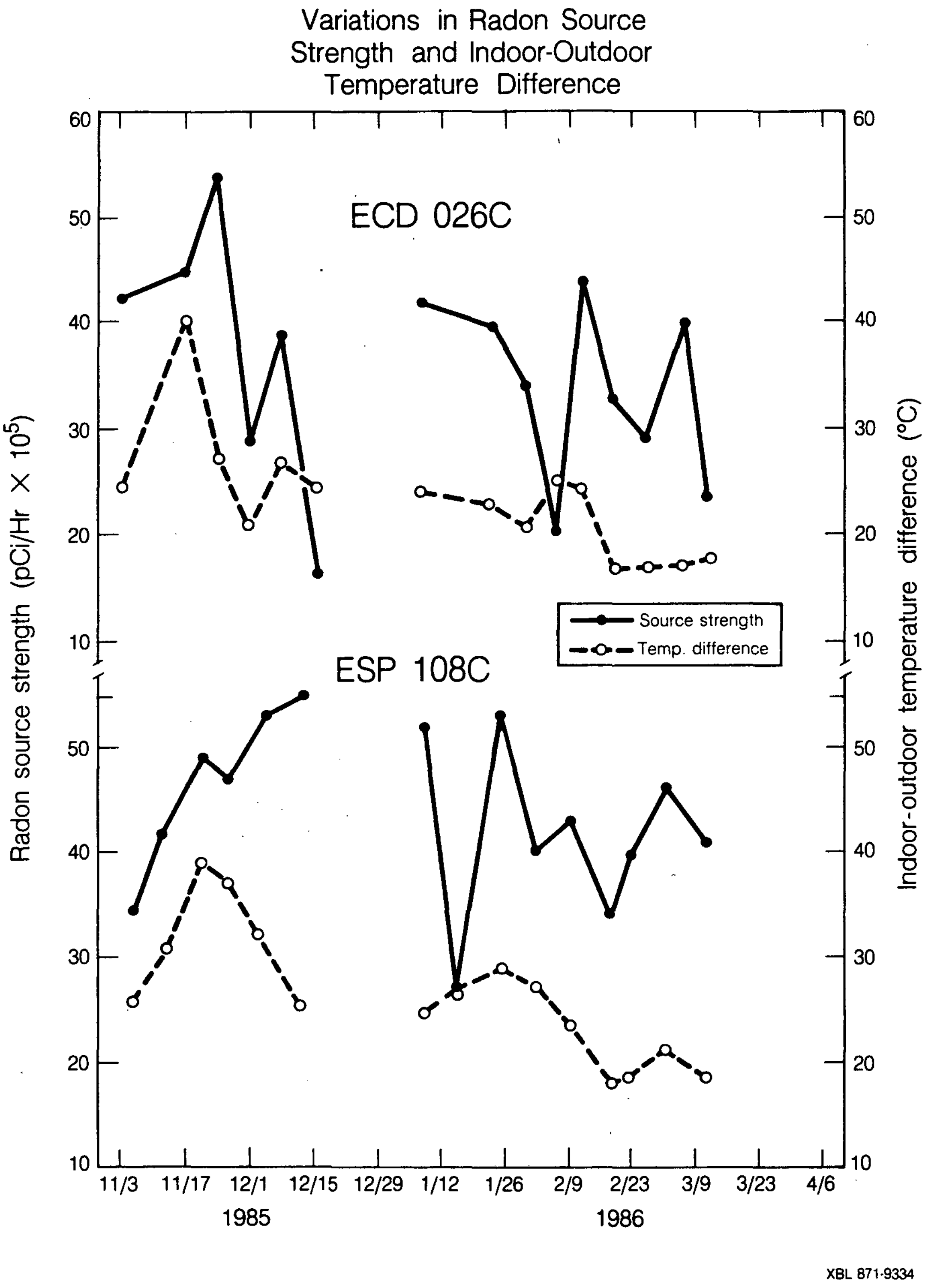

Figure 16 Variations in radon source strength and ΔT for two Control Homes. Source strength shows a weak dependence on ΔT.

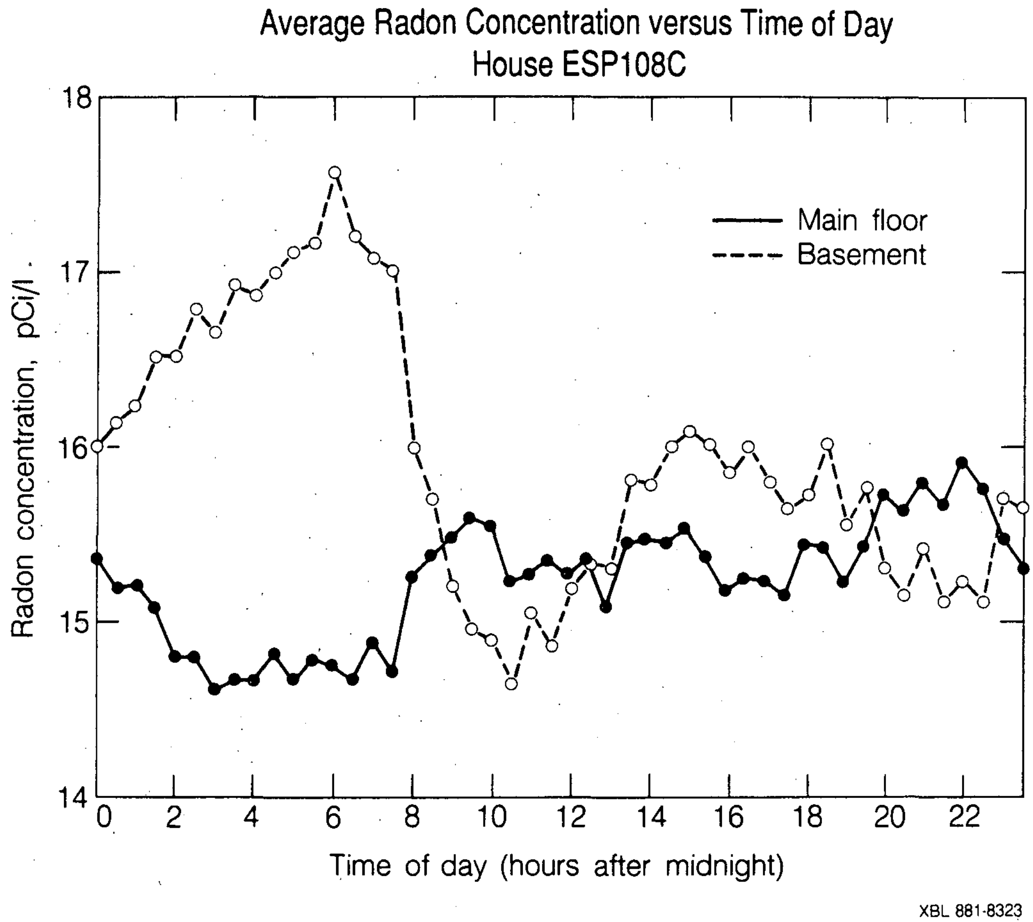

Figure 17 Average time-of-day radon concentrations, basement and main floor, for ESP108C over approximately 120 days before mitigation. The effect of furnace fan mixing is seen to create nearly equal concentrations in the two zones on each floor at 07:30 AM and 19:30 PM.

The floor-to-floor spatial differences for four other homes are seen in Table 9. Air mixing between basement and upstairs must often be quite good, even in the home with electric baseboard heat. Occupant activities, including opening the basement door, may be important. This is not always so between crawlspaces and occupied spaces. While both ESP119 and ECD026C had forced-air furnaces located in the crawlspaces, the key factor in the differences in zone-to-zone mixing is the fraction of air entering the house which comes from the crawlspace. This depends primarily on the greater area of structural openings between floors and duct leakage that was visually observed in ECD026C, and to the higher baseline crawlspace ventilation rate in ECD026C (~0.5 hr^{-1} vs. ~1.2 hr^{-1}). Six New Jersey homes with forced-air furnaces were monitored in a study-in-progress and tended to show greater differences between the upper floor concentrations and the substructure concentration than these homes in Spokane. This is likely due to differences in the availability and frequency of openings between the substructure spaces and the upper floor spaces (electrical, plumbing, heating, and other penetrations) and to the heating system configuration and operation (presence of forced-air furnace ductwork and its operation).

These variations in radon concentrations can have considerable influence on monitoring efforts to identify homes with elevated concentrations. Monitoring over too short a period may not provide data representative of the average concentration in a structure, the basis of most guidelines for exposure. If monitoring occurs during an interval with unusually high levels, then unnecessary radon remedial action may be recommended. If measurements were made during a period of abnormally low levels, remedial action will probably not be initiated and occupants will continue to be exposed to unnecessarily high health risks. While short-term monitoring (less than seven days) is useful as a screening process to find houses with elevated radon levels, it should be used very carefully in the summer and should be corroborated by longer-term monitoring. The location where monitoring is conducted is equally important. Concentrations measured on the upper floors can be considerably lower than those in the substructure. If the substructure is ever to be occupied, then concentrations should also be measured in that zone.

C. RADON CONTROL SYSTEMS

Mitigation Techniques Considered

The following sections are based on the earlier interim report (Turk, et al., 1986). After assessing the important factors, a mitigation plan was developed for each house. In some houses, several different techniques were examined for the purpose of comparison. These techniques were sequentially installed, operated, and their performance and effectiveness characteristics compared. As the study progressed, unsuccessful measures were abandoned and others substituted.

The following techniques were targeted for investigation. Installation procedures are described briefly and detailed system evaluations are provided in the next section. General references to radon control include Fisk (1986); DSMA (1979, 1980); Ericson, et al., (1984); Henschel and Scott (1986); Nitschke, et al., (1985); Sanchez and Henschel (1986); and Sextro (1985).

1) Sealing of Cracks and Holes.

To reduce the number of radon entry locations, asphaltic and mortar patch compounds were used to seal accessible cracks and holes in the substructure surfaces of five homes. Surfaces were first prepared by chipping and cleaning. Defects ranged from hairline cracks to large (40 cm. diameter) holes through slabs. For a general reference on this technique, see Scott and Findlay, 1983.

TABLE 9. SUBSTRUCTURE - UPPER FLOOR RADON CONCENTRATIONS BEFORE MITIGATION

HOUSE ID	HEATING SYSTEM[(a)]	AVERAGE RADON (pCi/l) - [STD. DEV.]		
		Upstairs	Basement	Crawlspace
ECD026C	FA	17.9 [6.60]	--	19.8 [8.88]
ECD027	FA	45.0 [11.74]	85.0 [27.29]	--
ESP108C	FA	14.7 [3.09]	16.1 [3.51]	--
ESP119	FA	49.4 [9.69]	--	111.4 [22.95]
ESP120	BB	115.2 [30.08]	140.0 [35.42]	--

(a) FA = Forced Air
BB = Baseboard Electric

2) House Ventilation with Heat Recovery.

New, ducted, central air-to-air heat exchangers (AAHX) were installed in the occupied basements of two homes as a method of reducing airborne radon and radon progeny concentrations. (See Nazaroff, et al., 1981). One home with an existing, poorly installed AAHX had delivery and return ducts modified.

3) Overpressurization of the Basement.

To reduce radon entry from pressure-driven flow of soil gas into the substructure, the pressure difference across the substructure shell was reversed by pressurizing the basement. Basements in five homes were first tightened to reduce air leakage to the upstairs and outside, using House Doctor techniques that involve depressurizing the space with a blower to aid the identification of air leaks with chemical smoke. These homes all had doors to the basement that were kept closed with spring - loaded hinges. The basement was pressurized with respect to the interstitial soil pore pressure with a 100 - 200 L/s fan. The fan pulled air from the upstairs and exhausted into the basement.

For those homes with forced-air furnaces and ducting in the basement, the upstairs air was supplied to the fan via the return air duct. All basement diffusers and ducts were closed by sealing the basement return air grille and installing a counter-weighted backdraft damper 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 ESP120 (the only home without a ducted heating system, it has electric baseboard heat) a hole was simply cut into the floor above the basement and air drawn directly from the upstairs. This hole was located under a clothes dryer for noise reduction and esthetic reasons. A one-to-two meter section of exhaust duct was attached to each fan to reduce fan and air movement noise and facilitate flow measurements. See Figure 18 for system details.

4) Sub-Surface Ventilation (SSV).

Another method of reducing radon entry due to pressure-driven flow is to alter the pressure difference across the substructure shell and/or the soil gas concentration immediately adjacent to the substructure. (See Sachs and Hernandez, 1984; Arix, 1982). In five homes, soil beneath the basement floor was ventilated through 7.6 cm (3 inch) PVC pipes that were placed through the slab in one to four locations per house. The pipes terminated approximately 30 cm below the slab in a 60 cm-diameter dry sump backfilled with washed gravel. The pipes were routed either singly or manifolded with other pipes to the outdoors. Flow and pressure control dampers were typically installed in the pipes. Centrifugal fans (with speed controllers) capable of delivering 25 L/s air flow at a pressure head of 125 Pa were installed on the pipes. Soil gas was then either exhausted from below the slab surface by depressurization (SSD) and vented outdoors or outside air was blown into the sub-surface soil by overpressurization (SSP). See Figure 19. A polyethylene sheet was sealed to the edge of the hole cut in the slab to minimize any short-circuit air leakage through a poorly applied mortar patch. Wire mesh was placed over the open soil end of the pipe to prevent rodents from entering the pipe. In more recent mitigation studies, these two procedures have been eliminated.

To reduce the possibility of the pipe being occluded by a rising water table, a series of holes may be drilled in the side of the pipe below the slab. The purpose of a large sump hole is to provide a larger surface area to enhance propagation of the pressure field through the soil near the house. Therefore, it may not always be necessary to excavate a large hole in those situations where a continuous gravel layer is under the slab.

Basement Overpressurization Systems

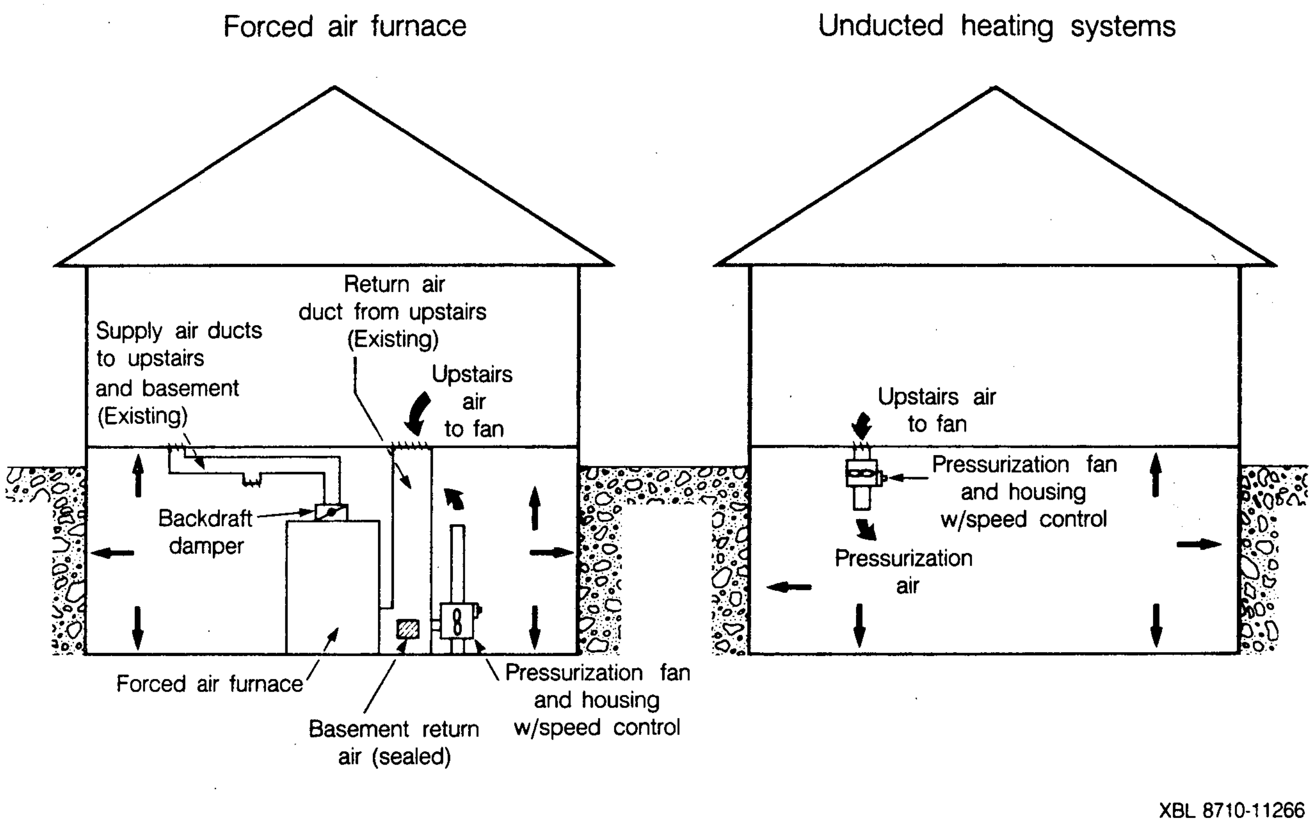

Figure 18 Typical basement pressurization systems for houses with forced-air furnaces and those with unducted heating systems. In a forced-air system, the existing return air duct from upstairs delivers air to the pressurization fan. The basement return air opening is sealed and a counter-weighted backdraft 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.

Schematic Diagram of Basement Subsurface Ventilation System.

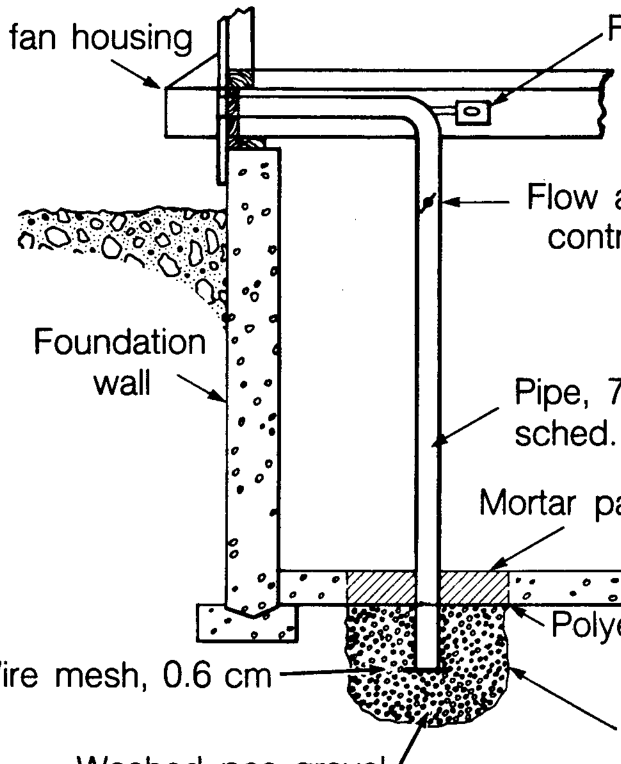

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Figure 19 Simplified schematic diagram of a basement subsurface ventilation system (SSV). Flows and pressures can be controlled either with the in-line damper or the fan speed control. The system can be operated under depressurization-drawing soil gas from under the slab and exhausting it outdoors, or under pressurization-blowing outside air into the soil beneath the slab.

Two other homes had similar systems installed exterior to the structure with the pipes extending into the soil along a basement wall. The pipes and dry sump extended under the footer. See Figure 20.

5) Crawlspace Sealing and Ventilation.

None of the study houses had only a crawlspace substructure. However, to satisfactorily reduce radon levels in the houses, it was necessary to control radon entry from these zones. (See Nazaroff and Doyle, 1985c). In addition to providing natural ventilation for crawlspaces, staged sealing and mechanical ventilation were investigated. In two houses, crawlspace soil floors were sealed with a plastic membrane. The basement of ECD027 was changed so that it effectively performed as a crawlspace. This space and the crawlspaces of two other houses were sealed and isolated from the occupied zones. An axial fan was used to boost crawlspace ventilation at two houses, and at one of these houses the fan was used to evaluate combinations of ventilation, pressurization, and depressurization.

6) Other Mitigation Techniques.

Two additional techniques were attempted. One involved ventilating the hollow-block wall of a fireplace at one house (See Henschel and Scott, 1986; Sanchez and Henschel, 1986). A PVC pipe was inserted into, and through, the blocks of this fireplace wall and attached to a fan as described above for SSV systems, and air from within the blocks and the other side of the wall was exhausted to the outside.

In one house, a perimeter baseboard duct ventilation system was installed as a means of reducing radon accumulation near the wall-floor joint entry crack. A channel was routed into the back of baseboard molding which was attached to the finished frame-construction interior perimeter walls in the substructure. A series of penetrations (of graduated-size to equalize flows along the duct) in these walls had been drilled through the gypsum board to access the stud-cavity, and thus the wall-floor joint crack in the substructure. At several locations, the baseboard duct system was attached to a blower which pulled air at roughly equal rates from each of the wall cavities and exhausted it to the outside. Figure 21 is a schematic diagram of this system.

Table 10 summarizes the specifications for the mechanical equipment used in the various mitigation systems evaluated in this study. The fans employed in the SSV systems were adopted from other applications (such as computer equipment cooling), but have worked well for the purposes of radon control.

Evaluation of Mitigation Techniques

Several effects (including occupant interaction with the mitigation system and environmental effects) must be considered in evaluating the performance of each mitigation technique. The environmental effects due to changing inside and outside temperatures and wind speed can occur on a short-term or long-term basis. We've already seen in Figure 14 dramatic changes in indoor radon concentrations that correlate well with wind speed and in Figures 12 and 13 longer term effects due to seasonal variations. While the seasonal variations may be smaller than daily variations, they can be significant. To reduce the possibility that these effects were causing falsely low radon levels following mitigation and to observe comparative mitigation system performance, some of the radon control systems were cycled on and off. In most cases, the period of pre- and post-mitigation monitoring was sufficient to demonstrate the effectiveness of mitigation.

Diagram of Exterior Subsurface Ventilation System

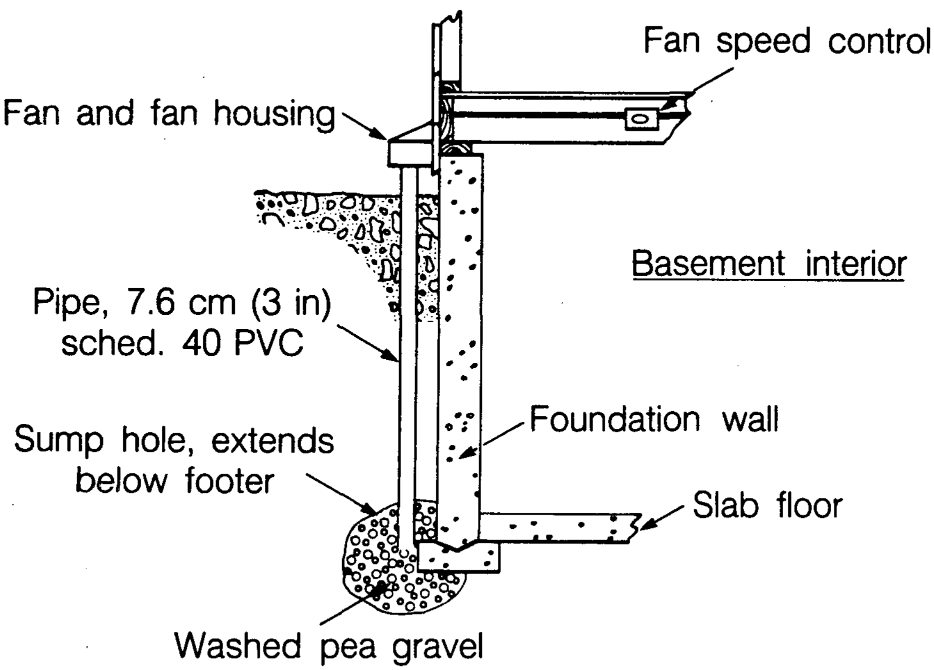

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Figure 20 Exterior subsurface ventilation system similar to that in Figure 19 used where an interior system is impractical to install.

