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Evaluation of Radon Reduction Techniques in Fourteen Basement Houses: Preliminary Results

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INTRODUCTION

Burgeoning public awareness of the associated health risks of indoor radon has stimulated increased support for studies of measures to control or correct elevated indoor concentrations.[1,2,3,4] These earlier studies were designed as demonstrations of new or existing techniques and were not necessarily intended to answer basic research questions regarding procedures to select an appropriate control system or understand in detail why these systems worked.

Although elevated indoor radon concentrations can be caused by radon release from high concentration domestic water supplies or diffusion from or through building materials, it is most commonly due to bulk transport of soil gas containing radon through cracks and openings in a buildings' substructure.[5,6] Movement of this soil gas is due to pressure differences across the building shell which in turn are caused by the thermal stack effect driven by the indoor-outdoor temperature difference, wind loading at the building, and, in some cases, the operation of mechanical devices in the structure.

Unfortunately, our understanding of the entry and removal processes and their relationship to the operation of mitigation systems is limited. Important factors affecting these processes include: environmental parameters such as indoor and outdoor air temperatures, wind speed and direction; soil characteristics including temperature, moisture content, radium concentration, and air permeability; structural design characteristics such as building height, air leakage distribution, substructure type, and its coupling to the soil via openings; and operation of the building by the occupants or its mechanical systems.

This paper reports the preliminary results of a study of radon control techniques in 14 homes in New Jersey. The study is part of a comprehensive project[7] supported by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency (EPA), and the State of New Jersey, and initiated to:

1. investigate the fundamentals of soil gas flow and radon entry into buildings and the factors that influence the entry rate,
2. develop a diagnostic procedure for specifying appropriate and effective remedial measures, and
3. better understand the operation of certain mitigation techniques and the parameters that affect them.

Reported here is a description of the radon control work that was conducted in the houses and a summary of the results of that work. At this time, a detailed analysis of the relationship between the parameters affecting system performance has not been conducted.

PROJECT DESIGN AND DESCRIPTION

Programmatic

Approximately 130 homes from north-central New Jersey had been previously identified by the New Jersey Department of Environmental Protection as having elevated levels of indoor radon and being suitable candidates for study. These homes were reviewed and a smaller group of 33 homes was selected for screening by a collaborative team of researchers from Lawrence Berkeley Laboratory, Princeton University, Oak Ridge National Laboratory, and the Air and Energy Engineering Research Laboratory of the U.S. EPA. The on-site inspection of each home included a blower door air leakage test, a preliminary radon entry survey, a detailed house structure survey, a radon source diagnosis survey, soil measurements of air permeability and radon gas, and an occupant information questionnaire. Following a review of the data and information collected for each of the 33 homes, a set of fourteen homes was selected for the study which met the following final criteria:

a) characteristic soil permeabilities representative of the 33 homes surveyed,

b) accessibility to interior basement walls and floors,

c) substructures representative of the regional housing stock with relatively simple geometries and combinations of substructure types,

d) occupant interest in the project, and

e) absence of any other factors that might hinder research operations.

Seven of these homes were chosen as study homes for LBL and seven for Oak Ridge and Princeton University. One home out of each seven home set served as a control home, and did not have a radon mitigation system installed until the latter part of the study. A map of the area with the general location of the study homes is shown in Figure 1.

A brief description of each house is found in Table I (note that house numbers for 01 to 07 were assigned to the Oak Ridge/Princeton study homes, 08 to 14 to the LBL homes).

Experimental

The intensive nature of this project required the utilization of many pieces of instrumentation and measurement methods. Testing and monitoring involved continuous measurements recorded by an on-site data logger, integrated sampling which generally included week-long measurements of ventilation, water vapor concentrations, and single-sample or periodic measurements of many other house, soil, and environmental characteristics. Table II summarizes the instrumentation and methods used. Those techniques that were employed in the diagnostics and system selection phase and those that are being used in evaluation of the mitigation systems are designated in Table II.