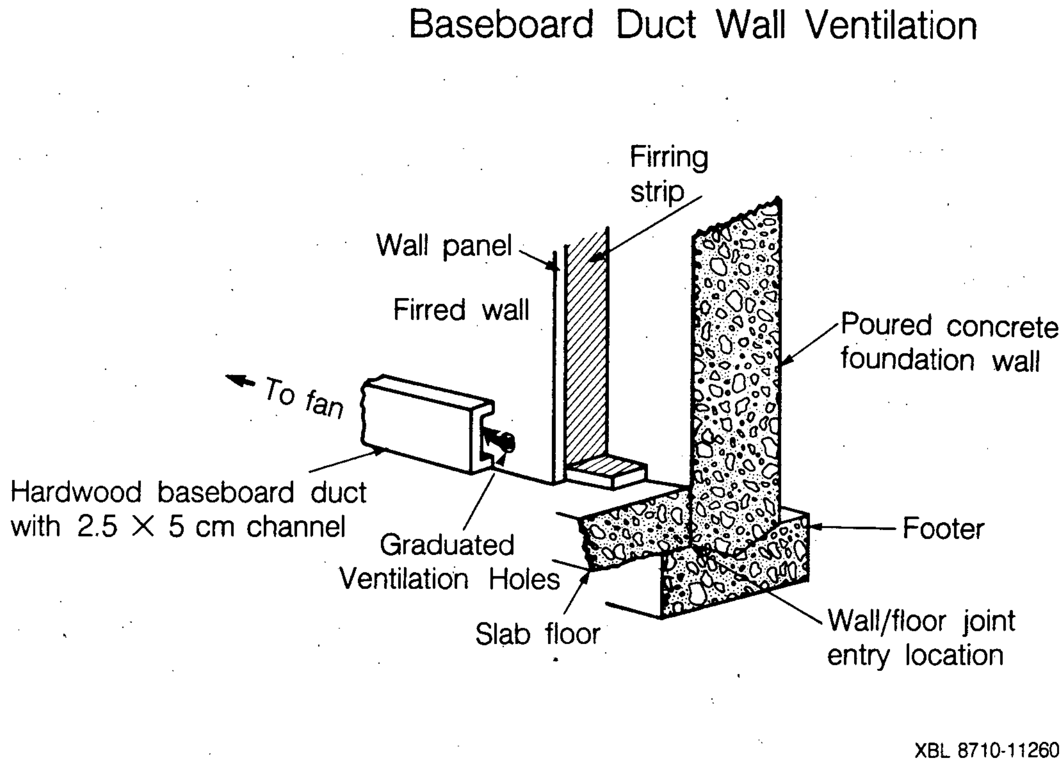


Figure 21 A cut-away diagram of the baseboard duct wall ventilation system showing the channel in the back of the baseboard cover molding. A series of graduated-size holes were drilled into the wall cavities (smaller holes near the fan, larger holes further away) so that each wall cavity space above the wall/floor joint entry location would be approximately equally ventilated. The fan attached to the channel exhausted the air outside.

TABLE 10. SPECIFICATIONS FOR MECHANICAL EQUIPMENT USED IN MITIGATION SYSTEMS

MODEL	USE	FLOW @ ZERO STATIC PRESSURE (L/s)	MAX STATIC PRESSURE (Pa)	MOTOR SPEED (RPM)	RATED WATTS	MAX DIMENSIONS (CM)
FANS:						
*KOOLTRONICS KBR60 CENTRIFUGAL	SUBSURFACE VENTILATION	26	575	3250	80	19 X 22 X 14
*KOOLTRONICS KBB47 CENTRIFUGAL	SUBSURFACE VENTILATION	94	625	3200	190	19 X 19 X 18
†KANALFLAKT K6 (IN-LINE METAL)	SUBSURFACE VENTILATION	127	>250	2150	90	19 X 29
†KANALFLAKT T2 (IN-LINE GLASS FIBRE)	SUBSURFACE VENTILATION	127	>250	2150	90	23 X 29
*DAYTON 4C667 CENTRIFUGAL	BASEMENT PRESSURIZATION	230	295	1580	157	26 X 28 X 25
DAYTON 4C668 AXIAL	CRAWLSPACE VENTILATION	264	ND	1650	36	25 X 9
DAYTON 4C548 AXIAL	CRAWLSPACE VENTILATION	26	ND	1800	11	12 X 12 X 4
AIR-TO-AIR HEAT EXCHANGER:						
VAN EE 2000 AAHX W/DEFROST	HOUSE VENTILATION	@100 Pa SUPPLY = 106 L/s RETURN = 120 L/s		VARIABLE	180	--

ND = No data

* Fan speed controllers were used to modulate operating pressures

† Not used in this study, but widely used by others.

Following are detailed descriptions of nuances and performances of each mitigation technique. Figures 23, 24, 29, 33, 41, and 43 summarize the results of the data for each system category and update the performance data issued in the earlier interim report. All data on indoor radon concentrations for pre- and post-mitigation periods in these figures were collected between November 1, 1985 and March 31, 1986.

Additional, detailed information on the operating condition, and modifications and changes made to mitigation systems in each house, is summarized in the Appendix C "Chronology of Operating Conditions and Mitigation Configurations" (Prill, et al., 1987).

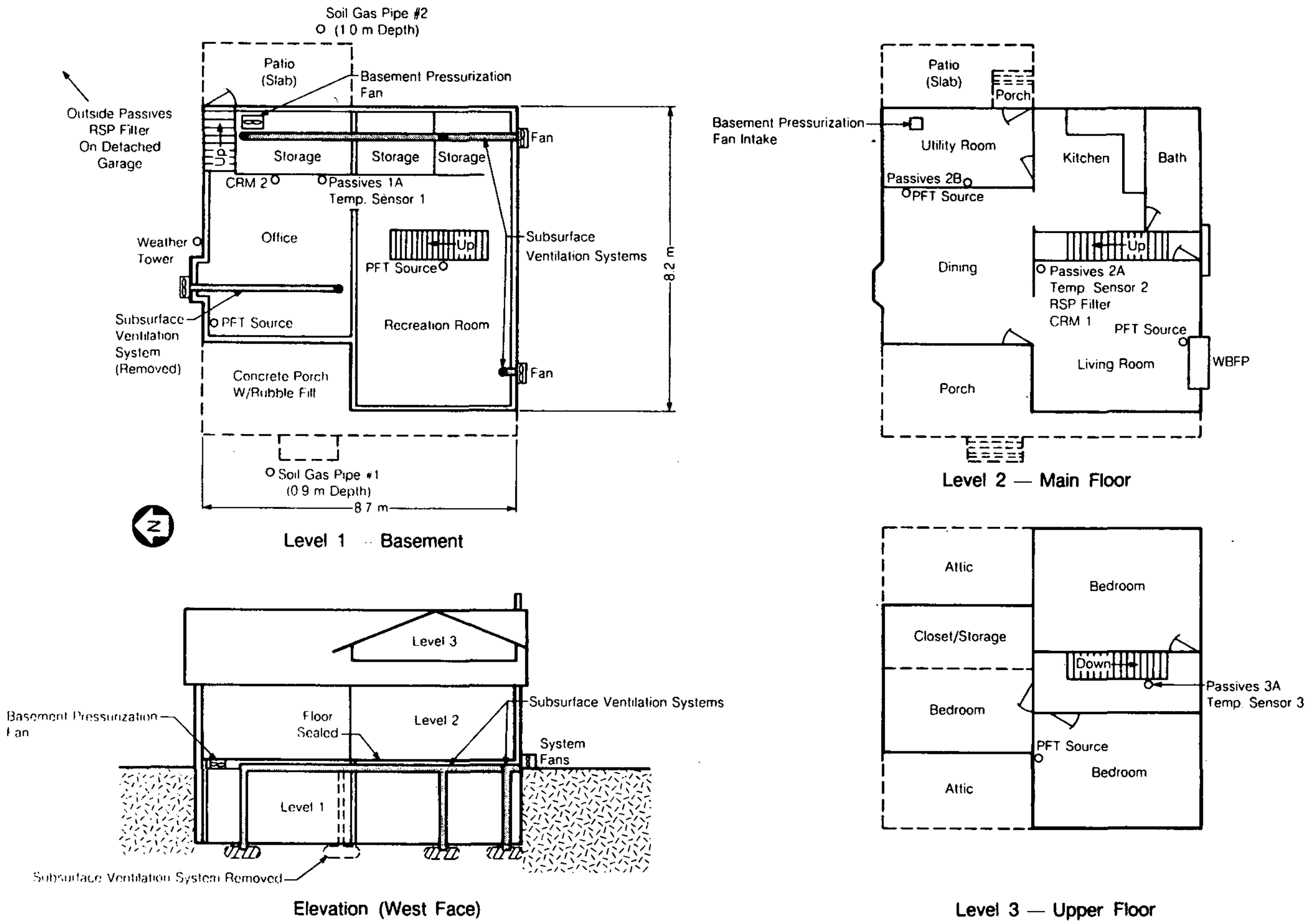
Appendix D, "House Floor Plans", contains floor plans and information on monitoring and mitigation system location. Figure 22 is an example which shows the locations of monitoring equipment and instrumentation (CRM's, passive samplers, RSP filters, α-track monitors, soil pipe-probes), ventilation measurement sources (PFT), and the radon control systems tested. In this particular house, one SSV pipe and fan in the northwest side of the basement were found to be ineffective and were eventually removed. Also shown, is the location of the basement pressurization fan that was compared to SSV system performance.

Sealing of Cracks and Holes

The sealing of floor-wall joints, floor and wall cracks, gaps around service penetrations, and holes from poorly laid slabs reduced indoor radon concentrations very slightly, if at all (Figure 23). Changes in radon levels after sealing were well within the range of natural long-term variations. The area of cracks and holes sealed at each house was different and depended somewhat on the visibility of accessible cracks. The total area sealed was not quantified. In some homes (particularly ESP111) considerable webbing, or minute cracking, was observed in the concrete floor slabs, but no attempt was made to seal these surfaces. Grab samples collected from under plastic sheets approximately 24 hours after they were taped over this floor showed concentrations of 52 pCi/L and 118 pCi/L. It may be that because generally only a small portion of the total crack and hole area is visible and accessible and therefore repairable, relatively little effect should be expected. Work done by Scott in Canadian and Florida homes (DSMA; Acres 1979, 1980; Scott, 1983) shows that careful and complete sealing can significantly reduce indoor concentrations.

It is also possible that the resistance to flow through the soil is much greater than the resistance to flow through all cracks. If so, sealing actions might begin to be effective once the total substructure crack resistance has been increased to a value similar to that of the soil resistance. A possible exception appears to be house ESP120, where the difference between the average before and after conditions (8.2 $\pm$ 1.8 pCi/L versus 4.1 $\pm$ 1.7 pCi/L) may be significant. However, these data are from a time period with a separate subsurface depressurization ventilation system (SSD) operating, which may simply indicate that sealing improved the performance of this system. Indeed, a test of the amount of basement air being pulled through the substructure walls and floor by the SSD system (discussed later) shows that these surfaces were very leaky even after sealing. The substructure walls in this house were of field stone and mortar.

The reduction observed in house EVA604, where 18.5 meters of floor crack were sealed, may also be significant, although corrections for differing radon entry and removal variables have not been made for either ESP120 or EVA604. Before sealing, grab samples of air below and above the carpet at the crack were 103 pCi/L and 88 pCi/L respectively, indicating that radon was entering the house at that point. The comparatively small amount of calculated soil gas entry for EVA604 (0.4 m^3/hr) suggests that the leakage area coupling between house and soil was small. Consequently, sealing this floor crack may have resulted in a sizable reduction of the total leakage area and thus of soil gas entry rates.



ESP 120 Floor Plan
(Not To Scale)

Figure 22 Detailed floor plan of ESP 120 showing locations of monitoring equipment and radon control systems. Passive samplers for HCHO, H_2O and the PFT ventilation measurement are denoted by "passives" followed by an alpha numeric code. The respirable suspended particle filter samples were collected at "RSP filter", temperature sensors are denoted by "Temp. sensor", and continuous radon monitors by "CRM". Also shown are ventilation measurement sources, denoted as "PFT source", soil pipe probe locations and the weather tower.

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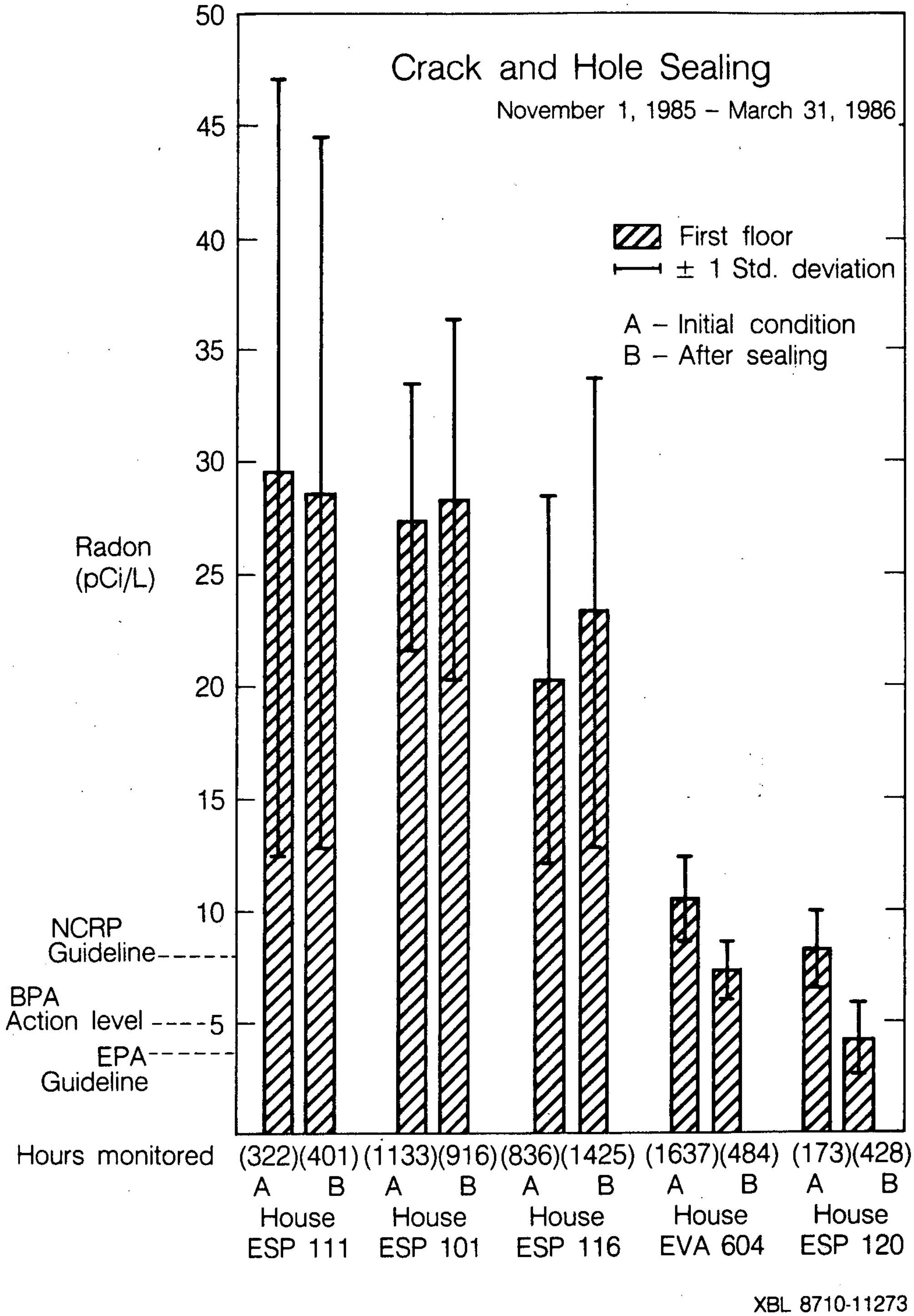

Figure 23 Summary of changes in indoor radon concentrations due to sealing of cracks and holes in five homes. No change was seen in homes ESP111, ESP101, and ESP116. The reduction in EVA604 may have been because the initial house/soil leakage was small. In ESP120 the sealing may have resulted in reduced levels by improving the performance of an SSD system in operation at this time.

No reductions due to sealing have been seen in any of the three houses where pre-sealing concentrations were above 20 pCi/L. The occupants of houses in this study typically perceived that this technique would be the only approach necessary to solve the problem of high levels and were surprised when it did not.

Disadvantages of this technique include:

1) the difficulty of determining whether a surface defect (e.g., crack) penetrates the entire thickness of the material;

2) the inability to access the majority of the substructure defects, especially in finished basements;

3) the amount of labor required, particularly if finished surfaces are to be repaired; and

4) the unknown durability of the patch when subjected to normal aging and additional substructure movement.

House Ventilation with Heat Recovery

The addition of balanced ventilation provided by air-to-air heat exchangers (AAHX) lowered indoor levels in three homes (Figure 24). In two of the homes (ESP121, and ESP109), the new, ducted, central ventilation/heat exchange systems were sized to add approximately 1.0 air change per hour (ach) of ventilation to the entire house. Since the radon obviously enters the house via the basement, both systems were installed to supply air to and return air from two basement locations. The data for these two houses represent conditions of maximum supply (heated, fresh air) and return (heated, stale house air) flow rates. Reductions of almost 75%, from an average of 11.2 pCi/L to 3.3 pCi/L, have been achieved in ESP121, and a reduction from an average of 6.9 pCi/L to 2.4 pCi/L in ESP109. At these levels, we consider the technique to be successful. Intermediate reductions occurred with "medium" AAHX flow rates: 4.4 pCi/L for ESP121 and 2.9 pCi/L for ESP109.

House NSP204 is a new (1984) energy-efficient home built according to BPA's Model Conservation Standard (MCS) that requires the installation of an air-to-air heat exchanger in these low air leakage homes. In its original condition, the AAHX, located in the crawlspace, returned air from the upstairs, but for unknown reasons supplied air only to the crawlspace and separate atrium. A staged series of modifications was made to improve the efficiency of the air distribution system for more effective radon control. The first change added supply air to the basement and return air from the heated crawlspace. Average levels were observed to fall from 26.3 pCi/L to 11.2 pCi/L. Additional work directed more supply air to the basement and increased the return air rate from the crawlspace, and resulted in further reductions to 7.8 pCi/L. Final modifications supplied air to the upstairs achieving average concentrations of 6.9 pCi/L. Since, at this optimum condition, indoor levels were still greater than the 5 pCi/L objective, an additional technique (basement overpressurization) was installed. The combined effect of both systems successfully reduced the radon to values below the 5 pCi/L target.

Figure 25 shows the result of AAHX operation in house ESP121 for a short period in February, 1986. Radon levels after mitigation by AAHX continued to exhibit considerable fluctuations, since the variations in source strength have not been controlled. Figure 26 shows actual vs. calculated reductions in indoor radon levels in the three homes due to the additional ventilation from the operation of the AAHX. The solid data symbols are the seven-day average baseline condition while the open symbols identify the post-mitigation period. The solid curves were calculated on the basis of the steady-state condition (Eq. 2) using data from

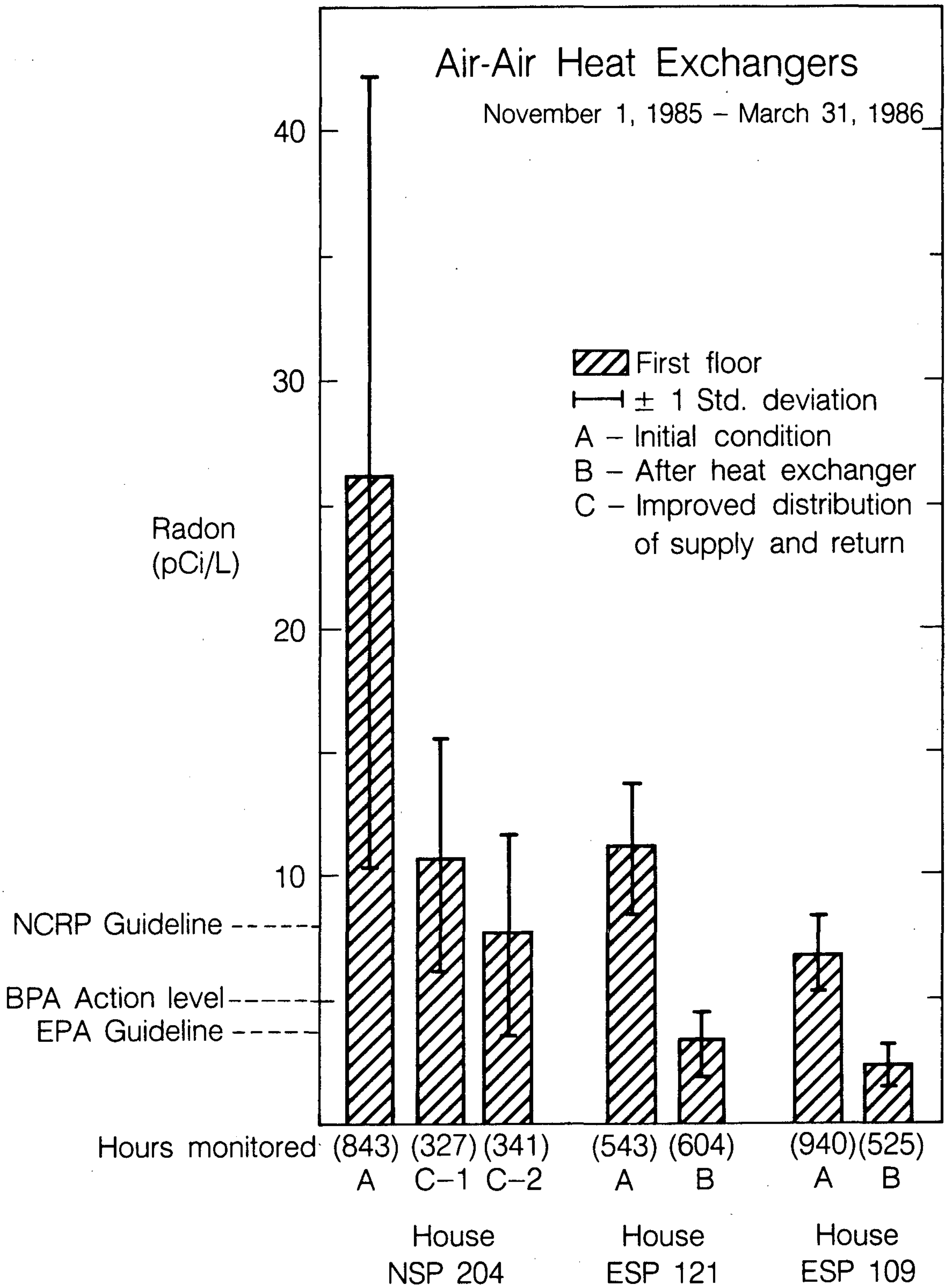

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Figure 24 Summary of radon reductions in three house due to additional ventilation provided by an AAHX. NSP204's existing AAHX performance was improved by modifying supply and return air distribution. Reductions in ESP109 and ESP121 are inversely proportional to the additional ventilation.