The pre-mitigation diagnostic measurements were performed in the 12 test houses in late October, November, and early December 1986. Diagnostics, as used by LBL in this project, were developed for research purposes and are not directly applicable for use by private contractors and consultants. The methods were subsequently modified by Princeton and Oak Ridge to be more practical and economical. Most of the procedures and measurements followed are detailed in Turk *et al.*,[8] but are summarized as an outline in Table III. The data from the diagnostic measurements were reviewed and systems were selected for each house. The main objectives for selection of mitigation systems were as follows: 1) the systems to be selected should be effective in controlling radon to below the EPA guideline of 4 pCi/L and economical to install and maintain, and 2) a variety of mitigation systems should be selected for the purposes of comparison.

Remediation began in the test homes during the third week of November, 1986 and continued throughout the heating season. The control houses were not corrected at that time, but awaited diagnostic measurements in June and system installation in July, 1987.

The plan was to first install those mitigation techniques that could be turned on or off. These would then be followed by the non-recoverable mitigation techniques such as the sealing of cracks and holes. In some homes, multiple systems were to be installed in stages. For instance, mitigation system #1 would be installed, modified and the efficiency improved. Once mitigation #1 was optimized, mitigation system #2 would be installed, modified and the efficiency improved. In other houses, a second system was not recommended because of the mitigation plan, expense, or limited promise for success.

Following the installation of the mitigation systems, it was important to perform post-mitigation diagnostics, including characterization of the system operating parameters. These measurements included flow rates, pressure differentials, energy usage, air stream temperatures, and radon concentrations and are briefly summarized on Table IV. These data are currently being analyzed.

Table V describes the important strategies that were employed in each house. They are listed in the order in which they were installed. Those techniques that are involved in final cycling are indicated with a Δ. The procedure of cycling in homes with multiple systems involved an initial baseline period of one week, followed by operation of mitigation system #1 for one week and then operation of mitigation system #2 for one week. Then the house is returned to the baseline condition to start the cycle over. As can be seen from Table V, many intermediate modifications of those techniques were evaluated. In fact, a large number of system operating conditions were tested but are not included on this list. They generally involved making small changes in pressures or location of ventilation pipes/ducts. Subsurface ventilation systems were installed in 11 homes, while three homes received block wall ventilation, six received perimeter drain duct ventilation, three had basement overpressurization systems installed, two had air-to-air heat exchangers, and two had systems incorporating drain tile ventilation.

RESULTS AND DISCUSSION

In order to be certain that low indoor radon levels following mitigation were, in fact, due to the remedial technique, unmitigated (baseline) conditions were periodically re-monitored throughout the study. Baseline conditions for time periods corresponding to similar mitigation periods are shown for two test houses in Figures 2 and 3. In most of the homes, radon levels were highest during the mid-November, 1986, monitoring period and tended toward lower concentrations into April, 1987. Since sealing was not reversible and was expected to have some impact on unmitigated indoor radon levels, it was important to determine the new "baseline" conditions after the sealing. The effect on baseline concentrations of sealing the floating slab ("french") drain is obvious in house LBL08, as indicated in Figure 2. In other houses where mitigation-related sealing occurred, changes in baseline concentrations are small and may be simply due to seasonal environmental effects. A specific example of the typical effect of mitigation on basement radon concentrations is shown in Figure 4. This is a 10-month plot of 24-hour average concentrations in LBL12 that includes initial baseline levels (September 12 - November 24), followed by modifications and experimentation with the subsurface ventilation (SSV) mitigation system (November 25, 1986 - February 22, 1987), routine weekly cycling of the system (February 23 - June 25), and more modifications and experimentation with the system (June 26 and later). With the system(s) off, concentrations rebound to high baseline levels.

The following is a brief description of the results of the various mitigation systems in selected houses. While subsurface ventilation was usually the system that produced the most dependable reductions in indoor concentrations, the other techniques may be as, or more, suitable in particular situations.

Subsurface Ventilation (SSV)

Thirteen of the 14 project homes were retrofitted with some form of subsurface ventilation system (SSV). PVC pipes were generally installed to penetrate the slab floor and were attached to a fan that either pulled air from below the slab by depressurization and exhausted it to outdoors (SSD), or that forced outside air below the slab, pressurizing it (SSP). In Figure 5, we see that subsurface ventilation always reduced the average basement radon levels, but not to below the EPA guideline in every instance (e.g. LBL12). Subsurface ventilation pressurization (SSP) was never as effective as subsurface ventilation depressurization (SSD) and was never retained as the final configuration. Only in PU/OR01 did SSP (connected to a perimeter drain duct) reduce indoor radon levels to below the EPA guideline, but it was also not as effective as SSD with the drain duct (Table VI). This contrasts with findings in Spokane-area homes where SSP was always the more effective technique (Turk *et al.*, 1987)[8]. The difference in the performance of the SSP systems can possibly be explained by the higher soil gas radon concentrations found around these New Jersey homes (soil gas concentrations were typically from four to 20 times higher than in Spokane). An SSP system can be assumed to rely on ventilation of the soil surrounding a house to be effective. The fresh outside air blown into the soil reduces the concentration of radon in the soil gas by dilution, while causing soil gas to enter the house at a greater rate due to the increased pressure difference across the building shell. Therefore, this greater volume of soil gas entering the house must be low enough in radon concentrations so that the total mass flow of radon into the indoor air is reduced. The radon concentration of the soil gas passing into the house with an SSP system operating is dependent upon the residence time of the fresh outside air in the soil (as determined by the soil path length, soil air permeability, and pressure difference) and on the emanating radium concentration of the soil. If we assume similar soil permeabilities and that we are diluting the soil gas in both Spokane and New Jersey homes by the same fraction with outside air from the SSP system, then the initially higher radon concentrations in the New Jersey soil gas will result in more radon entering than in the homes in the Spokane area.

Figure 5 also suggests that greater negative SSD pressures at a house tend to cause lower indoor concentrations. This is also true when a SSD system is attached to an open perimeter drain in the basement that has been sealed to form a duct. In both cases, the pressure field developed by the SSD system is extended further under the slab floor and in some cases up the exterior of the basement walls. For example in LBL08, the reduction in basement radon concentrations after initial SSV installation and perimeter drain duct ventilation was to only 5 pCi/L. Follow-up diagnostic tests indicated that pressure field communication between the drain duct and the inside of the block walls was poor and that flow restrictions in the SSD pipe limited the depressurization with respect to the basement air (at the pipe penetration) to between -54 and -86 Pa at a flow of 3.4×10^{-2} m^3/s (73 ft^3/min). Through modifications, the depressurization was boosted to between -95 and -213 Pa at 3.7×10^{-2} m^3/s (78 ft^3/min) and radon levels in the basement correspondingly dropped to 2.8 pCi/L. Follow-up diagnostic measurements indicated that communication to within the block walls was improved and that perhaps a significant portion of the radon was previously entering through sections of the block wall.

Average basement radon levels in LBL12 exhibited a gradual increase through the spring and summer, eventually rising above the target of 4 pCi/L. The cause of this increase has not yet been determined, and levels could not be rolled back by developing greater negative SSD system pressures (-115 to -325 Pa). Levels were ultimately brought under control by installing a block wall ventilation system in addition to the SSD system in the adjoining crawlspace.

Air-to-Air Heat Exchanger

An air-to-air heat exchanger (AAHX) was installed as part of this study in the basement of LBL09, while two AAHX's were already in place in PU/OR06. In LBL09, the estimated additional ventilation from the AAHX (~ 0.5 ach) reduced basement radon levels from 28 to 16 pCi/L and first floor levels from 18 to 14 pCi/L, as expected from the additional ventilation (see Figure 6). A SSD system was subsequently installed in the basement to reduce levels further to an average of 4.4 pCi/L. Figure 7 compares the performance of these two systems for a three-week period in February and March. Basement levels were brought below the target concentration by the installation of a SSD system in the adjoining crawlspace.