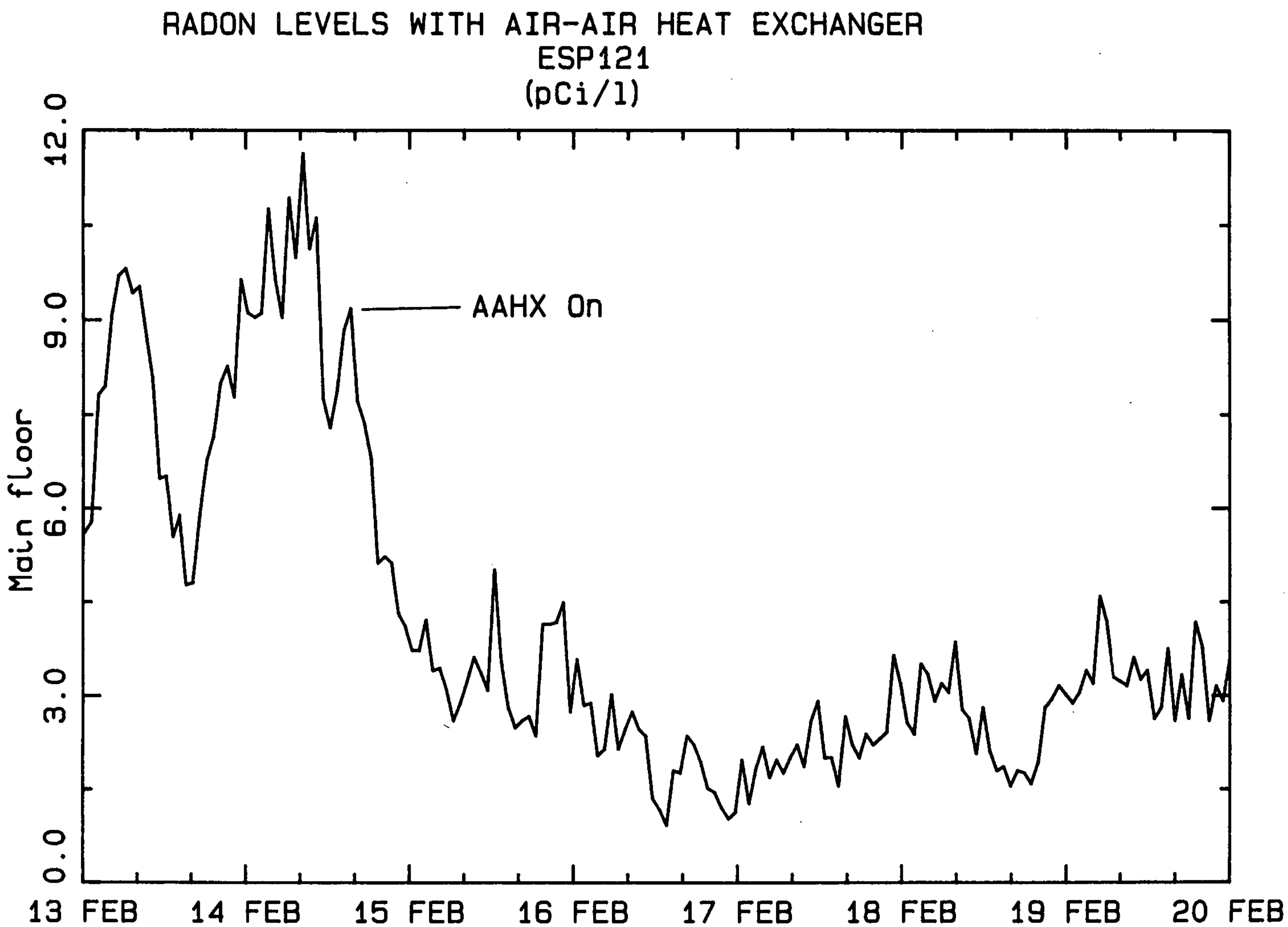

Figure 25 Operation of the AAHX in ESP121, initiated at 1600 PM on 14 FEB resulted in reduced, but still variable radon levels. XBL 881-8330

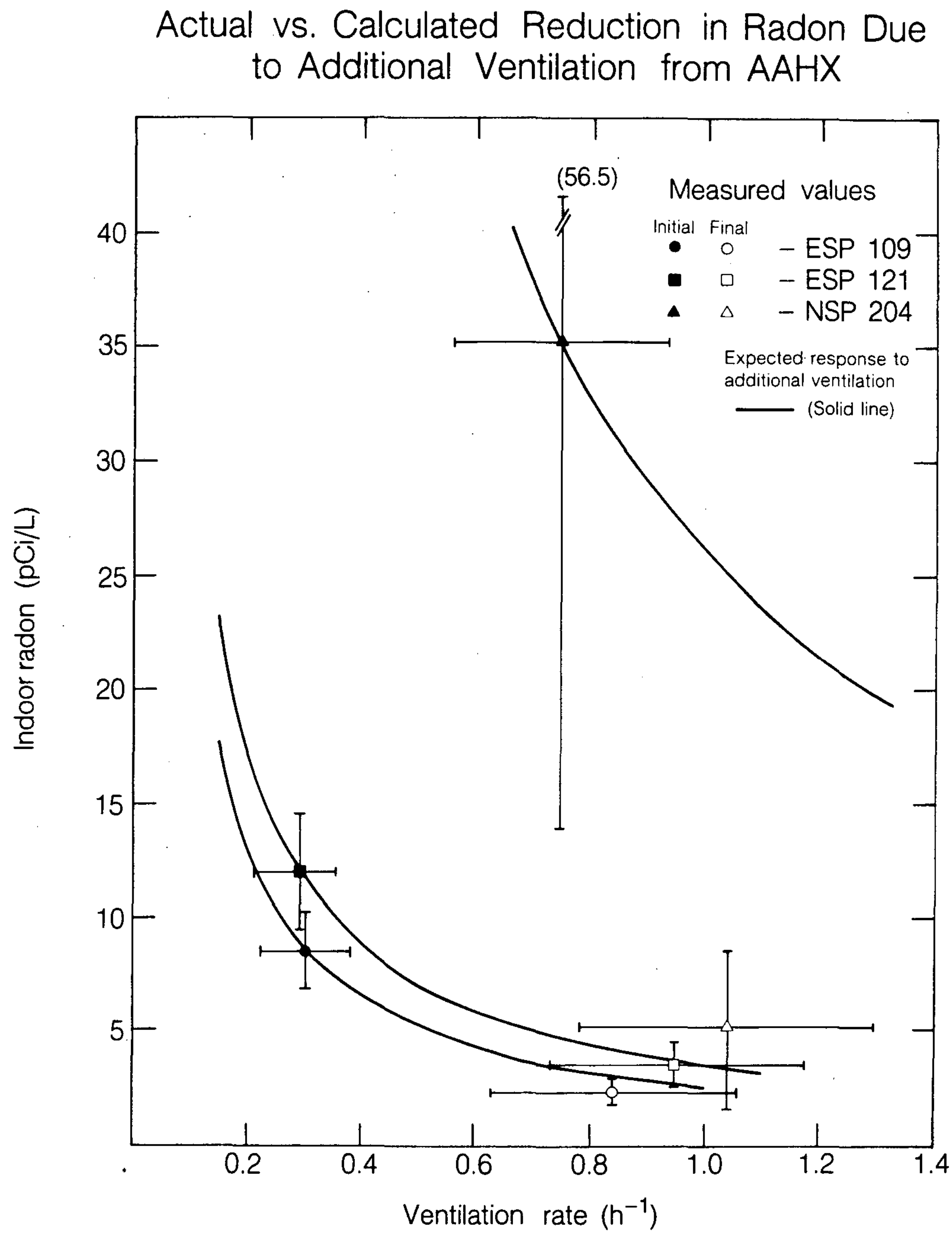

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Figure 26 Comparison of the calculated effect of additional balanced ventilation on radon levels with actual measured data for the three homes with an AAHX. The solid symbols identify the seven-day average pre-mitigation period, open symbols the post-mitigation period. ESP109 and ESP121 data are in excellent agreement with the expected inverse proportionality relationship indicated by the solid lines. The improved air distribution system in NSP204 reduced levels more than can be explained by additional ventilation alone.

the baseline condition -- measured ventilation rates and the measured indoor radon concentrations. For houses ESP109 and ESP121, the calculated curves fall very close to the actual post-mitigation measured data. The simple relationship in these two cases holds very well. Implicit in this relationship is the assumption that source strengths during the two time periods before and after mitigation were approximately equal. The actual additional ventilation did not meet the design objective of 1.0 hr^{-1}, being 0.53 hr^{-1} (0.31 to 0.84 hr^{-1}) for ESP109 and 0.65 hr^{-1} (0.29 to 0.94 hr^{-1}) for ESP121. In the case of house NSP204, agreement between calculated and measured levels is poor, as expected. This is probably the result of the changes made in the operation of the heat exchangers, as mentioned earlier. The distribution patterns for the air delivered and returned to the heat exchanger were modified and were, in fact, probably responsible for improving the effectiveness of radon control with the heat exchanger substantially, as indicated by the data in Figure 24. Thus, Equation 2 would not apply in this case.

The overall thermal efficiency of sensible heat exchange was calculated for the AAHX systems in ESP102 and ESP121. We define efficiency, η, as:

$$\eta = \frac{H_R - H_M}{H_E} \qquad [6]$$

where:

H_R = heat delivered to the house compared to the case of no heat recovery (watts),

H_M = power required by AAHX for motors (watts), and

H_E = maximum sensible heat recovery with a 100% efficient AAHX (watts).

If one assumes that supply and exhaust air stream flow rates are approximately equal, neglects the energy that is released when water vapor condenses in the AAHX, and neglects the small differences in air stream density between the supply and return, then:

$$\eta = \frac{Q_{MIN}\, C_P\, \rho\, (T_S - T_O) - H_M}{Q_{MIN}\, C_P\, \rho\, (T_R - T_O)} \qquad [7]$$

where:

Q_{MIN} = smaller of supply or return flow rates (m^3s^{-1}),

C_P = specific heat of air (1025 J kg^{-1} T^{-1}, T = °K),

ρ = density of air (1.2 kg m^{-3}),

T_S = supply air temperature (°K),

T_R = return air temperature (°K),

T_O = outside air temperature (°K), and

H_M = from Table 16, below.

Using periodic measurements of flow rates, continuous temperature measurements in the ducts, and measured values for the energy required to run the fan motors (Table 16 below), real-time efficiencies were computed and displayed over the periods shown in Figures 27 and 28. The occasional large variations in efficiency over time are perhaps due to two effects. During periods of mild outdoor temperatures, the calculation becomes very sensitive to the accuracy of the temperature sensors in the ducts, since the differences between T_S, T_R, and T_O become small. The calculated η can swing very high or low depending on small changes in these measurements. The operation of freeze-protection devices could also artificially increase efficiency by recirculating house air through the core and raising the supply air temperature. The mean overall energy efficiency for each of the units for this period is 55% (ESP121) and 63% (ESP109). In other words, 55 and 63%, respectively, of the energy in the stale house air returned to the AAHXs and then exhausted outside is recovered in the AAHX and returned to the houses in the fresh supply air stream. These efficiencies (at outside air temperatures averaging approximately 5°C) are similar to that determined by the Ontario Research Foundation (1985) for this particular AAHX at 0°C (51% to 62%).

Of all mitigation techniques, the AAHX had the highest prior recognition by building occupants for solving radon problems. This may have resulted from general public information in the media or specific BPA literature advocating the use of these units in high radon homes. However, there are several disadvantages to the use of air-to-air heat exchangers:

1) limited to applications 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) high initial cost for the installation of a ducted central unit (wall and window units with proper freeze protection under development may be more economical to install);

3) additional annual energy costs of roughly $100 are predicted in the Spokane area; and

4) maintenance of a fairly complex system that requires frequent changing of filters, blower lubrication in some units, and annual cleaning of the heat exchanger core.

Basement Overpressurization

In a technique similar to that used in mines to reduce the entry of radioactive gases (Franklin, et al., 1979; Bates and Edwards, 1981), a blower pulling air from a heated upper floor, pressurized the basement space with respect to the outside soil pores in five homes. In a sixth home (ECD027), a hybrid technique was used that both ventilated and pressurized the basement with outside air (see *"Crawlspace Sealing and Ventilation"*). This reversal of the indoor-outdoor pressure differential effectively inhibited convective flow of soil gas into the basements (Figure 29). In the homes in this study, basement overpressures of approximately two to three pascals above outside air or interstitial soil pore pressures (including the existing basement underpressure) appear to be sufficient for reducing radon levels below 5 pCi/L.

For houses ESP116 and ECD153, where a range of overpressures were tested, average upstairs radon levels fell from 23-24 pCi/L to 7.6 pCi/L (ESP116) and 6.0 pCi/L (ECD153) at pressures only slightly over neutral (< 1 pascal). At approximately 3 pascals overpressure, average radon concentrations were decreased to 2.5 pCi/L (ESP116) and 2.4 pCi/L (ECD153). At overpressures greater than 5 pascals, indoor concentrations were even lower - 0.5 pCi/L (ECD153). The pressures were typically measured outdoors at one of the soil probe pipes and indoors at mid-height of the substructure. These low pressure measurements are difficult to make, since they are in the range of noise resulting from natural influences such as wind fluctuations and door closings. The pressures discussed here are uncorrected for temperature

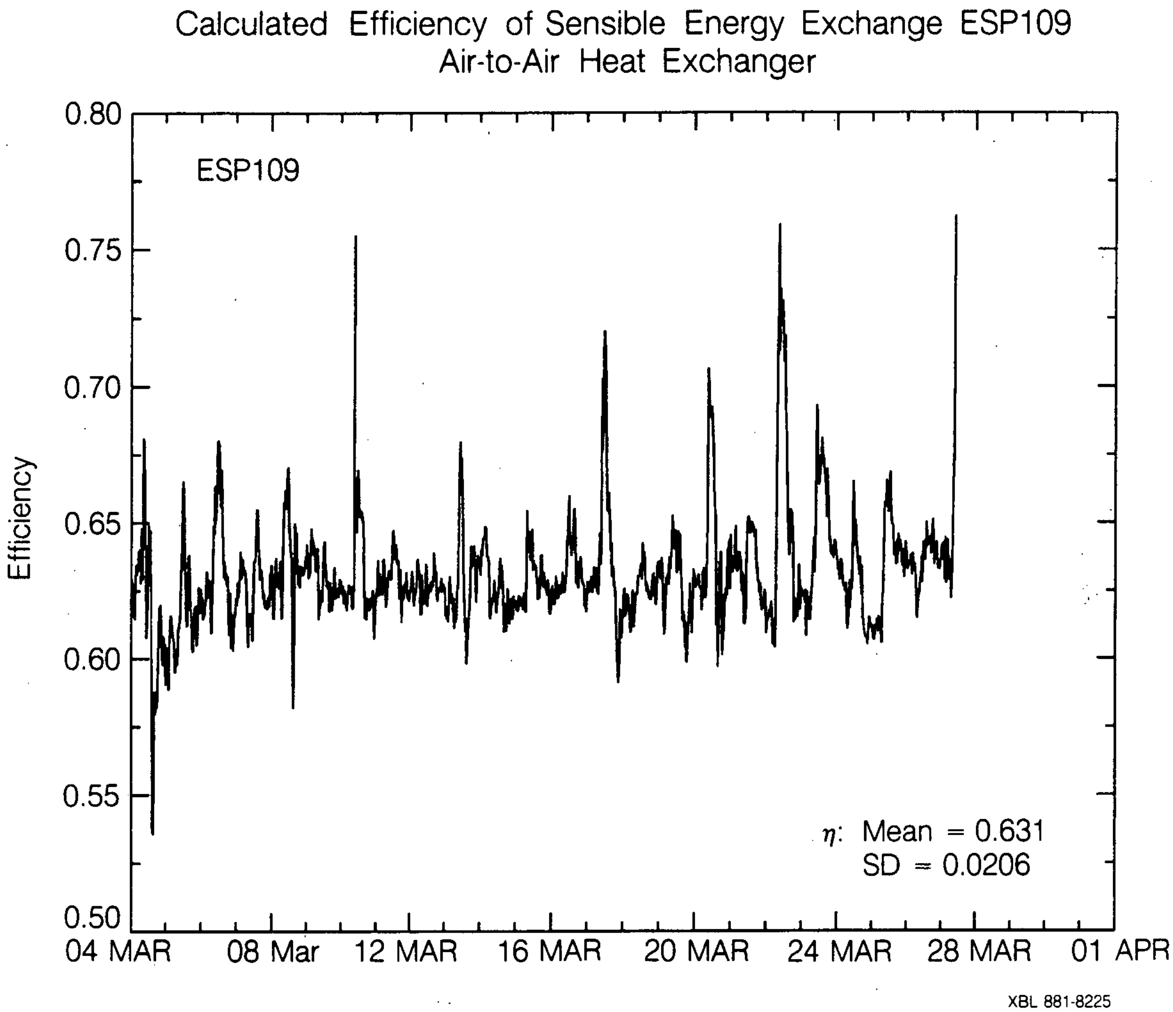

Figure 27 Calculated overall efficiency, η, of sensible energy exchange for the AAHX in ESP109 using periodic measurements of flow rates and continuous measurements of temperatures in the ducts and outside. Large variations in efficiency are probably due to operation of the frost-protection device and to the poor accuracy of the calculation during periods of small indoor-outdoor temperature differences.

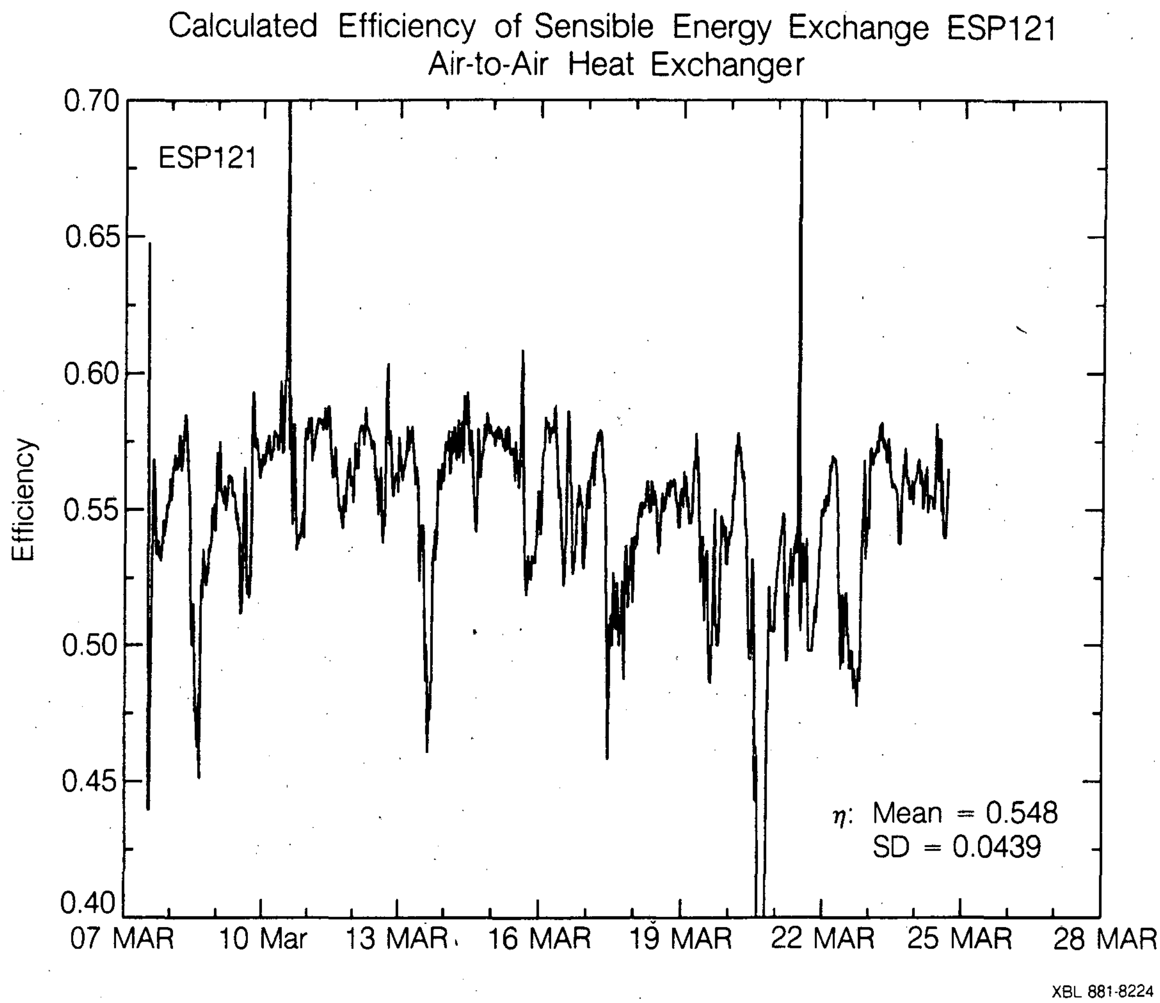

Figure 28 Same as Figure 27, but for the AAHX at ESP121.

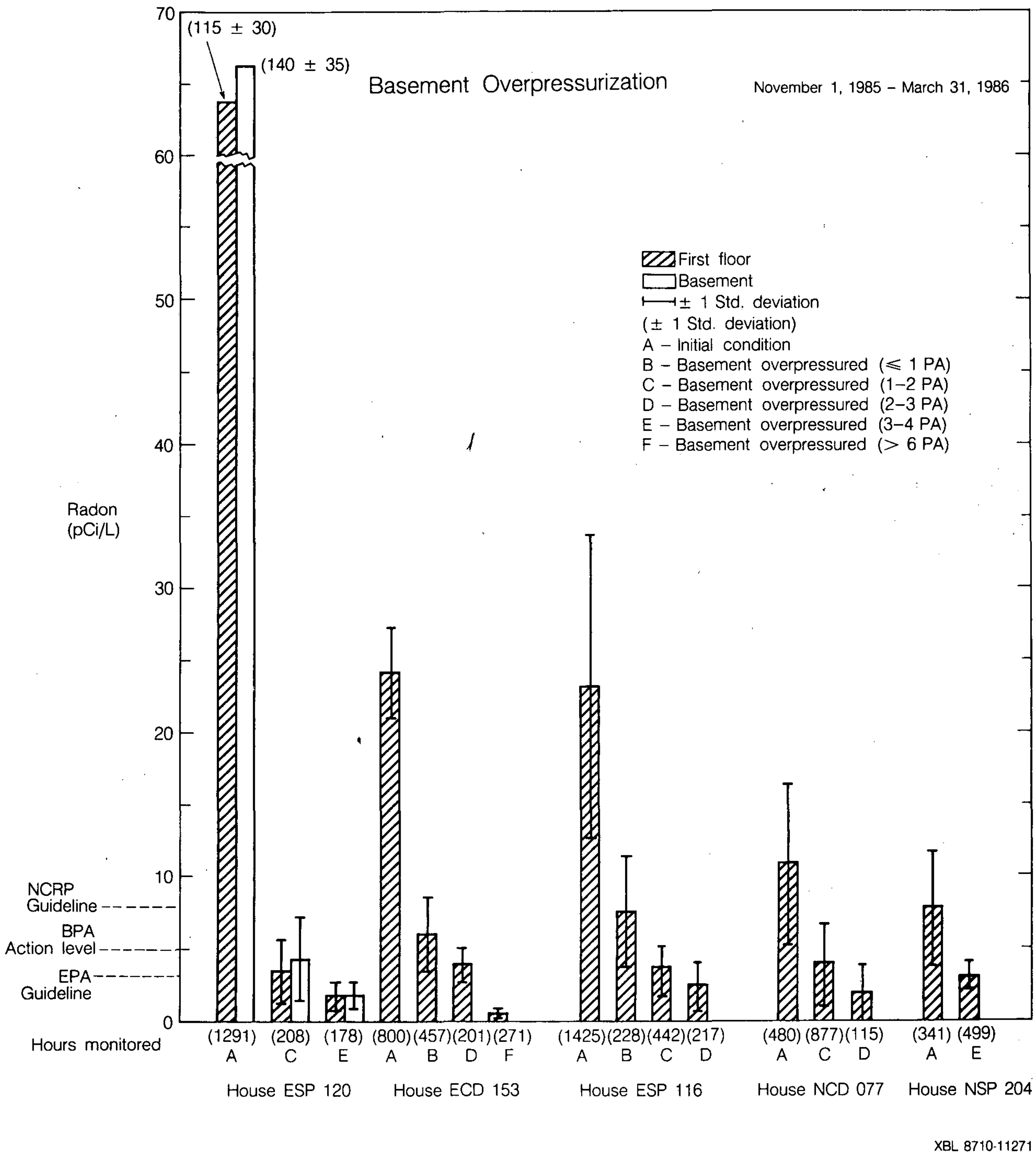

Figure 29 Where basement pressurization was practical to implement, it was always successful in reducing radon levels. Concentrations were reduced with increasing overpressurization.

differences in the sample tubes, and should be considered approximate. However, pressures measured in substructures under pre-mitigation conditions with no wind were in the range of 2 to 6 Pa, typical of the underpressure values calculated due to stack effect.

Fan flow rates from 138 to 229 L/s were necessary to develop 1.5 - 3 Pa overpressurization. Since the required flow is very dependent on the leakage of the basement shell, holes in the exterior walls as well as those between the basement ceiling and the upper floors were sealed. The flow necessary to achieve a prescribed overpressure also depends on the existing substructure underpressure at the time of the measurement.

This technique was first tested in homes with forced-air furnaces that could be operated continuously and easily unbalanced to deliver more air to the basement than upper floors. Unfortunately, the large furnace blower was not practically suited for this task, causing imbalanced heat distribution, excessive air movement throughout the house, noise, high electrical consumption, and extreme basement pressures and upper floor underpressures resulting in backdrafting of upstairs wood stoves and fireplaces. Yet, these simple tests proved the effectiveness of the general technique. Ironically, homes with forced-air furnaces may be the most difficult to pressurize with an independent blower because the ductwork provides a low resistance path for air flow throughout the building spaces. This problem was addressed by installing a separate fan that pulls air from the cold air return of the furnace, by sealing the basement cold air return, and by installing a counter-weighted backdraft damper in the main furnace supply (See Figure 18). These methods restrict the recirculation of air in the basement supply and return ducting and take advantage of the ducting to pull air from the upstairs return register. All homes but one (ESP120) in which this technique was applied had forced-air furnaces.

Figure 30 shows the very low radon levels in ECD153 while the pressurization system was on and the rapid increase after the system was shut off. Loss of basement pressurization occurred in ESP120 when the basement door was left ajar. Once again, radon accumulated very quickly (Figure 31) until the door was closed and overpressurization was restored. Radon concentrations then gradually decayed away, presumably through removal by ventilation.

To examine the relationship between basement overpressurization and radon entry rates, normalized radon entry rates and basement overpressurization data from four houses are presented in Figure 32. 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. As was seen in Figure 29, increasing overpressurization tends to decrease the radon entry. The data have not been fitted to any curve, since it appears that each house has an individual response sensitivity. One might expect that pressurization to the neutral/outside pressure point would be sufficient to retard soil gas entry. However, a slight overpressurization may be necessary to overcome the transient increases in natural underpressure caused by environmental extremes. By increasing the overpressurization, the percentage of time that the substructure is subjected to excursions below the neutral/outside pressure is reduced which means that the average radon entry rate is reduced as well.

Disadvantages of basement pressurization include:

1) implementation is possible only in basements with ductwork, ceilings, and walls that can be tightly sealed.

2) basement overpressurization can be easily destroyed by occupants opening basement windows or doors (occupants must be thoroughly familiar with the concept of the system);

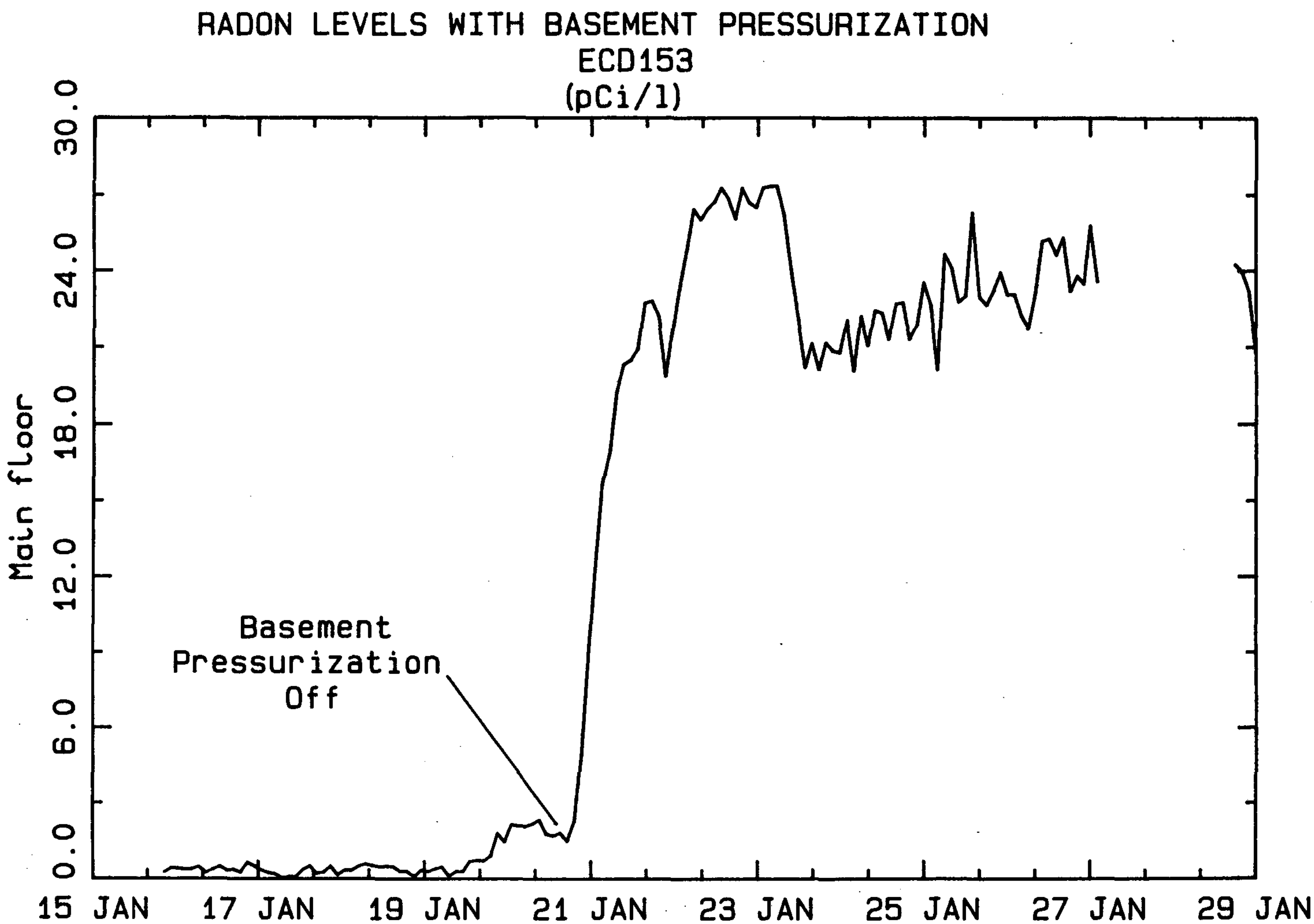

Figure 30 Demonstration of the effectiveness of a basement pressurization system in ECD153. When the system is shut off, radon levels rebound to pre-mitigation levels in a matter of hours.

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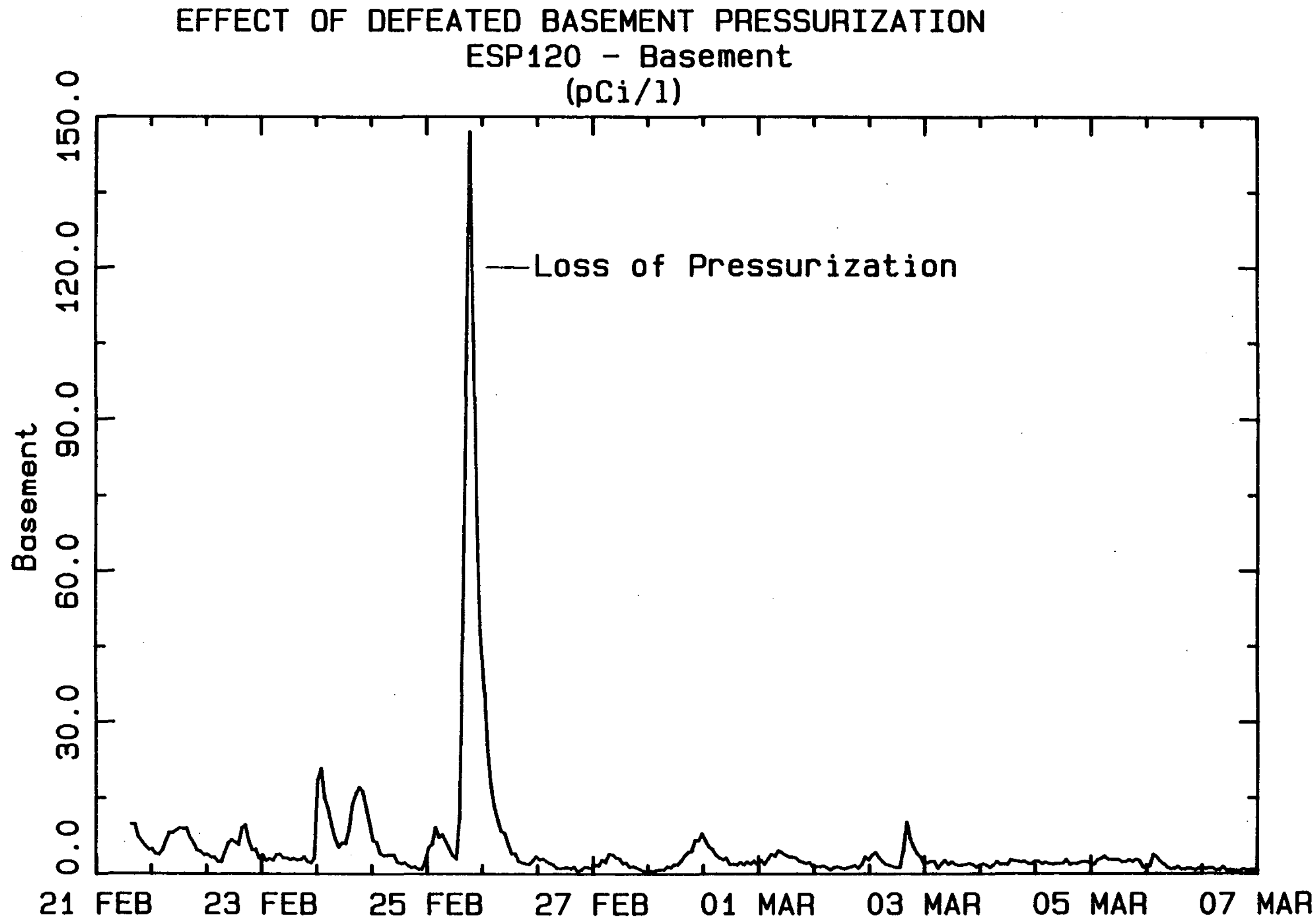

Figure 31 Loss of basement pressurization in ESP120 occurred when the basement door was left open. Basement radon levels rapidly increased until the door was closed and overpressurization was restored.

XBL 881-8331

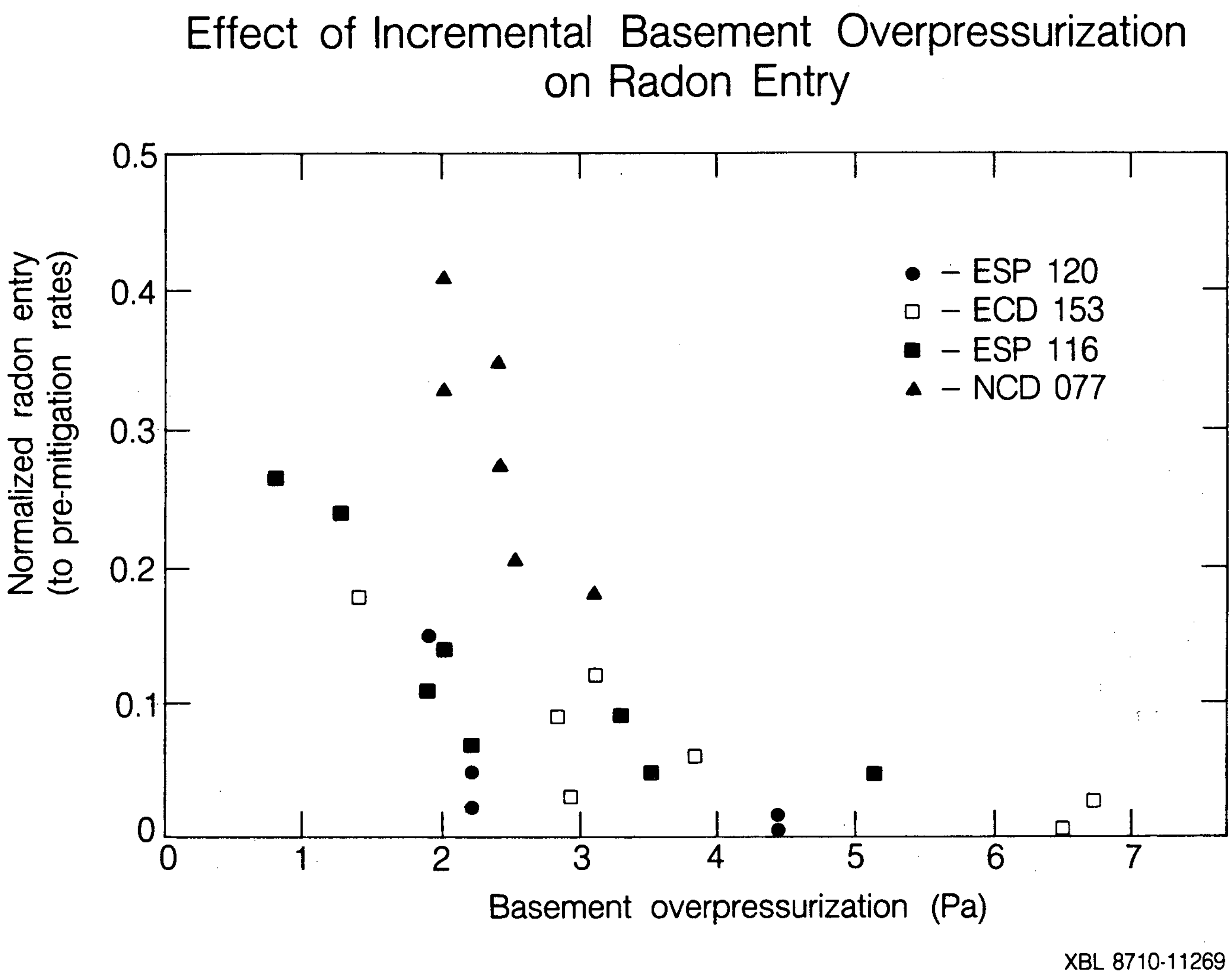

Figure 32 Incrementally increasing basement overpressurization in four homes resulted in lower average radon entry rates. Pressure differences in the figure were measured between mid-height in the basement and the outside air (or in a nearby soil probe pipe). As the overpressure increases, the percentage of time that environmental changes overcome the pressurization may be reduced. Each of these homes appears to respond differently.

3) maintaining the blowers for long-term quiet and efficient operation (periodic replacement will be necessary);

4) excessive upstairs depressurization can cause backdrafting of combustion-fired appliances and cold drafts from infiltrating air;

5) unintentional heating of basements by warm upstairs air can occur with attendant 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.

Sub-Surface Ventilation

Subsurface ventilation (SSV) was very effective in reducing radon levels in the six houses in which it was implemented (Figure 33). The target concentration of 5 pCi/L was always achieved, either initially or after system modification. Three variants of SSV were installed and tested: subsurface ventilation by depressurization (SSD) in five houses, subsurface ventilation by pressurization (SSP) in five houses, and SSV by pressurization or depressurization exterior to the foundation in two houses. The systems were typically evaluated at several operating pressures. All techniques performed well. However, it was discovered in every case where SSD and SSP were compared, SSP was more effective.

SSP was first implemented in ESP111 on 2/6/86, after previous SSD had proven only partially successful, reducing upstairs levels from an average of 47.9 pCi/L to 27.8 pCi/L at -426 Pa (as measured in the SSV pipe where it penetrated the basement slab). This was also the house with the largest improvement in switching to SSP, as levels were further reduced to 4.2 pCi/L at +581 Pa (Figure 34). An exterior SSV system of two pipes was installed and all pipes were again depressurized (-425 Pa) with levels climbing back to an average of 19.2 pCi/L. When all interior and exterior pipes were pressurized to approximately +248 PA, levels fell to 4.1 pCi/L. By increasing the pressure to +496 PA and removing one interior SSV pipe, final concentrations averaged 1.8 pCi/L upstairs and 3.3 pCi/L in the basement.

Four ventilation pipes were placed through the slab around the basement in ESP120, the house with the highest average pre-mitigation concentrations of the study (115 pCi/L upstairs, 140 pCi/L basement). On full depressurization, with a negative pressure of -369 Pa and a total flow of 94 L/s, average first floor concentrations of 4.1 pCi/L were measured, while basement concentrations averaged 10.6 pCi/L. All of the pipes contributed to the reduction since, as each was closed off on a rotating basis, radon concentrations increased. Using chemical smoke at wall and floor penetrations, basement air was observed to move into the soil, suggesting that the SSD system was properly depressurizing the soil around the substructure. Other sources were then investigated as the cause of the remaining radon in the house. Since system fans were mounted and exhausted at the level of the basement ceiling, we suspected that high concentration exhaust gases were leaking back into the building along with infiltrating outside air around the sill and basement windows. The radon concentration in the exhaust air stream was approximately 250 -435 pCi/L (Table 11). During a calm period, grab samples of outdoor air were collected at 0.3m and 0.6m from the fan exhaust (65 pCi/L and 4 pCi/L respectively), and in the air space between the basement window storm glass (71 pCi/L). To remedy the problem of elevated radon levels close to the exterior of the house, the fan was modified to exhaust several meters away from the house. No reduction in indoor levels resulted from this modification. It can be assumed that reentrainment of radon in the

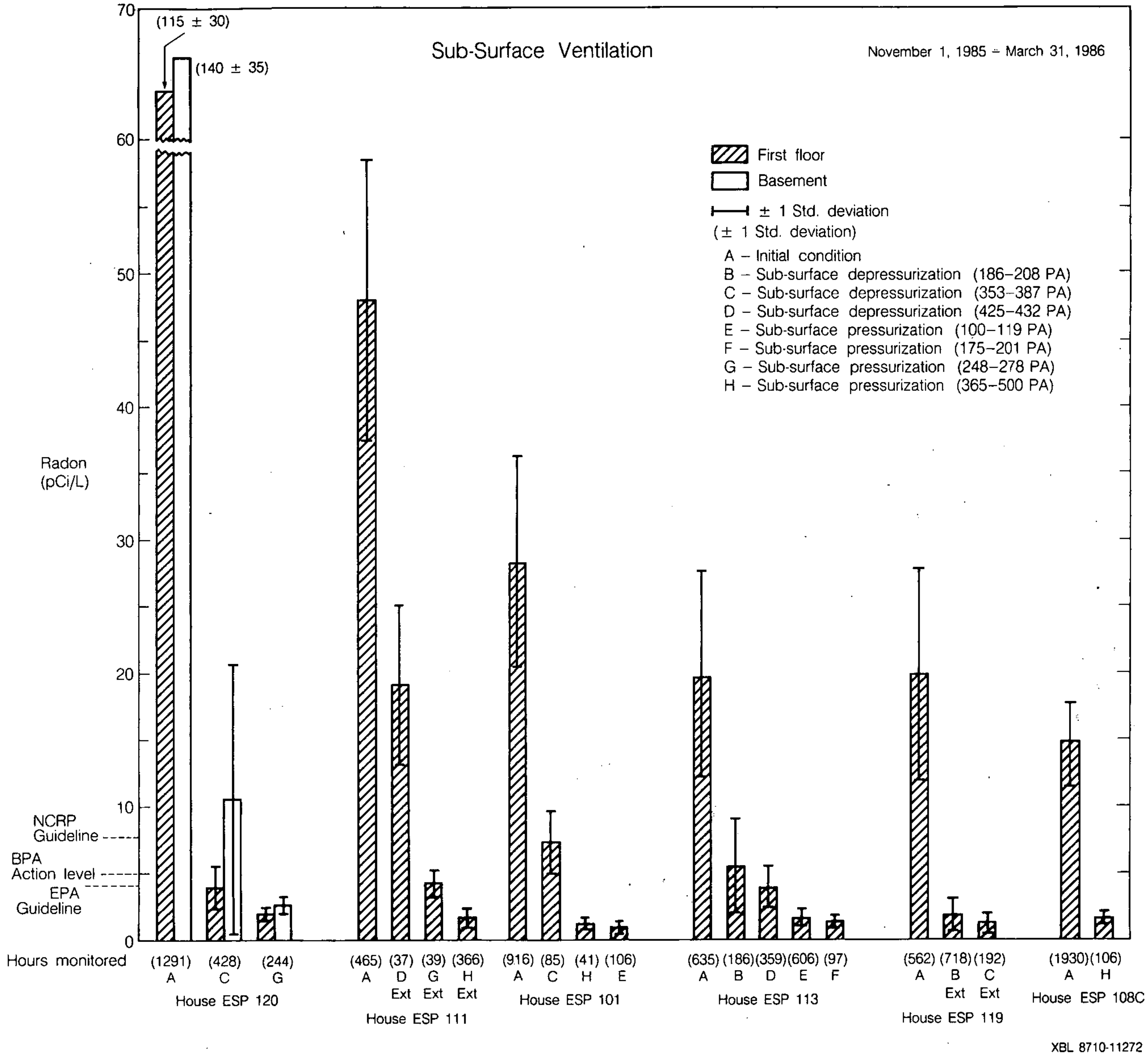

Figure 33 Subsurface ventilation (SSV) was always successful in reducing radon levels to below the 5 pCi/L target. SSV pressurization (SSP) was always more effective than depressurization (SSD) in the homes where they were compared (ESP120, ESP111, ESP101, ESP113). Exterior SSV systems were installed in ESP111 (along with an interior SSP system) and ESP119.

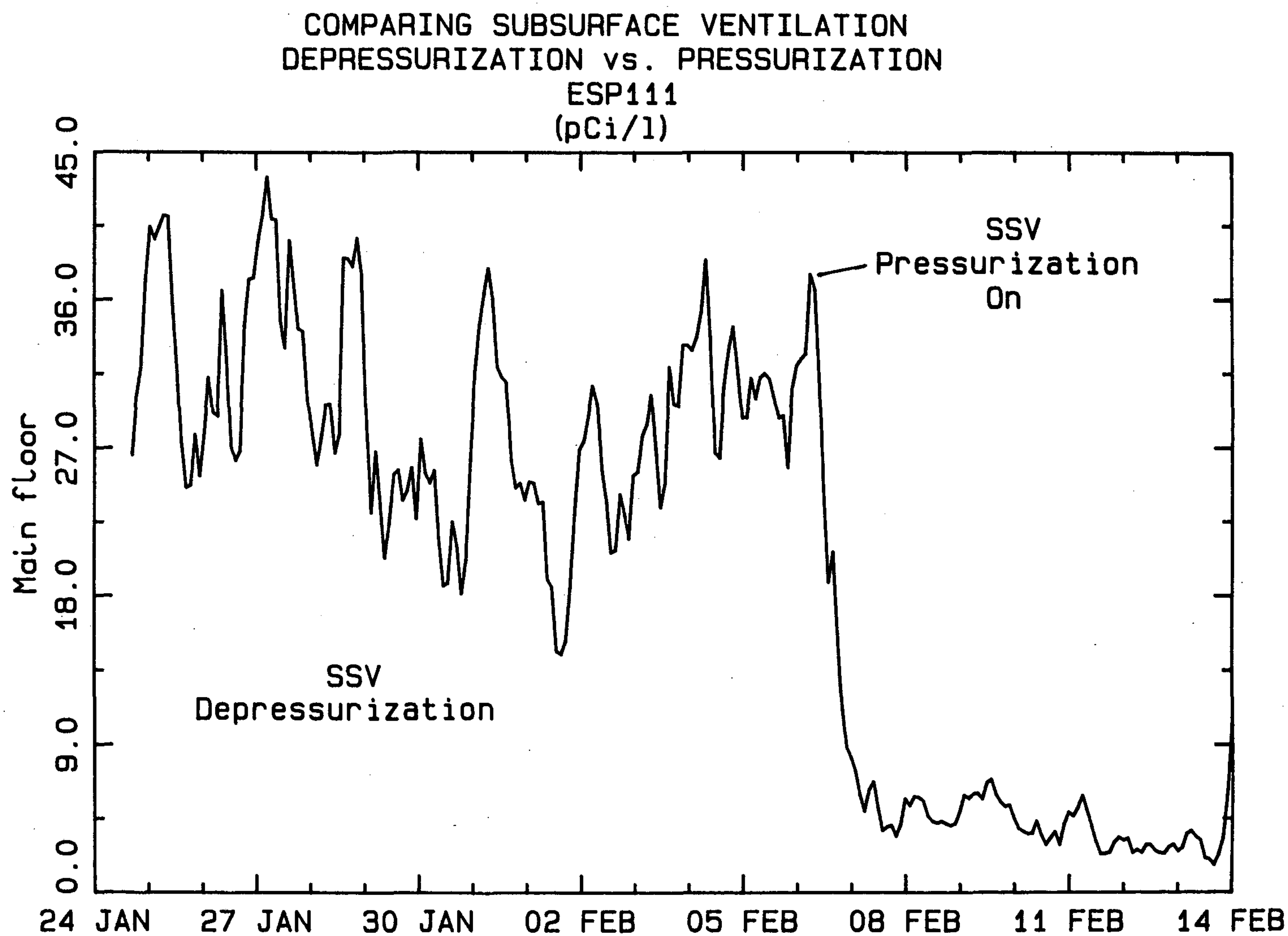

Figure 34 Greater effectiveness of SSP compared to SSD is seen when the system fans were reversed 2/6/86 in ESP111. Under SSD, upstairs concentrations averaged 27.8 pCi/L at -426 PA, while SSP at +581 PA lowered them to 4.2 pCi/L.

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infiltrating air was insignificant in these houses although Brennan (1986) has reported this as a problem in a Clinton, New Jersey home with a much higher SSD exhaust air concentration.*

TABLE 11. RADON CONCENTRATIONS IN SSD EXHAUST AIR

HOUSE ID	SSD PIPE LOCATION	SSD EXHAUST AIR RADON CONCENTRATION (pCi/L)		
ESP111	1/10/86 Full basement (Interior)	321		
	Half-basement (Interior)	326		
ESP113	1/8/86 Mainpipe	381	447	
	1/21/86 Mainpipe	447		
ESP119	2/11/86 Exterior system	241		
		12/12/85	12/15/85	1/10/86
ESP120	SE Pipe	-	-	272
	SW Pipe	435	-	271
	NW Pipe	-	250	356
	NE Pipe	425	-	260

The other source suspected in ESP120 was air infiltrating from an attached porch filled with rock rubble below the porch slab. Air samples collected from under the porch and the air infiltrating along the common wall ranged from 20 to 52 pCi/L. When these air leakage sites were sealed, no reduction in indoor levels was observed. Evidently, the quantity of radon in this infiltrating air was not sufficient to have a large effect on indoor levels.

The subsurface ventilation system was finally made more effective when the direction of the blowers was reversed and outside air was blown into the soil below the slab. At a pressure of + 270 Pa, levels were reduced to 2.2 pCi/L upstairs and 2.6 pCi/L in the basement. The SSP proved so efficient that after one pipe was removed the final concentrations remained low.

In an experiment designed to estimate the leakiness of the substructure walls and floors in contact with the soil, sulfur hexafluoride (SF6) tracer gas was mixed with the basement air to a concentration of ~50 ppm. The four-pipe subsurface depressurization system was then operated and concentrations of SF_6 were monitored in those pipes. SF_6 concentrations in the pipes were greater than 25 ppm, indicating that greater than half of the air in the pipes originated in the basement. The basement air was pulled into the soil through cracks and openings in the walls and floor by the negative pressure field in the soil surrounding the house. Additional evidence for this comes from study of the SSD exhaust air

*EPA has recommended that all SSD exhausts be routed to above the roof line and away from doors and windows to protect against reentrainment and inadvertent personal exposures to high radon concentrations in the exhaust. This is not always practical.

temperatures (measured in the SSV pipes where they penetrated the slab floor) which were high enough (15°C) to melt large patches of snow near to the exhaust. If we assume a soil temperature of 10°C and a basement air temperature of 20°C, then approximately half of the exhaust air will have come from the basement. Radon concentrations in the exhaust air (Table 11), which are approximately half of the soil gas concentrations (Table 7 and Appendix B), equivocally imply the same interpretation. However, it is likely that soil gas concentrations near to the house were depleted by operation of the SSV systems (later discussion and Figures 40). In any case, the sum of this data supports our presumption of the presence of a large total substructure/soil leakage area.