Block Wall Ventilation

Ventilation of the open cavities in block walls alone was only attempted in LBL10. Other homes (PU/OR01, PU/OR06, and LBL12) received block wall ventilation in conjunction with other systems (SSD). As seen in Figure 6, the system successfully reduced basement radon levels to 3.2 pCi/L. First floor levels were also lowered to 3.4 pCi/L. The system was installed so as to share the fan and piping of a SSD system. Therefore, by manipulating dampers to switch between systems, a side-by-side comparison of performance can be made (Figure 8). The effect of the two systems on indoor concentrations is almost identical. We assume that the reductions are comparable to those of the SSD system because the ventilation points of the pipes of the two systems are very close to one another, therefore both systems are effectively ventilating the same floor, wall, and soil surfaces.

Basement Overpressurization

By installing a fan to draw air from the upstairs and blow it into the basement, pressures in the basements of two tightly-sealed homes were increased to diminish radon entry. The basements of the homes were also air leak-tightened as much as practical. In Figure 9, the effectiveness of the systems is shown. Similar to other studies, radon reduction was related to the amount of overpressure achieved. For instance, in LBL12, because of leaky forced air furnace ductwork, the basement depressurization was reduced from - 4.0 Pa to approximately -0.9 Pa, not enough to overcome the natural depressurization caused by the thermal stack effect. As a result, average basement radon levels declined, but only to 24 pCi/L from a baseline of 64 pCi/L. In LBL11, initial basement pressurization was also insufficient to successfully control radon levels until a larger fan was installed capable of pressurizing the basement to between +3.7 and +6.1 Pa at a flow of 15.3 x 10^{-2} m^3/s (324 ft^3/min). Average basement radon levels then fell to 1.5 pCi/L. Unfortunately, the noise of this particular system was offensive to the occupants and made the technique unacceptable. Figure 10 demonstrates a fundamental operating difference between a SSD and basement overpressurization system. At LBL11 soil gas concentrations measured below the floor slab remain high during basement overpressurization while during SSD operation soil gas concentrations drop. The basement pressurization system is successful when soil gas (and thus radon) entry is kept at bay by higher basement pressures. The success of a SSD system also depends on altering this pressure gradient, but, in addition, it tends to ventilate and/or deplete the radon concentrations in the soil gas surrounding the house. Also note in Figure 10 the greater variability of indoor radon levels during basement overpressurization. Presumably, this results from the sensitivity of radon entry rates on basement pressures, which are, in turn, sensitive to indoor-outdoor temperature differences and windspeed. In this discussion, basement pressures are referenced to outdoor pressures measured two meters from the house two cm below the soil surface.

SUMMARY

The basement radon concentrations before and after mitigation system operation are summarized in Table VI. The interim results of mitigation system testing to date indicate that subsurface ventilation by depressurization is very often recommended and successful. Note that "high" SSV depressurization is defined as periods when the pressure difference at the SSV pipe before it penetrates the slab floor was more negative than -125 Pa. Most homes had permeable gravel layers below the slab floors. However, SSV pressurization was less effective than depressurization in all homes where it was evaluated. This is contrary to results seen in the Spokane study[3] where SSV pressurization was always more effective. We hypothesize that SSV pressurization is not successful in these New Jersey houses because soil gas radon concentrations are from four to 20 times higher than we encountered in the Spokane area. Since the SSP systems in the two regions are assumed to be diluting the soil gas with the same amount of outside air, the soil gas being forced into the New Jersey substructures is higher in radon concentration by the same factor of four to 20. Block wall ventilation performed well in the three houses that were selected for this technique. It may have been a satisfactory system in other homes where the radon levels were difficult to control (e.g. LBL08), but it was not employed in these homes because of budget limitations. In other homes, perimeter drain and drain tile mitigation systems appear to be effective due to the efficient distribution of the subsurface pressure field and soil gas ventilation.