House ESP101 also had significant reductions from an average of 28.3 pCi/L to 7.4 pCi/L (upstairs) after four SSV pipes were installed and depressurized to -353 Pa. The system was switched to SSP at an approximately equivalent (+365 Pa) pressurization, and additional reductions in indoor radon resulted (2.0 pCi/L). After removing one pipe and balancing pressures, average levels decreased to 1.1 pCi/L and did not change even at the final reduced pressure of + 100 Pa.

Of all five homes where SSV pipes have been installed, house ESP113 is the only one that has gravel underlying the concrete slab floor. As a result, the installation of one SSV pipe was sufficient for efficient sub-surface ventilation. Depressurizing to -208 Pa reduced average upstairs radon levels from 19.8 pCi/L to 5.6 pCi/L, and depressurizing to -432 Pa lowered levels further, to 4.0 pCi/L. When the system was changed to SSP, a pressurization of only +201 Pa lowered average levels even more, to 1.3 pCi/L.

Two homes with finished, half-depth basements (ESP111 and ESP119) received exterior SSV systems. At both homes, occupants preferred that pipes not be located in the living space. Exterior walls were accessible and footers were only 1.0 to 1.5 m below grade. Based on a diagnostic procedure involving mapping of radon concentrations at entry points, three pipes for exterior SSD were installed along one wall at house ESP119. Sealing and ventilation of the crawlspace had already reduced upstairs radon concentrations from 49.4 pCi/L to 20.0 pCi/L, but scintillation flask sampling detected high concentrations in several of the firred-wall cavities in the basement. The SSD system, operating at an underpressure of -387 Pa, diminished average radon concentrations to 1.2 pCi/L as seen in Figure 35. The depressurization was subsequently reduced to -186 PA, yet levels remained low (1.8 pCi/L). SSV overpressurization was not implemented at this house.

Because of the success of subsurface ventilation in homes ESP120, ESP111, ESP101, ESP113, and ESP119, this technique was selected for mitigating the radon levels in the two Control homes, ESP108C and ECD026C. SSP was successfully used at both homes. At ESP108C it reduced indoor concentrations from an average baseline condition of 14.7 pCi/L to 1.4 pCi/L at an overpressurization of +400 Pa. In this house, four pipes were placed down through the slab near the center line of the building. At ECD026C, measurements following SSP were made during mild weather conditions in April, 1986. These data are not reported on Figure 33. However, the SSP operation at +500 Pa did reduce average concentrations to 2.6 pCi/L from 8.8 pCi/L. Crawlspace ventilation had been previously installed to achieve the latter concentration after an average initial baseline concentration of 17.9 pCi/L.

An explanation of the advantage of SSV overpressurization for highly permeable, low emanation-rate soils can be constructed, but remains speculative. It is helpful to consider subsurface depressurization as a pressure field system that dissuades soil gas from entering structures, while subsurface overpressurization is a ventilation system that dilutes radon levels 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

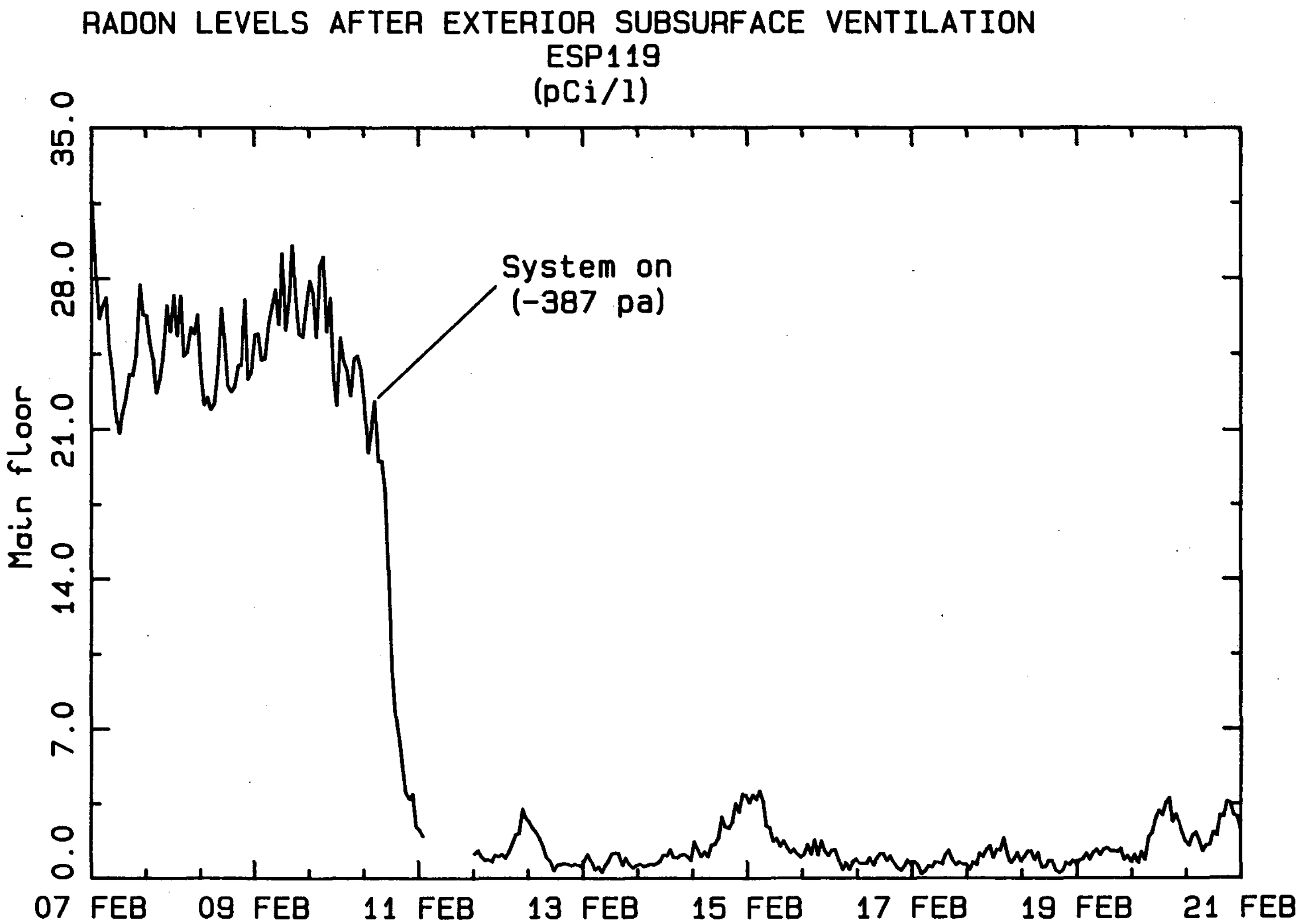

Figure 35 Rapid reductions in ESP119 indoor levels occurred when an exterior SSD system was installed along one half-depth basement wall.

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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 around the entire understructure of the house.

On the other hand, the SSV overpressure system will create a positive pressure field in the soil that always causes air to flow from the soil into the house through cracks in the substructure. 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 fresh air from the pipe at the house 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. The overpressure system possibly fails at the point where the pressure field has decreased to approximately equal the pressure of the surrounding soil. At this point, ventilation and dilution 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 re-enters the house picks up only a small amount of radon from the soil through which it is passing. Therefore, a short residence time of the 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.

This hypothesis may explain the comparatively poor performance of SSV overpressurization in the six New Jersey homes (in an ongoing study), where SSD systems were the more effective technique. In that study, soil gas radon concentrations are higher than at Spokane by approximately a factor of 10. If the outside air dilution ratio is the same for homes in these two studies, then soil gas being forced back into the New Jersey houses would be approximately 10 times higher in radon concentration than that in these Valley/Prairie homes. Additional theoretical work, including modeling, and field measurements are necessary to validate this explanation.

Penetration of basement slab floors for SSV pipe placement can apparently cause a large temporary increase in the substructure/leakage area or coupling that leads to a dramatic rise in indoor radon levels (Figure 36). In house ESP101, concentrations went from typical pre-mitigation concentrations of approximately 30 pCi/L to over 100 pCi/L as four floor holes were opened over a period of several days. This has implications for the exposures received by workers installing these systems.

Radon levels fell after the holes were patched and the SSD system was activated. Interestingly, we see a slight rise in levels after the system is switched to SSP. The effect is more marked in Figures 37 and 38. It can be interpreted as the system forcing initially high radon concentration soil gas into the house, causing the spike in indoor levels. As the soil gas becomes diluted by outside air, less radon accompanies the soil gas flowing into the house, resulting in lower concentrations.

Of some concern is the possibility of freezing soil and sub-slab materials when pressurizing with cold, outside air. To collect preliminary data on this issue, temperature sensors were placed at the top and bottom of an SSV sump in ESP101. The system began pressurizing with outside air on 2/28 and continued until 3/3 when the SSV system was shut off. These data, along with outside air temperatures, are displayed in Figure 39. The outside air temperature is highly variable throughout this period, reaching lows of -15°C, while the sump temperatures follow a regular diurnal pattern, never going below 2°C. Apparently the warm, interior piping and material comprising the slab and subsurface region near the pipe

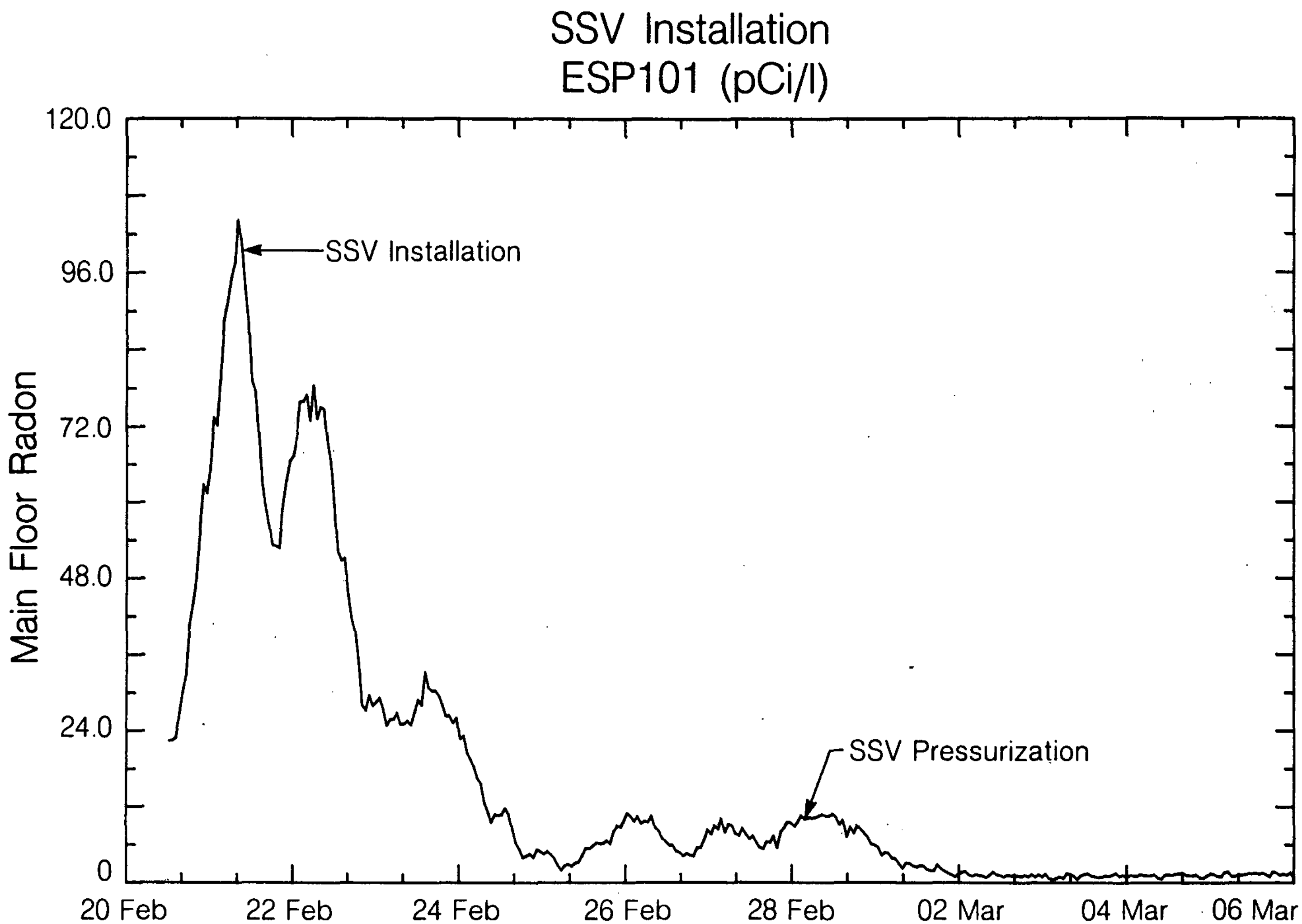

Figure 36 Opening the slab floor to install SSV pipes increases the radon entry rate in ESP101 until the holes were patched and the system was depressurized. A slight rise in indoor radon coincided with a change to a pressurization system. See Figure 37 and 38.

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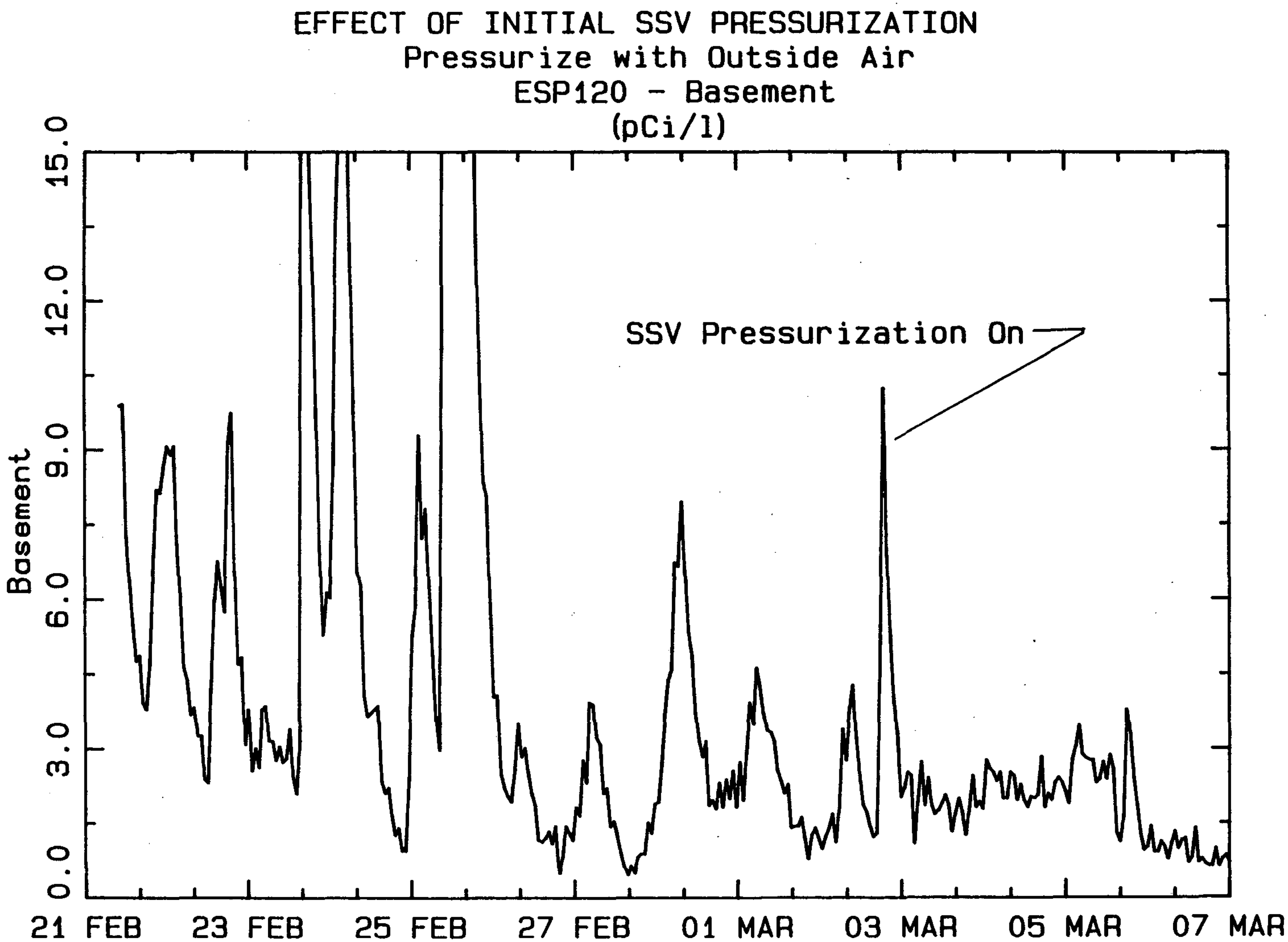

Figure 37 The effect of initial SSV pressurization is demonstrated in ESP120. High radon concentration soil gas is forced into the structure at a greater than normal rate, until the soil gas is diluted by outside air. The radon entry rate is then diminished and indoor levels fall. In ESP120, a basement pressurization systems was operating prior to SSP.

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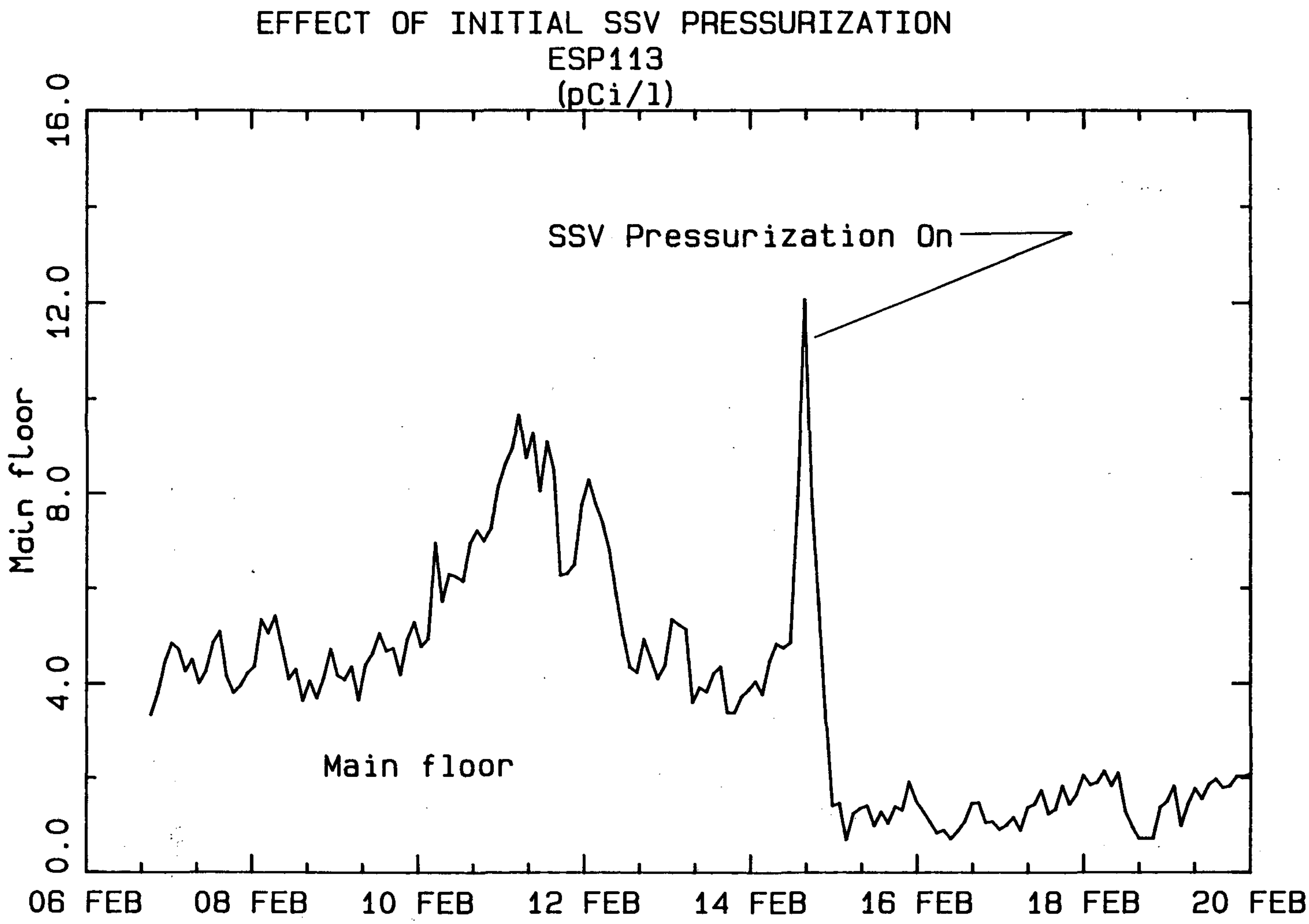

Figure 38 Demonstrating the same effect as Figure 37 for ESP113 where a SSD system was operating prior to SSP.

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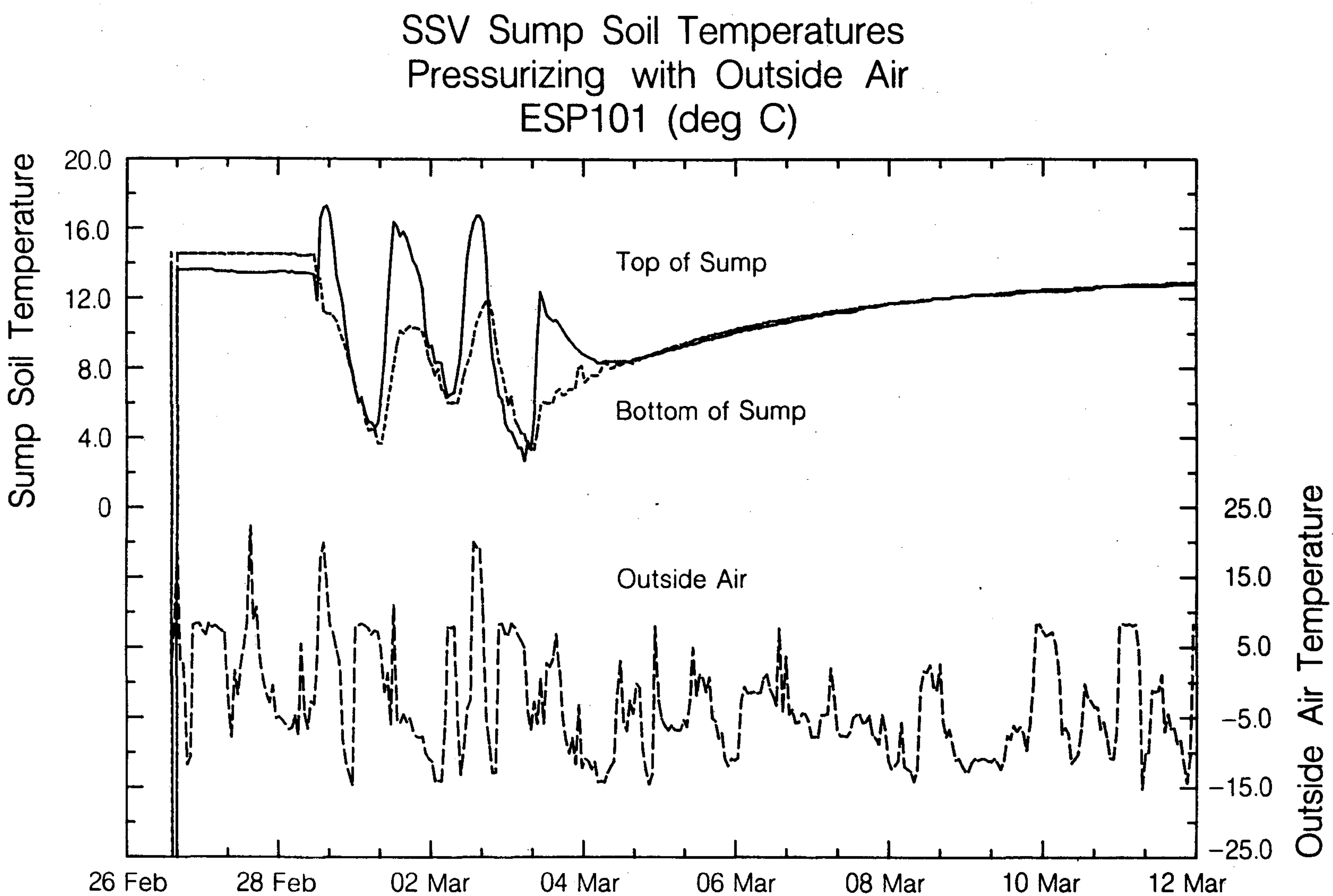

Figure 39 Temperatures in an SSV sump at ESP101 are monitored while cold outside air pressurizes the sub-surface. While air temperatures are tempered by the warm piping and slab and sub-slab materials, it is possible for them to drop below freezing if outdoor temperatures become lower than the -15°C seen here.

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somewhat 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.

The various SSV techniques can reduce near-house radon concentrations in soil gas by depletion (SSD) or dilution (SSP). For three houses (ESP111, ESP113, and ESP120), soil gas radon concentrations (from Appendix B) exhibited the largest change following SSV operation and are plotted in Figure 40 a,b,c. All reductions occurred after the SSV systems were operating: both ESP111 and ESP113 in the pressurization mode, and ESP120 in either depressurization or depressurization (pressurization appears to cause the greatest reduction - See Figure 40c). If these concentrations are compared with the soil gas concentrations at the Control homes (Figures 10 and 11), we see less change in these latter concentrations for the same period. If, as we assume, that the SSV systems caused the reduction in soil gas concentration at these three houses, it implies that very large volumes of soil are being affected, since the soil probe pipes were up to approximately 10m distance from the nearest SSV pipe. Because another house with an operating SSV depressurization system (ESP119), did not have the same magnitude reduction in soil gas concentrations, we must be careful that other factors, such as different local soil permeabilities, are not responsible for the differences in change in soil gas.

Soil air permeability (K) as measured in undisturbed soil one to seven meters from each house was found to have typical values of 10^{-11} to 10^{-10} m^2 (Table 5 and Figure 9). An understanding of house construction suggests that permeabilities very near to the house, at the substructure/soil interface, might be considerably higher. This would be due to the air gaps that are common between walls and floors and the soil, to less tightly-packed soil material backfilled against the wall exteriors, to gravel fill often placed beneath concrete slabs, or to leakage in the substructure wall and floor materials below grade. The performance of SSV systems, with pipes extending just below the slab or adjacent to footers and walls, may be as (or more) dependent on the near-house permeability than on soil permeability farther than one meter from the house. However, because of the intimate pressure field coupling between these two soil regions, the SSV system will actually "see" an overall, or effective, permeability that is a complex combination of the varying permeability of those soils surrounding the substructure. Applying Equation 1 to flow, pressure, and pipe diameter data measured at the various SSV pipes, a summary of the calculated permeabilities is shown in Table 12. Note that Equation 1 is intended for an unobstructed sphere of soil around the open pipe - it does not account for the presence of the basement floor. However, we assume that the computation is within a factor of two of that for the actual geometry. There is very little variation in the data, regardless of whether the SSV systems were pressurized or depressurized, there was gravel or soil below the slab, it was an interior or exterior system, or the undisturbed soil permeability measurement was high or low. The average for all SSV pipes was 2.29×10^{-9} m^2 and is approximately 10 to 10^4 greater than the undisturbed soil permeability measured at these six houses, as we had expected. The soil removed from the half-depth basement SSV at ESP111 was observed to be unusual for this area in that it was tightly-packed fine sand and clay. This is a confirmed by the effective permeability of approximately 6×10^{-10} m^2, the lowest of the 16 pipes measured. The fact that this pipe was eventually removed, because it made little or no contribution to radon reductions, is perhaps an indication of the potential utility of this measurement. If sufficient measurement data, such as this, were collected on a number of SSV systems, then the possibility would exist for creating an index that would assist contractors in the selection, design, and installation of mitigation systems. For example, by drilling a 5 cm diameter test hole in the basement slab floor, a contractor could perform measurements of flow and pressure to calculate and quantify the suitability of a SSV system in a particular house.

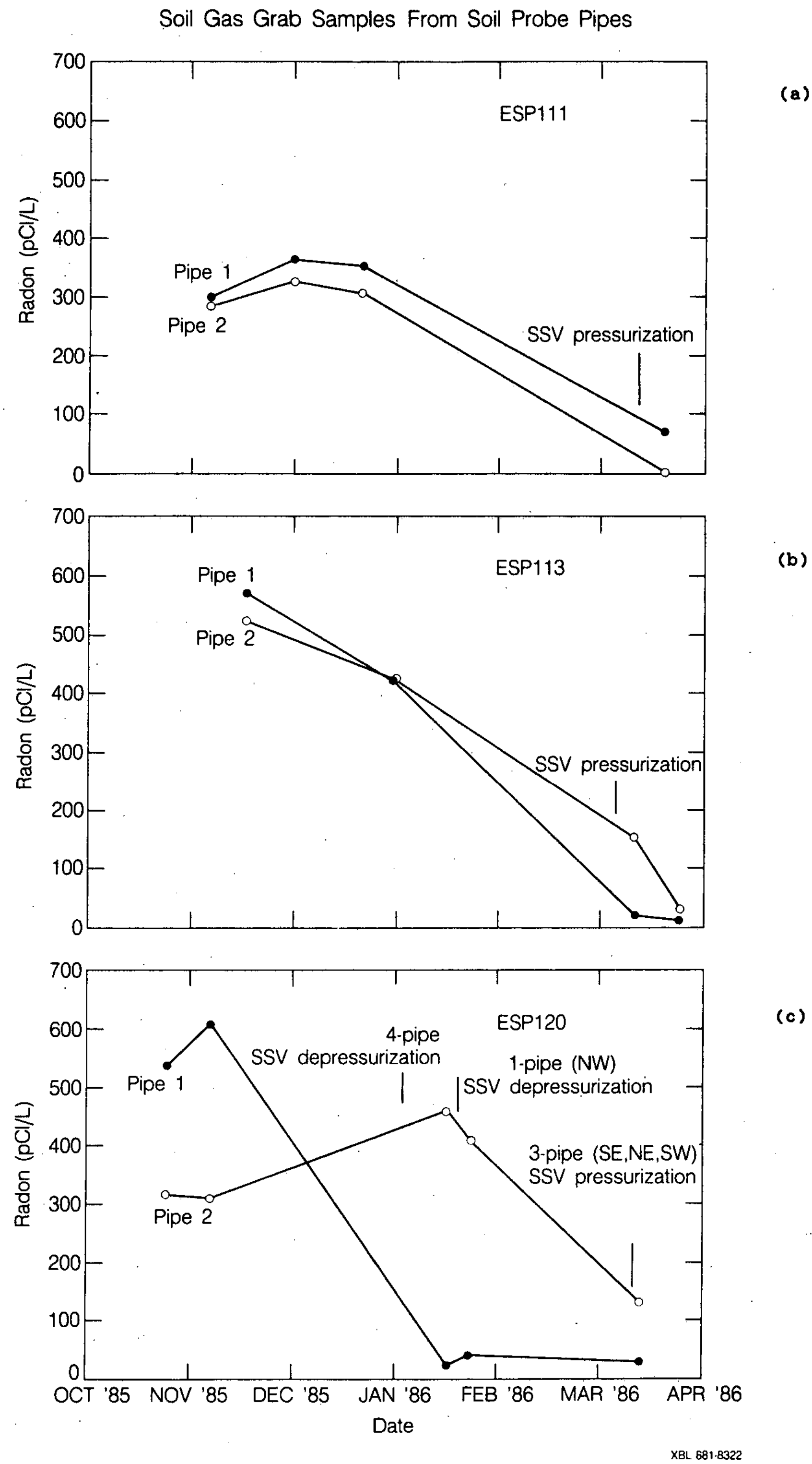

Figure 40 a,b,c Reductions in soil gas radon concentrations at soil probe pipes exterior to three houses, presumably due to dilution or depletion by an operating SSV system. Each point represents a grab sample collected periodically throughout the study at each of two probe pipes. SSV system operation is indicated. Some probe pipes were more than 10m from the nearest SSV pipe. For locations see Appendix D.

TABLE 12. EFFECTIVE SOIL AIR PERMEABILITY AT SSV PIPES

HOUSE ID	DATE	ΔP (Pa)	K (m^2)	ΔP (Pa)	K (m^2)	ΔP (Pa)	K (m^2)	ΔP (Pa)	K (m^2)
ESP101:	SSV LOCATION-	NW		SE		SW		1/2 BSMT	
	*02/26/86	-371	8.5×10^{-9}	-291	1.6×10^{-9}	-296	2.3×10^{-9}	-456	1.4×10^{-9}
	*03/03/86	+383	1.1×10^{-9}	+293	2.3×10^{-9}	+260	2.6×10^{-9}	+525	1.7×10^{-9}
	*03/05/86	+219	1.3×10^{-9}	+150	2.9×10^{-9}	+150	2.9×10^{-9}	ND	
ESP108C:	SSV LOCATION-	SHOP		STORAGE		OFFICE		CLOSET	
	*03/28/86	+437	1.5×10^{-9}	+412	1.3×10^{-9}	+375	1.3×10^{-9}	+375	1.3×10^{-9}
ESP111:	SSV LOCATION-	FULL BASEMENT		1/2 BASEMENT					
	01/19/86	-419	2.0×10^{-9}	-432	6.4×10^{-10}				
	02/03/86	-412	1.8×10^{-9}	-442	6.2×10^{-10}				
	02/19/86	+562	1.7×10^{-9}	+600	5.9×10^{-10}				
	*02/25/86	+537	2.0×10^{-9}	ND					
	*03/10/86	+250	2.7×10^{-9}	ND					
	*03/13/86	+472	2.0×10^{-9}	ND					
ESP113:	SSV LOCATION-	CENTRAL							
	01/13/86	-425	1.6×10^{-9}						
	01/16/86	-206	2.1×10^{-9}						
	01/18/86	-209	2.1×10^{-9}						
	01/21/86	-212	2.0×10^{-9}						
	02/09/86	-209	2.1×10^{-9}						
	*02/26/86	+121	2.6×10^{-9}						
ESP119:	SSV LOCATION-	3 PIPES COMBINED							
	*02/28/86	-175	6.1×10^{-9}						
	*03/13/86	-190	2.7×10^{-9}						
	*03/25/86	-192	2.9×10^{-9}						
ESP120:	SSV LOCATION-	NW		NE		SE		SW	
	12/12/85	-437	2.2×10^{-9}	-362	2.0×10^{-9}	-412	2.2×10^{-9}	-337	4.3×10^{-9}
	12/16/85	-422	2.2×10^{-9}	-350	1.9×10^{-9}	-380	2.5×10^{-9}	-330	4.5×10^{-9}
	01/23/86	-395	2.2×10^{-9}	ND		ND		ND	
	01/28/86	ND		-300	2.1×10^{-9}	-325	2.5×10^{-9}	ND	
	01/28/86	-400	2.3×10^{-9}	ND		ND		ND	
	02/04/86	-425	2.2×10^{-9}	-337	2.0×10^{-9}	-387	2.3×10^{-9}	-325	4.6×10^{-9}
	02/10/86	-441	2.1×10^{-9}	ND		ND		-321	4.5×10^{-9}
	*03/12/86	+466	2.5×10^{-9}	+275	2.6×10^{-9}	+272	3.3×10^{-9}	+320	6.6×10^{-9}
	*03/25/86	ND		+250	2.5×10^{-9}	+228	3.6×10^{-9}	+237	8.0×10^{-9}

*Flow measurements made with replacement hot wire anemometer

Sign of applied SSV pressure (ΔP) denotes: (-) Depressurization
(+) Pressurization

ND = No data

Disadvantages of the use of sub-surface ventilation include:

1) the cost, effort, and disruption of installing ventilation pipes through concrete slabs;
2) obtaining long-life blowers that develop sufficiently high pressure with moderate flow rates at low electricity consumptions;
3) the problem of maintaining the blowers for quiet and efficient long-term operation (periodic replacement will be necessary);
4) possible water vapor condensation on the exterior surfaces of the SSV depressurization pipes in the summer and the SSV overpressurization pipes in the winter (perhaps becoming frost);
5) the risk of freezing the soil, water pipes or drain pipes below the slab when using a SSV overpressurization system (colder slab floors and increased heat loss through the floor and SSV pipe may also result);
6) the unknown long-term effects of blowing/sucking large volumes of air through the soil; and
7) properly routing SSV depressurization exhausts away from ground level, windows, and doors.

Crawlspace Sealing and Ventilation

Five homes in this study had crawlspaces that received remedial action. No home in this study had a full crawlspace under the entire house. The crawlspaces were always in combination with half-depth basements and/or slab-on-grades, however, mitigation always began with remediation of the crawlspace. One, ECD153, had an air-tight plastic membrane sealed over the soil floor under the mistaken assumption that the crawlspace was a source of radon. After the mitigation, it was determined that radon had not been accumulating in the crawlspace, so it was not surprising that sealing the floor had no measurable effect on indoor levels.

Figure 41 summarizes the results in the remaining four houses. Three of these (ECD026, ESP119, and NCD077) had a crawlspace combined with a half-depth basement, each of which contributed radon to the building. A variety of crawlspace mitigation techniques were staged at all homes, except NCD077.

In house ESP119, the crawlspace concrete walls and soil floor were first sealed with an air-tight plastic membrane that reduced initial average house concentrations from 49.4 pCi/L to 34.0 pCi/L and crawlspace concentrations from 111.4 pCi/L to 62.5 pCi/L. In fact, bulk soil gas entry caused this tight, lightweight plastic membrane to fill and "balloon" until it eventually occupied one half the volume of the crawlspace. Grab samples of the air from under this plastic had radon concentrations of 311 and 280 pCi/L on two separate days, verifying that the air had passed through the soil. Based on approximate filled volumes and time to fill, the gas entry rate was crudely estimated to be 5 to 7 m^3/hr (1.4 to 1.9 L/s). This undesirable side effect was temporarily alleviated by using a vacuum cleaner to exhaust the gas and then adding the weight of boards and planking on top of the plastic. The second stage involved both sealing and isolating the house from the crawlspace (closing and patching openings in the kneewall and floor to the house), and insulating the house floor and kneewall, and ducts and water pipes. This action reduced the crawlspace leakage area from 513 cm^2 to 153 cm^2 and diminished average house concentrations to 28.8 pCi/L, but increased the average crawlspace concentrations to 87.4 pCi/L. The final stage, natural ventilation of the crawlspace, added

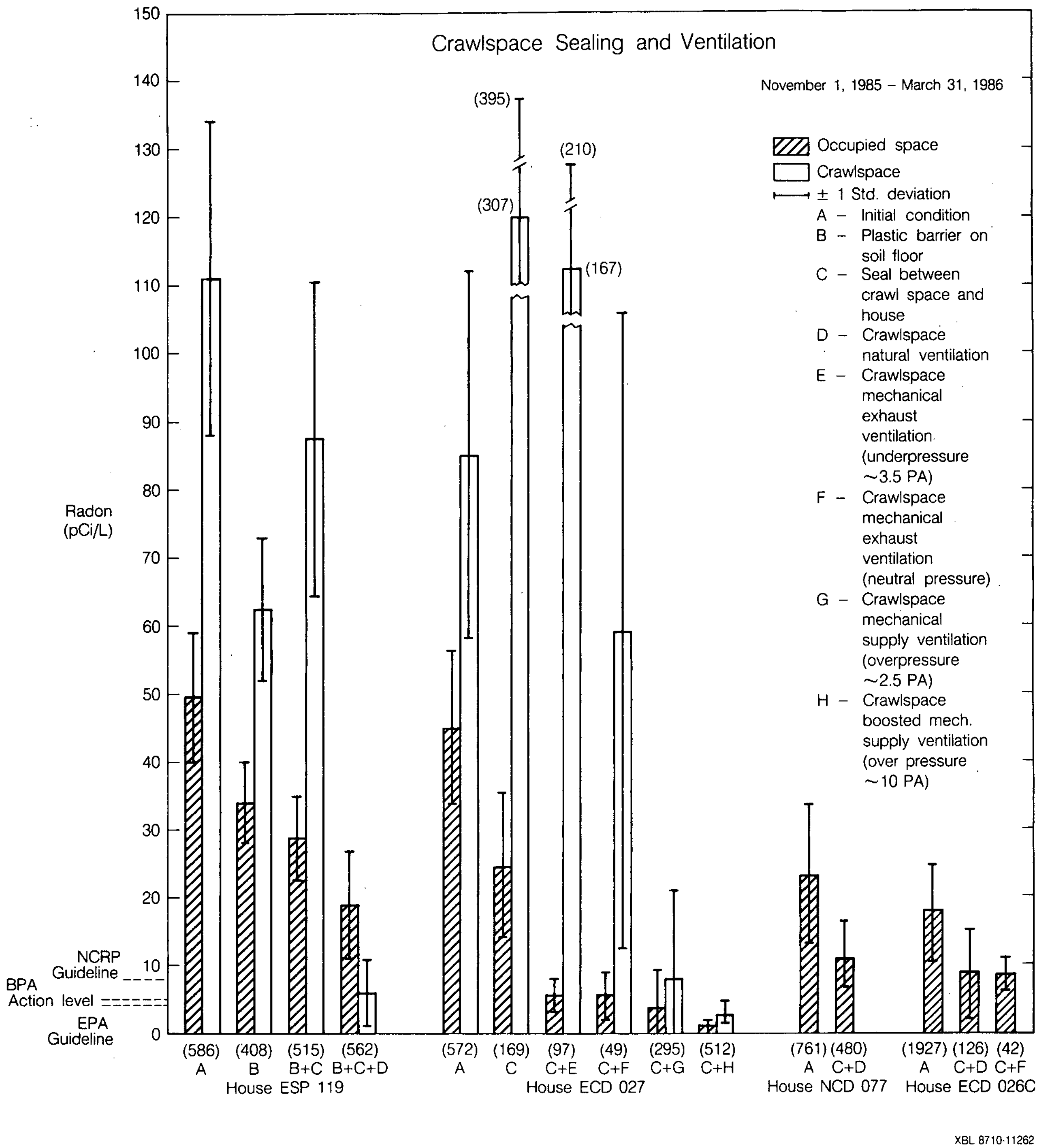

Figure 41 Radon reductions due to various phases of crawlspace sealing and ventilation. All homes had adjoining substructures, with those in ESP119, NCD077 and ECD026C, contributing half of the radon.

approximately 0.5 m^2 of free air vents (1 m^2 for every 100 m^2 of crawlspace floor area) and lowered average house concentrations to 20.0 pCi/L and crawlspace concentrations to 6.2 pCi/L. The levels within the house were later reduced by the exterior half-depth basement SSD system.

Opening vents into the crawlspace probably has two effects. The first, obviously, is removal of radon in crawlspace air by flushing the space with outside ventilation air. The second is to destroy the pressure coupling between the warm house and the soil, thereby reducing the applied negative pressure at the soil surface and the resulting convective flow of soil gas into the crawlspace. Diffusion of radon from the soil into the crawlspace will still occur, where it will be available for the depressurized house to pull in through air leakage paths in floors and walls. This second effect would explain why, after vents were opened into this crawlspace, the plastic membrane over the soil floor was no longer inflated by the movement of soil gas.

In house NCD077, crawlspace sealing and ventilation were performed in one step. Original average first floor radon levels of 23.3 pCi/L were reduced to 10.8 pCi/L, which after basement overpressurization was decreased further to 3.7 pCi/L. One step sealing and ventilation was also performed in Control house ECD026. With natural ventilation, average first floor house concentrations fell from 17.9 pCi/L to 9.0 pCi/L. Since local shielding limited wind-driven air movement at the vents, crawlspace ventilation was boosted with two small fans providing 71 L/s of balanced ventilation. First floor concentrations did not change (8.8 pCi/L) , but were subsequently mitigated by a half-depth basement SSP system.

House ECD027C is atypical in that the "crawlspace" was actually an unused, unheated, soil floor basement. Originally, a forced-air, wood furnace was located in this space, and large openings were present between this basement and the first floor. The first remedial action combined the removal of the furnace and placement of a wood stove on the first floor with sealing of all large openings between the basement and upstairs. The sealing also included floor insulation and installation of a membrane of Tyvek® below the insulation to prohibit air infiltration from the basement to the upstairs yet allowing moisture to pass out of the insulation. Sealing the large openings reduced the basement leakage area from 9419 cm^2 to 905 cm^2, while the addition of the Tyvek® resulted in a leakage area of 819 cm^2. This work reduced average house radon concentrations from 45.0 pCi/L to 24.5 pCi/L and increased average basement levels from 85.0 pCi/L to 307 pCi/L.

House construction limited the number and area of basement vents for natural ventilation so average concentrations were reduced by natural ventilation only marginally in the house, to 21.2 pCi/L, but more substantially to 208 pCi/L in the basement. Adding 104 L/s of mechanical exhaust ventilation slightly underpressured the basement (-3.5 pascals) and decreased house concentrations to 5.3 pCi/L. Radon entry into the basement presumably increased but was offset by the additional ventilation, yielding a basement concentration of 167 pCi/L. The pressure differences were determined by measuring mid-height basement pressures and outside pressures at soil level.

Next, with a ventilation flow of 80 L/s, basement pressures were neutralized by opening the basement door to add vent area. House concentrations did not change (5.4 pCi/L) and basement levels dropped to 59.3 pCi/L. Then by closing the basement door and reversing the blower to maintain the same flow rate, the basement was slightly overpressured (+2.5 to 3.8 Pascals) so that house levels fell to 3.9 pCi/L and radon entry into the basement was reduced, as indicated by basement concentrations that averaged 8.1 pCi/L.

In the final configuration, a 60 watt axial fan, pulling air from an unconditioned garage, boosted the basement overpressure to +5 to +9 Pascals and lowered upstairs radon concentrations to 0.6 pCi/L and basement radon levels to 1.3 pCi/L. The coupling between the main floor and basement and the processes involved during these various phases of mitigation can be discussed in terms of the ratio of main floor to basement radon concentration (Table 13). As expected, sealing of the floor (#1) reduced the flow of basement air to the upper levels and changed the ratio from 0.53 to 0.08. The small additional outside vent area and natural ventilation (#2) affected the pressure coupling and removal rate only slightly, the ratio equaling 0.10. By mechanically depressurizing the basement (#3), the basement to main floor air flow direction was generally reversed, resulting in a ratio of 0.03. With natural pressures restored and basement ventilation rates increased (#4), concentrations fell, but the main floor/basement ratio returned to approximately the value of #1, (0.09) suggesting that similar amounts of basement air were flowing to the upstairs, but at lower concentrations. Finally, basement overpressurization forced more lower concentration basement air to the upstairs with ratios approximating the original value, regardless of the degree of pressurization (0.48 and 0.46).

TABLE 13. HOUSE/BASEMENT COUPLING BY EXAMINING RATIOS OF MAIN FLOOR TO BASEMENT RADON CONCENTRATIONS DURING MITIGATION ECD027

HOUSE/MITIGATION CONDITION	RATIO OF MAIN FLOOR TO BASEMENT RADON CONCENTRATION	BETWEEN FLOOR AIR MOVEMENT
Baseline	0.53	Rapid Basement to Main Floor
1) Sealing Floor Between Basement and Main Floor	0.08	Reduced
2) Add Small Vents and Natural Ventilation	0.10	Unchanged
3) Mechanically Depressurize Basement and Ventilate	0.03	Main Floor to Basement
4) Natural Pressures, Increase Basement Ventilation	0.09	Same as #1 and #2
5) Mechanically Overpressurize Basement and Ventilate:		
+2.5 to +3.8 Pa	0.48	Rapid Basement to Main Floor
+5 to +9 Pa	0.46	

Figure 42 is an example of adding the crawlspace ventilation during house weatherization. From the earlier study of BPA standard weatherization programs, house ECD150, was observed to have average indoor radon levels of 45.2 pCi/L (Turk et al., 1988). The house weatherization included insulation and ventilation of the crawlspace. Following the ventilation of the crawlspace, mean radon concentrations fell to 4.8 pCi/L, and remained low even after house doctoring work reduced the air leakage area of exterior surfaces of occupied zones in the structure.