We observed that basement overpressurization can be effective in tightly sealed houses. The three houses selected for this technique PU/OR05, LBL11, and LBL12, showed that the magnitude of reduction in indoor concentrations is related to the degree of basement overpressurization. In houses LBL12 and PU/OR05, overpressurization did not successfully reduce indoor levels because air looping back through the forced air furnace heating ducts limited pressurization. See Hubbard *et al.*[9] for a discussion of PU/OR houses 01 to 05. In Table VI, "high" overpressures refer to conditions where the basement-to-outside pressure difference was greater than +2 Pa.

The air-to-air heat exchangers performed as expected. Further reductions could have been achieved if larger and more costly exchanger units with more air flow were installed. As has been observed by others, air-to-air heat exchangers are generally successful when initial indoor radon levels and ventilation rates are both low and reductions can be achieved by dilution or by modified air distribution. While these data are still preliminary, it is unlikely that the results and interpretation will be changed by the final data.

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Table I. House description.

House ID	Age (yrs.)	Stories Above Grade	Heating Systems	Substructure Description[a]
PU/OR01	3	1	Gas FAF[b] & DHW[c]	Daylight basement w/attached slab-on-grade, ducting runs below slab-on-grade, perimeter french drain with sump and weep holes, basement walls unpainted
PU/OR02c (control)	10	2	Gas FAF & DHW	Daylight basement with one wall above grade, walls unpainted, perimeter floor/wall crack (~1 mm), sump
PU/OR03	2	2	Oil FAF, elec. DHW	Full basement, walls unpainted perimeter french drain, sump
PU/OR04	30	2	Oil FAF, elec DHW	Basement w/attached slab-on-grade, 2 sumps, basement walls painted
PU/OR05	4	1	Elec. FAF w/oil backup, elec. DHW	Full basement, walls unpainted, perimeter french drain, sump
PU/OR06	35	1 1/2	Oil FAF & DHW	Basement w/attached slab-floor crawlspace and attached slab-on-grade, sump, perimeter floor/wall crack (~1 mm), basement walls unpainted
PU/OR07	15	2	Gas FAF & DHW	Basement w/attached unvented slab-floor crawlspace, perimeter french drain in both, sump, basement walls unpainted
LBL08	7	1	Oil FAF & DHW	Full basement, walls partially painted, perimeter french drain with sump
LBL09	26	2	Gas FAF & DHW	Basement w/two attached unvented slab floor crawlspaces, basement walls painted perimeter floor/wall crack (~1 mm)
LBL10	14	2	Gas FAF & DHW	Basement w/attached slab-on-grade, walls mostly painted, heating system ducting runs below slab-on-grade

Table I. (continued)

LBL11	3	2	Oil BBHW[d] & DHW	Daylight basement w/one wall entirely below grade, walls unpainted, built over loose fill
LBL12	7	2	Elec. FAF & DHW	Basement w/attached, unvented slab floor crawlspace, painted walls
LBL13	11	2	Oil FAF, elec. DHW	Full basement, walls unpainted, perimeter floor/wall crack (~1 mm)
LBL14c (control)	6	2	Propane FAF & DHW	Full basement, painted walls

[a]All substructure walls are concrete or cinder block.
[b]FAF = Forced Air Furnace
[c]DHW = Domestic Hot Water
[d]BBHW = Baseboard Hot Water