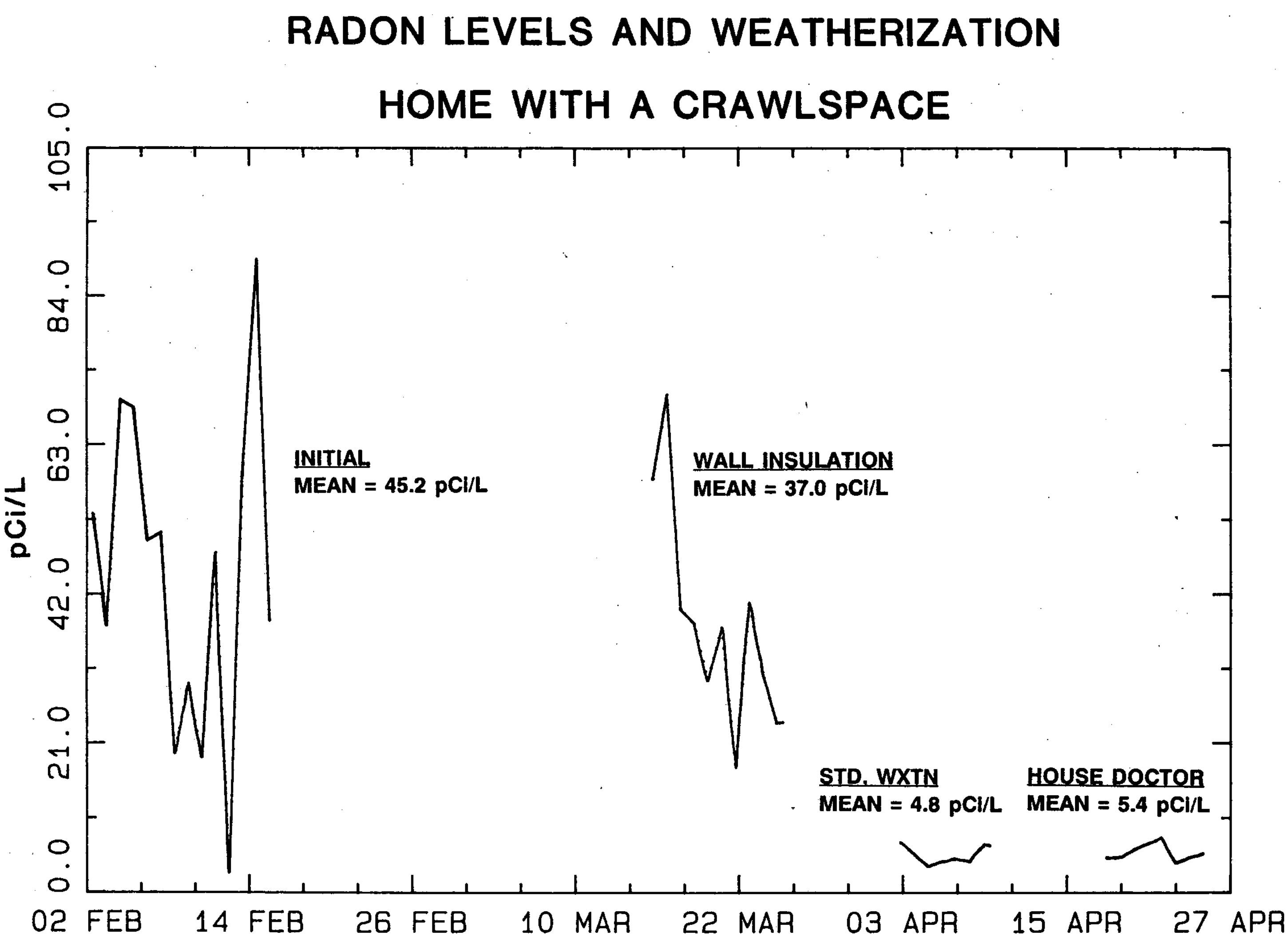

Figure 42 As part of BPA's standard weatherization program, crawlspace ventilation reduced radon levels in a house not in this study (Turk, et al., 1988).

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While the data from the sealing techniques described in this section is informative, ventilation by itself will eliminate most of the radon from crawlspaces. Disadvantages of this technique are few, since the additional ventilation also helps to remove moisture from the crawlspace (basement). Possible disadvantages are freezing of exposed pipes in cold climates; and additional structure energy loss from adjoining floors, walls, and heating/cooling delivery systems, unless thermal insulation is added.

Other Mitigation Techniques

The two other mitigation techniques evaluated in this study were unsuccessfully applied, but are included here for the sake of completeness. A modified block wall ventilation system was used to ventilate an open-cavity block wall supporting fireplaces and flues in ESP101. Grab samples of air taken from the blocks had concentrations of 74 pCi/L and 113 pCi/L suggesting that these walls were potentially an important radon source. Although operation of the block wall system reduced concentrations inside the block to 43 pCi/L, average house radon levels were possibly lower, from 27.6 pCi/L to 22.2 pCi/L, may be due, in part, to increased house ventilation (0.16 hr^{-1} to 0.25 hr^{-1}). See Figure 43. It is important to note that this technique has been effectively used in several houses studied by others (Henschel and Scott, 1986). Since the source in this house was not limited to these block walls, a basement-wide SSP system was installed to successfully reduce indoor levels.

In ESP113, radon entry was suspected to be from a wall/floor joint crack around the entire basement perimeter. Because only 3m of this crack was accessible to sealing behind a finished, frame wall, an experimental baseboard duct wall ventilation system was installed to ventilate the wall cavity space above the crack. However, source removal in the wall cavity was compromised by large amounts of air that entered into the cavity from openings high in the wall that made it difficult to achieve satisfactory ventilation at distant points along the duct. This is evident from the low radon concentrations measured at the baseboard ventilation fan exhausts (18 pCi/L to 55 pCi/L) and in the relatively high levels found in the wall cavities after mitigation (See Appendix E). Average indoor radon concentrations on the main floor were only slightly reduced from 19.8 pCi/L to 17.2 pCi/L. They were ultimately lowered to target levels with a single-pipe SSP system. Other drawbacks to this technique are that it is labor intensive and costly, and that the long-term integrity and seal of the duct are uncertain.

D. POST-MITIGATION INDOOR AIR QUALITY AND VENTILATION RATES

Changes in ventilation rates and concentrations of other pollutants following the installation of some mitigation systems were anticipated. Table 14 summarizes these changes for basement pressurization, AAHX, and SSV systems. Here, all post-mitigation values are normalized by pre-mitigation conditions. Outdoor concentrations of HCHO and H_2O vapor are subtracted from the respective indoor levels. Therefore, data greater than one indicate an increase, while those less than one indicate a decrease in that parameter. Where data are available, the PFT technique can estimate the amount of outside air infiltrating directly into a substructure and the total ventilation rate (including air flowing from other building zones) of a substructure. With the exception of AAHXs, ventilation rate changes will not be reflected in the radon concentrations, since the mitigation techniques are intended to control radon at the source and not by removal through ventilation. The ratios for radon are shown for comparison.

As already discussed, the AAHX did provide additional ventilation which resulted in lower radon levels. The effect on HCHO and H_2O is uncertain, since changes in the concentration of these pollutants also strongly depend on occupant water use and humidity control (H_2O), and relative humidity and indoor temperature (HCHO), and because data are available from

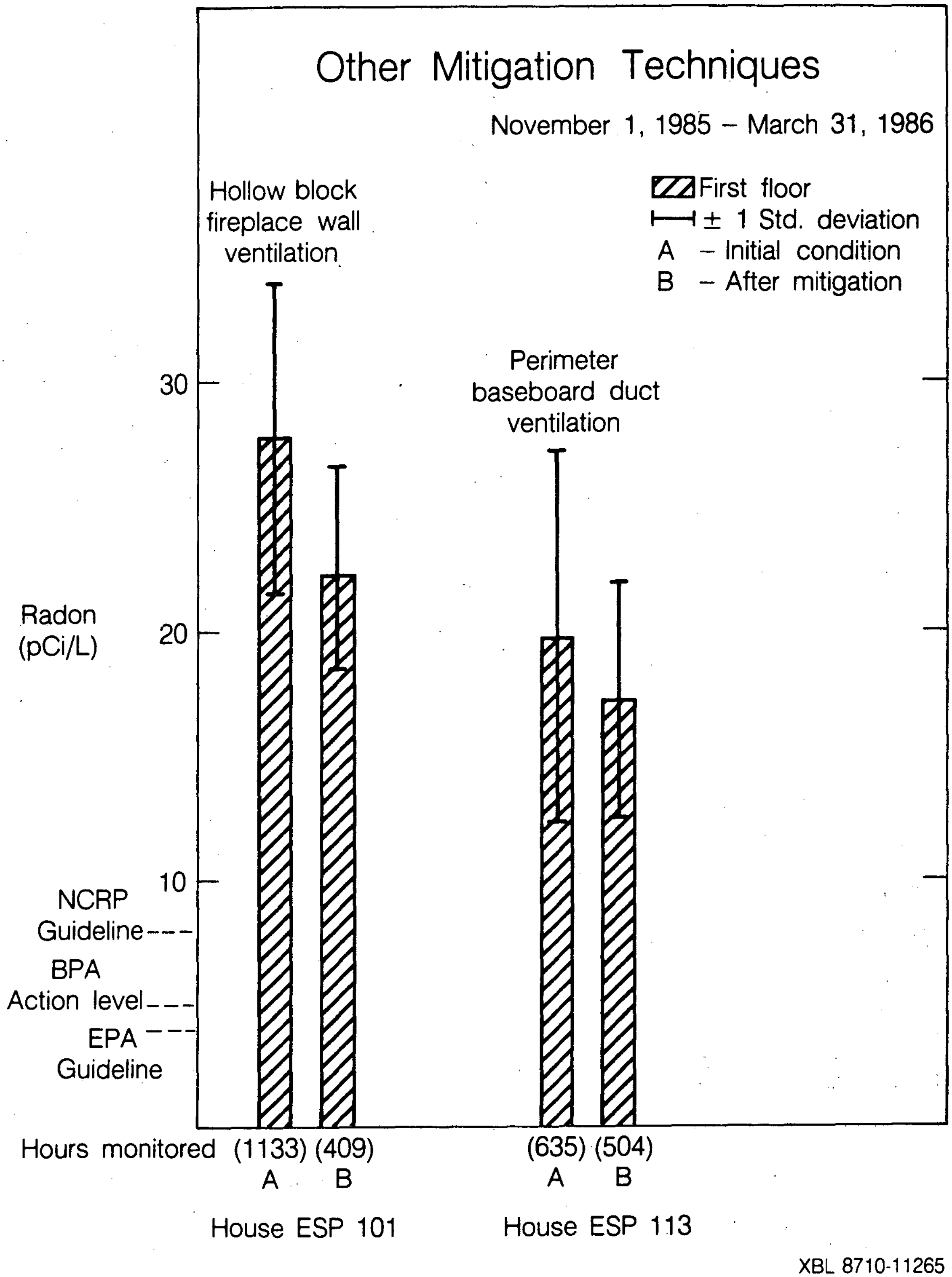


Figure 43 Poor results were obtained from a block wall ventilation system at ESP101 and a baseboard duct ventilation system at ESP113.

TABLE 14. CHANGES IN VENTILATION RATES AND POLLUTANT CONCENTRATIONS AFTER MITIGATION (NORMALIZED BY PRE-MITIGATION CONDITIONS)

MITIGATION TYPE/ HOUSE ID	POST-MITIGATION: PFT-MEASURED NORMALIZED VENTILATION RATES[a]: Whole House	Bsmt or Crawl: Total[b]	Bsmt or Crawl: Infil[c]	NORMALIZED RADON[a] CONCENTRATIONS MAIN FLOOR	NORMALIZED HCHO[d] CONCENTRATIONS HOUSE AVERAGE	NORMALIZED H_2O VAPOR[d] CONCENTRATIONS HOUSE AVERAGE
BASEMENT PRESSURIZATION						
ECD 153	0.64	1.29	0.29	0.14	1.61	0.92
ESP 116 (MIT B)	0.69	3.61	0.00	0.27	0.54	0.97
(MIT E)	0.67	2.19	0.11	0.41	1.02	1.06
ESP 120	1.55	4.54	0.13	0.01	<0	0.78
NCD 077	0.87	1.75	0.00	0.12	1.52	1.27
NSP 204 (MIT G1)	1.70	4.09	0.00	0.06	0.50	0.42
AAHX						
ESP 109	2.71	ND	3.53	0.27	ND	ND
ESP 121	3.24	ND	3.42	0.29	0.37	0.87
NSP 204	1.41	1.56	4.88	0.14	1.21	0.39
SSV DEPRESSURIZATION						
ESP 119	0.72	ND	ND	0.15	0.91	1.41
ESP 120	1.90	1.18	1.02	0.02	0.32	0.58
SSV PRESSURIZATION						
ESP 101	2.13	0.69	2.79	0.04	0.54	0.37
ESP 108	0.58	ND	0.67	0.10	1.55	0.76
ESP 111	1.78	0.57	0.66	0.04	2.85	0.45
ESP 113	3.75	ND	ND	0.08	9.25	0.55
ESP 120	1.30	1.23	1.26	0.02	0.34	1.02

(a) $\frac{\text{Post-mitigation}}{\text{Pre-mitigation}}$

(b) Total of all ventilating air from other house zones and from outside, whether by mechanical or passive processes

(c) Outside air that passes directly into substructure zone

(d) $\frac{(C_{in} - C_{out})\ \text{Post-mitigation}}{(C_{in} - C_{out})\ \text{Pre-mitigation}}$

ND = No data available

only two houses. Theoretically, basement pressurization could have increased whole house ventilation rates by developing larger-than-natural pressure differences across the building shell. Measurements show that total basement ventilation was boosted considerably, and that the amount of directly infiltrating outside air was either reduced or stopped entirely. However, from these data, there is no clear trend in whole house ventilation rates.

We may also argue that basement pressurization, as well as subsurface ventilation, could have reduced the indoor H_2O vapor levels by restricting entry of soil gas that has presumably high H_2O vapor concentrations. Because concentrations of soil gas H_2O vapor were not measured, it is unknown whether this was a source of H_2O vapor before mitigation. If we assume that soil gas is saturated at 10°C (water vapor concentration is ~ 8 g/kg) and that it is then heated to 20°C upon entering the house, the relative humidity of the gas would drop to approximately 50% - not considered elevated. In any case, H_2O vapor concentrations show a modest dependence on ventilation removal rates rather than on a source control mechanism (Figure 44). As in Table 14, the radon data are shown for comparison, since no ventilation rate dependence (except for control by AAHX) is expected.

Additional whole house and substructure ventilation was possible when SSD or SSP was used, as air was probably being drawn out of the house (SSD) or blown into the house (SSP) through the substructure openings to the soil at a greater rate than would naturally occur. Once again, the data from this study do not exhibit a consistent tendency to higher ventilation rates. As mentioned above, this mitigation system does not appear to be controlling a major H_2O vapor source from the soil. Normalized radon and indoor minus outdoor H_2O vapor concentrations are shown compared with ventilation rates after mitigation with basement pressurization or subsurface ventilation in Figure 44. H_2O vapor generally is inversely proportional to the ventilation rate and does not behave like a source-controlled pollutant, as radon does. Figure 45 is a similar figure, but includes HCHO and segregates the data by mitigation system type; basement pressurization and subsurface pressurization. The only observable difference between the two systems is that HCHO and H_2O show less dependence on ventilation rates where SSP is operating. The reasons for this are unclear and considering the small amount of data, may be insignificant.

Indoor respirable suspended particle (RSP) concentrations were dependent on the presence of tobacco smoking. For example, in the three homes in which one or more of the occupants smoked, EVA604, ESP121, and ECD153, RSP levels were often much higher ($64 \mu g/m^3$ to $427 \mu g/m^3$) than the National Ambient Air Quality Standards (NAAQS) of $75 \mu g/m^3$ per year or $260 \mu g/m^3$ per 24 hours for total suspended particles (TSP) or of $50 \mu g/m^3$ per year or $150 \mu g/m^3$ per 24 hours for particles smaller than $10 \mu m$ in diameter. Indoor RSP also depended somewhat on the presence of an actively used fireplace or woodstove and on very high outdoor RSP concentrations that accumulated from vented wood smoke during calm weather and periods of atmospheric temperature inversions. Radon mitigation had no observable effect on this pollutant.

Appendix F is a summary of the average indoor and outdoor pollutant concentrations, and PFT ventilation rate measurements for the whole house and substructure during the monitoring period. Also included is the specific leakage area (SLA) as measured by a blower door.

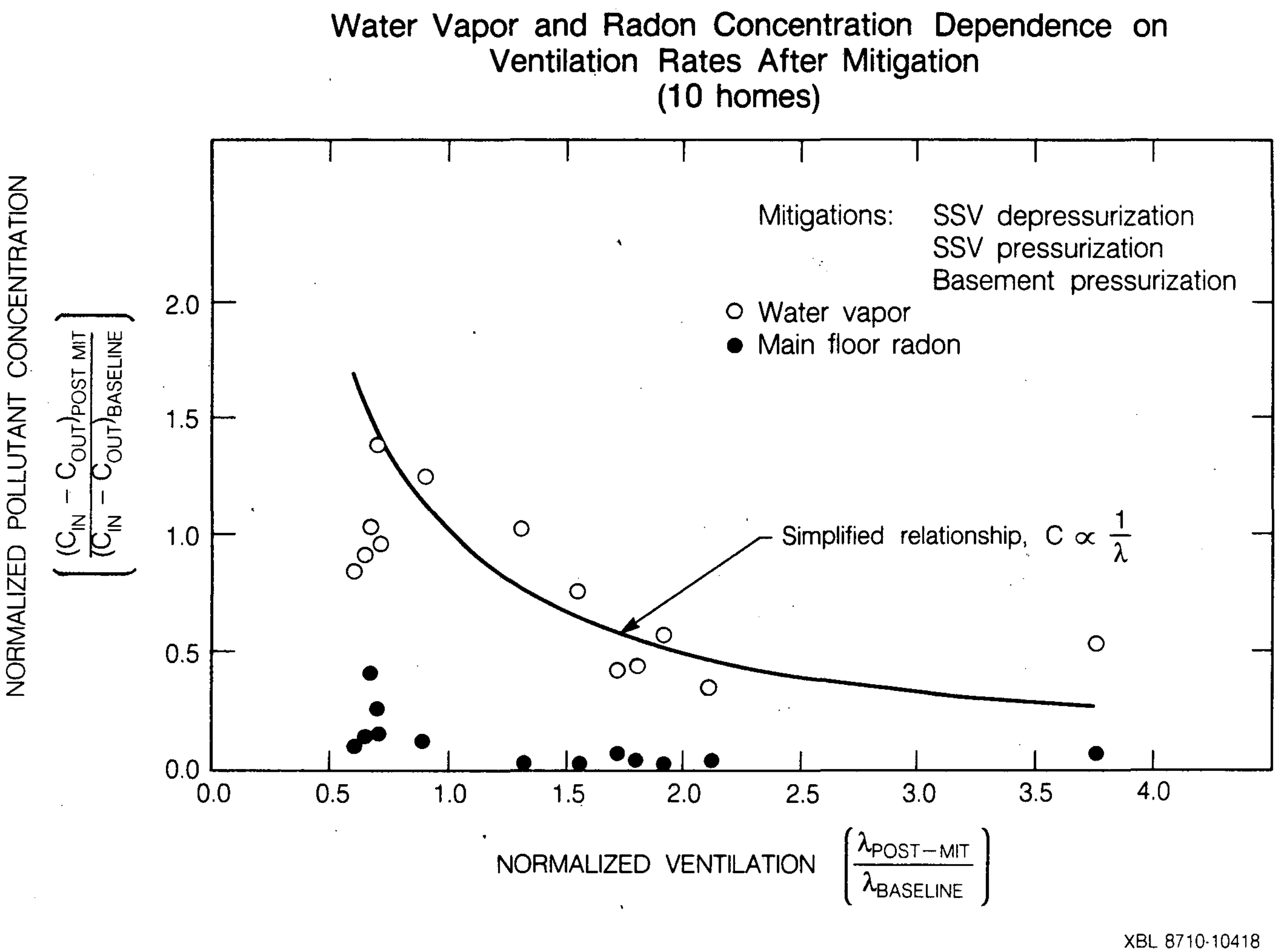


Figure 44 Normalized H_2O vapor concentrations after mitigation tend to respond in a manner that is inversely proportional to the ventilation rate. Compare this to radon, which behaves as a source-controlled pollutant.

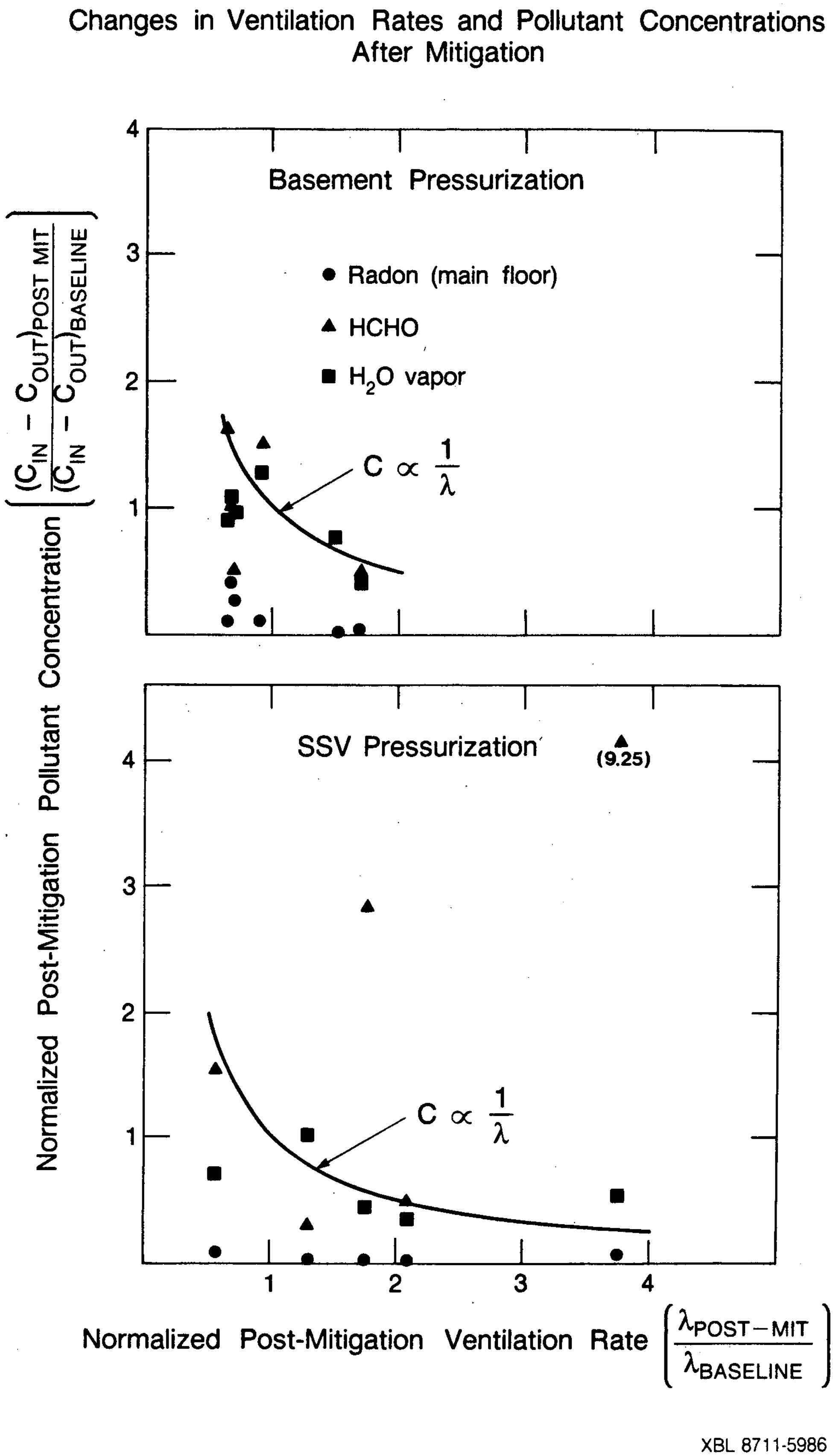


Figure 45 Similar to Fig. 44, but includes HCHO and shows segregation by basement pressurization and subsurface pressurization mitigation techniques.

E. MITIGATION COSTS

The cost of controlling radon is an important, and perhaps overriding, issue for occupants, buyers, and sellers of radon-contaminated properties. We have attempted to collect and summarize cost data on the installation and operation of the major mitigation techniques evaluated in this study. Several points should be kept in mind while reviewing these data: 1) since this was a research project, we did not always economically optimize installation and operation of the systems because of other competing interests, 2) a wide variety of house-specific conditions and system equipment has resulted in a large range of installation and operating costs, and 3) contracted labor rates, materials cost, and overhead and profit can be considerably higher than those shown here.

Installation Costs

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. LBL prepared detailed specifications describing each system to be installed and submitted them to the contractor. LBL personnel accompanied the workcrews during many of the earlier installations to assure that the work was performed according to specifications. It was occasionally noted that materials and practices varied from those that were specified. This resulted in call-backs to the job that necessarily increased the cost of the installed system. This has been factored out of the detailed listing of materials and labor that the contractors provided to LBL. Note that labor effort also includes supervision, travel time, and gathering of materials. These data are summarized by system type and technique in Table 15. As can be seen from the table, the cost for a technique varied by greater than a factor of four. The large range 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. Labor costs of $18.00/hr were typical and are applied to the labor effort listed in column 2. Material and equipment costs listed in column 4 do not include any sales tax. An overhead and profit of 20% were used in column 5. The last column is the unit cost of treated floor area. For example, in the case of a vented crawlspace, this is the area of the crawlspace; for a subsurface ventilation system, it is limited to the basement floor area. The treated unit cost for the air-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 it was necessary, making this technique almost equivalent in cost to that of the subsurface ventilation systems. Crawlspace sealing and ventilation was surprisingly expensive, being as high, or higher, than other techniques. This may be due to the unusual plastic membrane installed over the soil at ESP119 and ECD153, the air infiltration barrier under the house floor at ECD027, and the insulation of ducts, floors and pipes at ESP119, ECD027, and NCD077.

These data, alone, should not favor the selection of one technique after another. Rather, an appropriate selection should be based on suitability, potential effectiveness, occupant acceptance, and installation and operating costs.

TABLE 15. MITIGATION SYSTEM INSTALLATION COSTS

MITIGATION TECHNIQUE / HOUSE ID	LABOR Effort (Man-hrs)	LABOR Cost ($, @ $18/hr)	MATERIAL & EQUIP. ($)	OVERHEAD & PROFIT ($, @ 20%)	TOTAL COST ($)	TREATED FLOOR AREA[f] UNIT COST ($/m^2)
SUBSURFACE VENTILATION						
ESP101 - Interior, 3 pipes, 1 fan, finished	82.0	1476	538[a]	403	2417	23.53
ESP108C - Interior, 4 pipes, 1 fan, finished	51.3	923	300[b]	245	1468	8.90
ESP111 - Interior, 1 pipe, 1 fan, unfinished	30.5	549	237[b]	157	943	16.34
- Exterior, 3 pipes, 1 fan	20.8	374	184[b]	112	670	12.05
- Total	51.3	923	421	269	1613	14.24
ESP113 - Interior, 1 pipe, 1 fan, unfinished	23.3	419	378[a]	160	957	11.21
ESP119 - Exterior, 3 pipes, 1 fan	24.8	446	403[a]	170	1019	19.71
ESP120 - Interior, 3 pipes, 2 fans, partial	62.8	1130	598[b]	346	2074	31.96
ECD026C - Interior, 1 pipe, 1 fan, partial	21.5	387	298[a]	137	822	13.61
- MEDIAN	51.3	923	403	245	1468	14.24
CRAWLSPACE SEALING AND VENTILATION						
ESP119 - Seal soil floor	19.0	342	222	113	677	13.84
- Seal to house, insulate, ventilate	34.3	617	264	176	1057	21.62
- Total	53.3	959	486	289	1734	35.46
ECD026C - Seal to house, ventilate	14.5	261	140	80	481	7.96
ECD027 - Seal to house, insulate, ventilate	41.0	738	613	270	1621	24.49
- Install fan	2.0	36	79	23	138	2.08
- Membrane to house floor	18.0	324	317	128	769	11.62
- Total	61.0	1098	1009	421	2528	38.19
ECD153 - Seal soil floor, ventilate	9.5	171	200	74	445	25.00
NCD077 - Seal to house, ventilate, insulate	26.0	468	319	157	944	15.28
- MEDIAN	26.0	468	319	157	944	25.00
AIR-AIR HEAT EXCHANGER						
ESP109 - Finished basement	54.0	972	990[c]	392	2354	30.03
ESP121 - Finished basement	33.0	594	1036[c]	326	1956	25.70
- MEDIAN	43.5	783	1013	359	2155	27.87
CRACK AND HOLE SEALING						
ESP101	13.0	234	26	52	312	3.04
ESP116	2.3	41	3	9	53	0.62
ESP120	24.8	446	59	101	606	9.34
EVA604	18.0	324	20	69	413	5.23
- MEDIAN	15.5	279	23	40	363	4.14
BASEMENT OVERPRESSURIZATION						
ESP116 - Seal basement, install fan	27.3	491	675[d][e]	233	1400	16.34
ESP120 - Seal basement, install fan	9.0	162	121[d]	57	340	5.24
ECD153 - Seal basement, install fan	22.4	403	298[d][e]	140	842	8.96
NCD077 - Seal basement, install fan	17.6	317	325[d][e]	128	770	12.20
NSP204 - Seal basement, install fan	22.3	401	372[d][e]	155	928	16.34
- MEDIAN	22.3	401	325	140	842	12.20

(a) Includes cost of fan(s) - $151
(b) Includes cost of fan(s) - $102
(c) Includes cost of AAHX unit - $738
(d) Includes cost of fan - $58
(e) Includes cost of backdraft dampers - $100
(f) Generally refers to substructure floor-type being treated (crawlspace, basement, slab-on-grade)

Operating Costs

Table 16 summarizes estimated costs to operate three different systems. Fan power ratings were determined by measuring electrical consumption for a minimum of 19 hours to 23 days with an induction-type watt-hour meter for the homes shown here. The power rating for fans used in this study were similar. Other fans are now available that have lower ratings yet are still suitable for these applications. 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 assume there would be no costs associated with additional ventilation in the summer, unless the structure was air conditioned. An estimate of the additional house ventilation caused by system operation is shown in columns 6 through 8. The data are corrected by changes in ventilation measured in the Control houses over the same period. While these ventilation changes may not be real, they serve to demonstrate the effect of a range of changes in ventilation on operating cost.

It is possible that, in some homes, basement pressurization 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 originally occupied and heated. All operating costs were calculated assuming electricity as the primary fuel with a cost of $0.03/kWh.

We see that the range of total annual energy costs for the three systems are similar; basement overpressurization -$66 to $116, SSV - $88 to $172, and AAHX - $62 to $106. Because of the uncertainty in ventilation changes, we do not know where most homes would fall within the range. Although the energy operating costs of AAHXs are comparable to the other techniques, they would be unable to control the high radon concentrations that are effectively reduced by the other systems. Therefore, larger units would be required that could provide greater ventilation rates which, in turn, would increase the energy costs and possibly occupant discomfort.

F. DEVELOPMENT OF A DIAGNOSTIC APPROACH

As discussed throughout the text, measurements were made before, during, and after installation of mitigation systems to evaluate their performance and operating characteristics. The tests conducted on soil and non-soil sources were the first step toward classifying the source of the radon problem. Other tools and techniques that were used included a detailed survey form that directed the investigator's attention toward specific areas in a house where radon may have been entering. The blower door was used to estimate flow rates necessary for basement pressurization, flow and pressure measuring devices were used to evaluate system performance, and grab samples assisted in identifying radon entry locations. These were early steps in the development of a diagnostic procedure that could be used by private contractors for house-specific radon source identification and mitigation system selection. These diagnostic procedures have been expanded in a study of New Jersey homes and are reported by Turk, et al., (1987c).

Grab samples of air were collected from various building zones and potential radon entry points in several of the buildings. These samples were often taken at the electrical boxes of firred wall cavities adjacent to the wall-floor joint around the perimeter of the building and at penetrations and holes in the substructure walls and floor. The radon concentrations of the samples that were gathered before, during, and after mitigation clearly show the effects of the mitigation system installed. (Figure 46). Study of additional maps for five other houses in

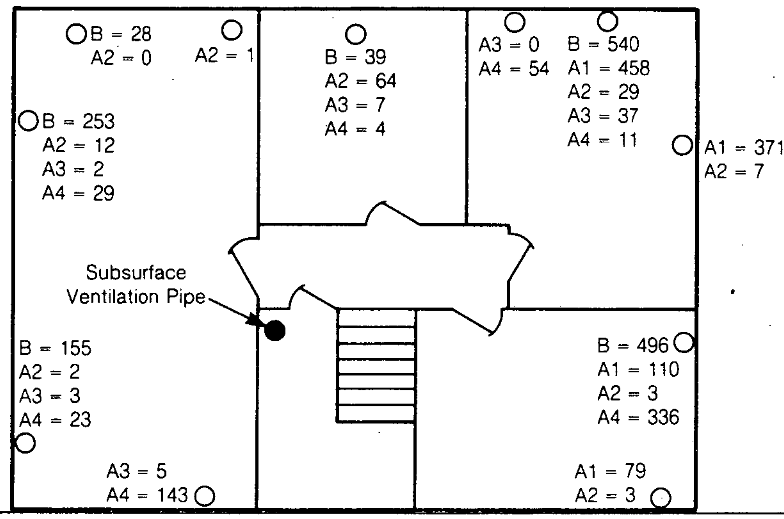
TABLE 16. MITIGATION SYSTEM OPERATING COSTS

		SYSTEM FAN			ESTIMATED ADDITIONAL VENTILATION			ESTIMATED TOTAL ADDITIONAL ANNUAL ENERGY COST	
MITIGATION TECHNIQUE	House ID	Rating (Watt)	Annual Energy (kwh)[a]	Annual Oper. Cost ($)[b]	ACH[c]	Annual Energy (kwh)[d]	Annual Cost ($)	Energy (kwh)	Cost ($)
BASEMENT PRESSURIZATION	ESP116	157	1375	41.25	-0.05	--	--	--	--
	ESP120	122	1069	32.07	+0.20	2804	84.11	3873	116
	ECD153	151	1323	39.69	-0.02	--	--	--	--
	NCD077	99	867	26.01	+0.08	1318	39.55	2185	66
SUBSURFACE VENTILATION	ESP108C	168	1472	44.16	--	--	--	--	--
	ESP111	148	1296	38.88	+0.27	4439	133.16	5735	172
	ESP120	156	1367	41.01	+0.10	1402	42.05	2769	83
	ECD026C	44	385	11.55	--	--	--	--	--
AIR-AIR HEAT EXCHANGER	ESP109	160	1402	42.06	+0.45	--	--	2051[e]	62
	ESP121	195	1708	51.24	+0.67	--	--	3539[f]	106

(a) System operated continuously for 12 months
(b) Electrical rate 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 63.1%
(f) Using energy exchange efficiency of 54.8%

ESP 113 DIAGNOSTIC MAP OF RADON GRAB SAMPLING

Half-Depth Basement



Key to Symbols
(pCi/L)

			Level 2 Room Air (pCi/L)
B (1/28/86)	=	Baseline, Mitigation Systems Off	32
A1(12/18/85)	=	Baseboard Duct Ventilation, Initial System	19
A2 (2/2/86)	=	SSV Depressurizing At −425 PA	5 (4-BSMT)
A3 (2/6/86)	=	SSV Depressurizing At −425 PA	3 (2-BSMT)
A4 (2/14/86)	=	SSV Depressurizing At −200 PA	6 (7-BSMT)

NOTE: Samples Taken From Finished, Firred Wall Cavities At Electrical Boxes.

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Figure 46 Results of radon grab sampling surveys at ESP113 before, during, and after mitigation. Samples were collected from firred wall cavities above the perimeter wall/floor joint crack at locations denoted by open circles. These data demonstrate that the baseboard duct ventilation system was ineffective in removing the radon at the source, while SSV systems were very effective. Maps for five other houses in the study are in Appendix E.

Appendix E also indicates that this survey procedure was useful for locating potential "hot spots" and siting SSV pipes. In some cases, the map data suggested that the entire substructure should be under the influence of a radon control system.

Chemical smoke tubes were used to monitor air movement in and out of entry points. Subsurface ventilation was determined to be effective if, at locations identified by a grab sample as being especially high in radon, the air moved from the building interior through the entry point and into the soil. For many houses, selection of an appropriate mitigation system would depend on detailed, site-specific measurements such as this.

An interpretive map of a New Jersey house (Figure 47) is an example of second generation diagnostic procedures. This map contains much additional information that may not be practically collected by or useful to a private mitigation contractor. However, with this detail it is a useful research tool. The map contains measurements of permeability, relative air movement measured with chemical smoke tubes, and radon grab samples collected not only at potential radon entry points, but also at test holes drilled through the structure.

Refinement of these data and procedures should enable contractors to optimize installations and minimize installation and operating costs. For instance, follow-up measurements made after system installation have been useful in implementing modifications or in tuning the system. These measurements have included flow rates, pressures, and temperatures in SSV pipes and in basement pressurization and AAHX ducts.

Another diagnostic technique involving blower door tests of basements satisfied two objectives. First, it provided an estimate of basement leakage area, and second, it gave an estimate of the flow rates necessary to overpressurize the basement. These were useful for determining whether this mitigation technique would be practical. In Table 17, these data are summarized for four houses and are compared to actual measured flows developed by basement pressurization system fans at several pressures. It is important to note that the pressurization defined here is the total of the existing natural underpressure plus the blower-induced overpressure as referenced to the outside air or adjacent soil probe pipe. It is this total pressure difference that a pressurization fan must develop in order to be successful. In tests to specifically predict necessary flows, the blower was placed in a doorway between the basement and either the outside or the first occupied floor and the basement was pressurized. Several points of overpressurization were run including very low pressures, between approximately 2 and 20 Pa. A power curve was generated for each substructure based on these tests to determine the parameters K and n in the flow model

$$Q = K (\Delta P)^n \qquad [9]$$

where: Q is the flowrate through the structure (m^3/h),

ΔP is the pressure imposed by the blower (Pa),

n is a flow exponent ranging from 0.5 to 1.0, and

K is a flow coefficient ($m^3\ h^{-1}\ Pa^{-n}$).

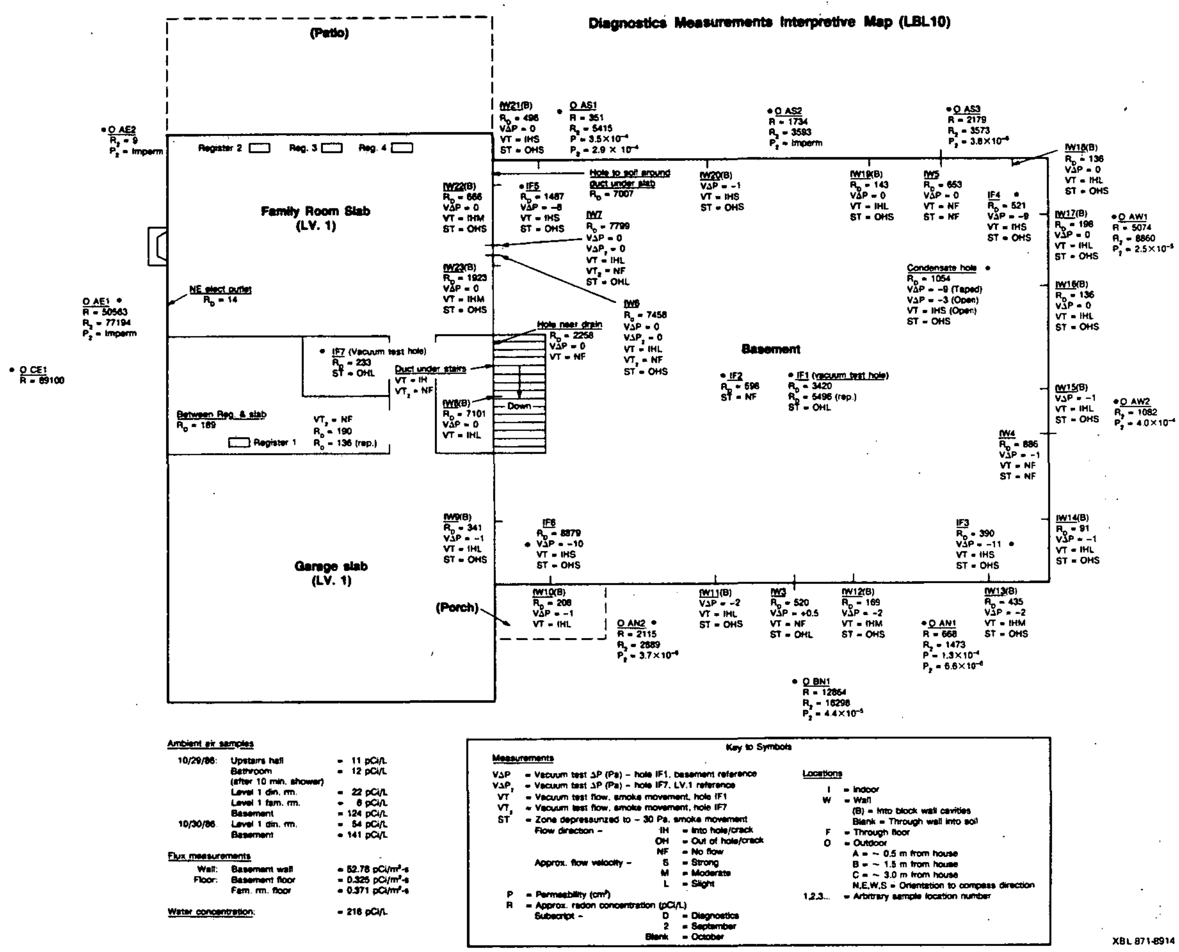

Figure 47 A similar map to Figure 46, but containing more information on soil permeability, air flow potential under the slab, and more grab sample locations. This map, of a New Jersey house, assisted in locating a successful SSV system through the common wall between the family room slab and basement (Turk, et al., 1987c).

TABLE 17. COMPARISON OF ACTUAL FAN FLOW RATES NECESSARY TO ACHIEVE BASEMENT OVERPRESSURIZATION WITH FLOW RATES PREDICTED USING A CALIBRATED BLOWER AS A DIAGNOSTIC TOOL.

HOUSE ID	BASEMENT OVERPRESSURIZATION[(a)] (Pa)	MEASURED FLOW RATES BASEMENT PRESSURIZATION FAN (m^3/hr)	BLOWER DOOR PREDICTED FLOW RATES (m^3/hr)		MEASURED EFFECTIVE LEAKAGE AREA (cm^2)	COMMENTS
			Test 1	Test 2		
ESP120	3.0	547	340	396	525	- before sealing of basement shell, including floor between basement basement and upstairs
	3.3	552	369	423	-	
ECD153	4.0	729	535	438	488	- after sealing and installation of backdraft dampers in forced-air furnace supply air plenum
	~5.9	770	664	557	-	
ESP116	~4.1	831	924	715	735	- after sealing of basement shell
	~4.3	816	948	697	-	
NCD077	~3.1	498	-	428	556	- after sealing and installation of backdraft dampers
	~3.5	506	-	462	-	
	~4.2	535	-	518	-	

(a) Pressurization above naturally-induced basement depressurization (existing underpressure + blower-induced overpressure)

Test 1 = Test specifically for prediction of overpressurization flows
Test 2 = Test to calculate leakage area of basements, not always coincident in time with test 1

A similar calculation was made based on data collected during those tests to measure the effective leakage area (ELA) of the substructure. In general, however, data points from the ELA tests did not extend under 10 Pa. For both tests, flowrates were calculated for the pressure differences in the second column of Table 17, at which pressurization system flow rates were measured. The flow rates predicted with the blower door do not replicate particularly well between the two different tests conducted on a basement. For houses ESP116 and NCD077, predicted flow rates are within 15% of measured rates that were necessary to actually achieve the pressurization indicated using an installed system fan. Predictions for the other two houses range from 27 to 38% below the measured rates. The results show promise that a calibrated fan can be used to indicate whether basement overpressurization is a viable remediation system in a particular house. To make this evaluation meaningful, any specification on the magnitude of overpressurization necessary to inhibit radon entry should also stipulate what pre-existing underpressure needs to be overcome. This design underpressure will depend on local climatological conditions.

Long-term measurements of radon in these houses are being conducted by deploying alpha track detectors for three month seasonal averages after mitigation efforts were completed. This information will be vital for follow-up of system performance and long-term reliability and durability. Preliminary indications are that radon levels may be increasing in some homes with mitigation systems operating. A detailed study of the concentrations following mitigation and the causes for increases in the concentrations is in progress.

IV. SUMMARY AND CONCLUSIONS

In the Spokane River Valley/Rathdrum Prairie area, 65% of 46 residences monitored had indoor radon levels above the EPA guideline of 4 pCi/L and 57% had indoor levels above the BPA Mitigation Action Level of 5 pCi/L. The combination of the moderate generation rates of radon in the soil, high transport rates of gas in the high-permeability (10^{-10} to 10^{-13} m^2) soil, and adequate entry paths through house substructures were the primary contributors to the high indoor concentrations. Measured concentrations of radon in soil gas were approximately 283 to 673 pCi/L. Based on the radium concentrations in soil samples, calculations of maximum radon concentrations in soil gas ranged from 420 to 833 pCi/L. Fourteen homes from this area and one from Vancouver, Washington were selected for more intensive monitoring and testing of remedial action techniques. For these homes, estimated soil gas entry rates were very high: 0.4 to 39 m^3/hr and comprised 1% to 20% of the total infiltrating air for these houses.

Other, non-soil radon sources such as outdoor air, natural gas, potable water, and emanation from building materials, were not significant contributors to the high levels in these homes. Concentrations of radon in water and building material emanation rates were similar for both the homes with high indoor radon levels and another group of homes with low radon levels. Contributions to indoor air concentrations were estimated to be less than 0.3 pCi/L from water, and less than 2.6 pCi/L from building materials, and approximately 0.5 pCi/L for outdoor air.

In the two unmitigated Control Houses, wide daily and seasonal variations in indoor radon levels were not always explainable, although other houses did show strong correlation to ΔT and wind speed. Complex interactions with parameters not monitored are suspected causes for some of the variation. More recent studies have included continuous and semi-continuous data collection on soil permeability, soil gas radon concentrations, soil temperatures, sub-slab radon concentrations, pressure differences measured across different surfaces, etc. (Sextro, et al., 1987b), to help gain a better understanding of this variability in radon concentrations.

Winter indoor radon levels averaged 12.6 times higher than summer levels, while they were only 2.5 times higher for the low radon homes. This implies that seasonal variations in radon entry rates and/or removal mechanisms are different between the two groups of homes. Ratios of upper floor to substructure radon levels were always less than one and were very dependent on the leakage area between floors and the presence and operation of a forced-air heating system, both of which encouraged mixing of air between the floors.

Several promising techniques for reducing excess radon concentrations in houses were identified. These include basement overpressurization, subsurface ventilation (SSV) by depressurization (SSD) and overpressurization (SSP), and crawlspace ventilation. All techniques, properly applied, reduced radon levels in these homes below the BPA guideline.

Basement overpressurization (or a variant of) was successful in six houses where basements were sufficiently air-tight so that a fan pulling air from upstairs could pressurize the substructure to 1 to 3 Pa above the neutral or outside pressure. Incremental increases in the pressure tended to decrease radon entry. Because ductwork of forced-air heating systems provides a low resistance by-pass for air flow, the system may be more easily installed and operated in houses without forced-air furnace systems. Long-term reliability is unknown, since occupants may easily defeat the substructure overpressures.

Subsurface ventilation (SSV) was effective in the seven houses where it was installed. Surprisingly, in these houses, blowing outside air into the soil (SSP) always resulted in greater reductions of indoor levels than depressurizing the soil beneath the substructure (SSD). This is probably due to the moderate radium concentrations and high permeability of the local soils. Because of this, SSP may not work as well in other regions with lower soil permeability. In those homes with a SSD system operating, tracer test results indicate that significant amounts of basement air can leak through many substructure openings into the soil, to be exhausted by the SSD system.

Less tightly-packed soils near to the houses, gaps at the substructure/soil interface, and leakage through the below-grade surfaces of the substructure presumably resulted in higher (by a factor of 10 to 10^4) effective permeabilities as seen by the SSV system pipes than in the undisturbed soil away from the house. A determination of the effective permeability by mitigation contractors may be useful for evaluating the appropriateness of an SSV system for radon control.

Staged crawlspace radon mitigation was performed at four houses. While sealing of soil floors and of the crawlspace from the house (isolation) were partially effective, ventilation of the crawlspace was the most important component in reducing radon entry from the crawlspace. Crawlspace ventilation is essential for controlling indoor radon in homes with crawlspaces, but it may not control radon to below guideline levels in homes that also have basements.

Air-to-air heat exchangers were effective in two houses with low initial ventilation rates and only moderately high radon concentrations. Reductions in radon were directly proportional to increases in house ventilation. The sensible heat exchange efficiency was 0.55 and 0.63 respectively for these two homes. In a third house, radon levels were lowered by improving the air supply and return distribution of an existing AAHX.

Sealing of cracks and holes between the substructures and the soil was generally ineffective for these homes, because not all openings were accessible and could not be sealed economically. Other techniques, including block wall ventilation and perimeter baseboard duct ventilation, were also ineffective in the situations in which they were applied during this study.

With the exception of the AAHXs, radon mitigation had no observable effect on ventilation rates or other pollutants monitored in this study. This was not surprising, because the systems were generally intended to control the source of radon and not provide additional ventilation.

Mitigation system installation costs were very dependent upon house-specific construction, interior finish, and homeowner demands. Crack and hole sealing costs, normalized to treated floor area, were the lowest ($0.62 to $9.34/m^2), SSV and basement pressurization costs were similar (medians: $14.24 and $12.20/m^2 respectively), crawlspace sealing and ventilation costs were higher than anticipated ($25.00/m^2) possibly because of the additional expense of staging the work, and purchase and installation costs of AAHXs were the most expensive ($27.87/m^2). Operating costs were difficult to determine, because of uncertainty in measuring the amount of additional ventilation, but estimates ranged from $62 to $172 per year for the active mitigation systems: SSV, AAHX, and basement overpressurization.

Experimental pre- and post-mitigation diagnostic procedures, including grab sample mapping; detection of air movement at entry points; house air leakage area measurements; sizing of basement pressurization fans by using a blower door; and mitigation system flows, pressures, and temperatures, were found to be very important in identification of radon entry points and selection of appropriate corrective measures. These procedures will continue to be modified so that selection and implementation of mitigation systems is optimized.

Seasonal alpha track monitors have been deployed in these homes since completion of the mitigation to evaluate the long-term reliability of the techniques. Preliminary results indicate the importance of this follow-up, since radon levels in some houses may be increasing. A study-in-progress is investigating the causes for rising concentrations, including factors such as degraded system performance and low occupant acceptance of certain mitigation techniques.

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LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720