Table II. Instrumentation and measurement methods used throughout the study

	Parameter	Device or Method
	Continuous Measurements:	
(P)[a]	Air, soil temperature	IC and RTD Temperature sensors
	Relative humidity	Electronic (PU/OR only)
(P)	Differential pressure	Variable capacitance transducer
(P)	Wind speed	Magnetic pickup pulse generator
(P)	Wind direction	Variable resistance potentiometer
(D[b],P)	Radon	1. Continuous flow scintillation cell 2. Wrenn chamber (PU/OR only)
	Radon soil flux	Wrenn chamber (PU/OR only)
	Radon progeny	Alpha spectroscopy
(P)	Barometric pressure	Piezo-electric crystal
(P)	Rainfall	1. Heated tipping bucket 2. Graduated cylinder rain gauge
(D,P)	Ventilation rates	Constant concentration tracer gas unit (PU/OR05)
	Integrated Sampling:	
(P)	Ventilation measurements	Constant injection and sampling of tracer gases
(P)	Indoor water vapor	Passive water vapor sampler (LBL only)
(P)	Radon	Passive radon detector (alpha track)
	Single-Sample or Periodic Measurements:	
(D,P)	Building air leakage area	Blower door depressurization
(D,P)	Soil air permeabiliy	1. Field-based *in-situ* air permeameter 2. Lab-based soil core permeameter
(D,P)	Radon in air	Scintillation - cell grab samples
(D,P)	Air flow	1. Pitot tube 2. Heated element anemometer
(D,P)	Differential pressure	1. Liquid-filled point-gage manometer 2. Electronic micromanometer
(D)	U, Th, K in soil	1. Field-based γ-spectrometer 2. Lab-based γ-spectrometry
(D)	Rn emanation rate	Lab-based charcoal adsorption and γ-spectrometry
	Soil grain size	Mechanical sieve; liquid suspension
(P)	Soil moisture	Tensiometer probe
	Temperature	Hg thermometers

Note: Some devices or methods were also useful during pre-mitigation diagnostic procedures (D)[b] or in post-mitigation system evaluation (P)[a].

Table III. Outline of general diagnostic procedures for premitigation diagnostics.

I. Characterize structure and identify soil gas entry points
   A. Identify potential entry locations: conduct visual inspection
   B. Alpha-scintillation cell air grab sample survey of radon:
      - under natural conditions and mechanically depressurized
      - from building zones, likely entry points, soil probes, test holes
   C. Soil gas movement:
      - measure and/or observe soil gas flow at likely entry points, test holes
   D. Air infiltration leakage area:
      - blower door measurement of superstructure, substructure, whole house
      - identify bypasses to upper floors
      - infrared scan to locate leakage points (PU/ORNL only)
   E. Subsurface or near-surface air flow communication:
      - industrial vacuum to induce flows below slabs and within walls
      - measure extent of air flows
   F. Effects of appliance operation on substructure depressurization
   G. Characterize near-house soils:
      - on-site soil air permeability
      - emanating radium of soil sample

II. Measure radon in water
   A. Water grab sample for gamma spectrometric analysis
   B. Closed bathroom, shower operating, room air grab sample

III. Radon flux from building materials
   A. Charcoal adsorption from earth-based construction materials (LBL only)

Table IV. Post-mitigation diagnostics and system optimization.

I. Measure system operating parameters
   A. Temperatures and flow rates in ducts and pipes
   B. Differential pressures
   C. Radon concentrations in exhaust streams
II. Observe condition of system
   A. Materials
   B. Noise and vibration
III. Repeat pre-mitigation diagnostics measurements
   - alpha-scintillation cell air grab sample survey of radon
   - soil gas movement
   - subsurface or near-surface air flow communication
IV. Measure average indoor radon concentration
V. Modify or improve mitigation system
   - repeat post-mitigation diagnostic measurements
VI. Conduct long-term follow-up indoor air measurements

Table V. Significant mitigation techniques in order of deployment.

House			Mitigation Technique
PU/OR01	Δ	1.	SSV Depressurization
	Δ	2.	Block Wall Ventilation
		3.	Seal Cracks and Holes in Block Wall
		4.	SSV Depressurization with Drain Duct, Seal Sump and Weep Holes
		5.	SSV Pressurization with Drain Duct
PU/OR02c*	Δ	1.	SSV Depressurization
		2.	Seal Cracks and Holes
PU/OR03	Δ	1.	SSV Depressurization with Drain Duct, Sump Sealed
		2.	SSV Pressurization with Drain Duct, Sump Sealed
PU/OR04	Δ	1.	SSV Depressurization via Interior Drain Tile Ventilation
		2.	SSV Pressurization via Interior Drain Tile Ventilation
PU/OR05		1.	Basement Overpressurization
		2.	Seal Cracks and Holes, Perimeter Drain, Sump
	Δ	3.	SSV Depressurization with Perimeter Drain Duct, Sump Sealed
PU/OR06		1.	AAHX Ventilating both Basement and Crawlspace
	Δ	2.	SSV Depressurization in both Basement and Crawlspace
		3.	Wall Depressurization in Basement
		4.	Seal Cracks and Holes and Sump
PU/OR07	Δ	1.	SSV Depressurization with Drain Duct in both Crawlspace and Basement
		2.	SSV Pressurization wth Drain Duct in both Crawlspace and Basement.
LBL08		1.	SSV Depressurization
		2.	SSV Pressurization
		3.	Seal Floating Slab Drain
		4.	Low-Pressure SSV Depressurization with Drain Duct
	Δ	5.	Seal Cracks and Holes
	Δ	6.	High-Pressure SSV Depressurization with Drain Duct

Table V. (continued)

LBL09		1.	AAHX Ventilating Both Basement and Crawlspace
		2.	AAHX Ventilating Crawlspace Only
	Δ	3.	AAHX Ventilating Basement Only
		4.	SSV Depressurization
	Δ	5.	SSV Depressurization and Interior Drain Tile Ventilation
	Δ	6.	Seal Cracks and Holes
LBL10	Δ	1.	SSV Depressurization of Slab-on-Grade
		2.	SSV Pressurization of Slab-on-Grade
		3.	Block Wall Ventilation
	Δ	4.	Seal Cracks and Holes
LBL11		1.	SSV Depressurization
		2.	SSV Pressurization
		3.	Seal Floating Slab Drain
	Δ	4.	SSV Depressurization with Drain Duct
		5.	Low-Pressure Basement Overpressurization
	Δ	6.	High-Pressure Basement Overpressurization
	Δ	7.	Seal Cracks and Holes
LBL12	Δ	1.	SSV Depressurization
		2.	SSV Pressurization
		3.	Low-Pressure Basement Overpressurization
	Δ	4.	Seal Cracks and Holes
LBL13	Δ	1.	SSV Depressurization
		2.	SSV Pressurization
	Δ	3.	Seal Cracks and Holes
LBL14c*		1.	Seal Open Block Wall Cavities
	Δ	2.	SSV Depressurization

Δ Those mitigation techniques involved in routine system cycling.
* Control home mitigation system installed in July 1987.

Table VI. Summary of basement radon concentrations before and after mitigation (in pCi/L). (Except as noted, data are through April 1987).

	Baseline		SSV Only							Base. Pressure[b]	
			Depressure[a]		Pressure	Depress & Drain[a]					
House I.D.	Pre-Seal	Post-Seal	High	Low		High	Low	AAHX	Block Wall	High	Low
PU/OR01	37.2		7.6		2.3	0.2					
PU/OR02c	20.0[c]		0.8[c]								
PU/OR03	171.0	124.0				0.9					
PU/OR04	55.9		4.1		27.9						
PU/OR05	59.6	54.7				0.7					45.2
PU/OR06	50.0		3.4					19.9			
PU/OR07	33.4		0.7		22.9						
LBL08	70.4	26.2		24.0	58.9	2.8	5.0				
LBL09	28.4		4.4					16.3			
LBL10	209.7	145.9		3.5	52.0				3.2		
LBL11	36.5	27.9			16.2	2.7				1.5	7.3
LBL12	63.6		4.0	4.2	36.5						24.1
LBL13	83.8		1.6		42.1						
LBL14c	23.0		<2								

[a] "High" pressures are pressure differences at the SSV pipe more negative than -125 Pa, "low" pressures are those less negative than -125 Pa.
[b] "High" overpressures are those basement-to-outdoor pressure differences greater than +2 Pa, "low" pressures are those less than +2 Pa.
[c] August 1987 data

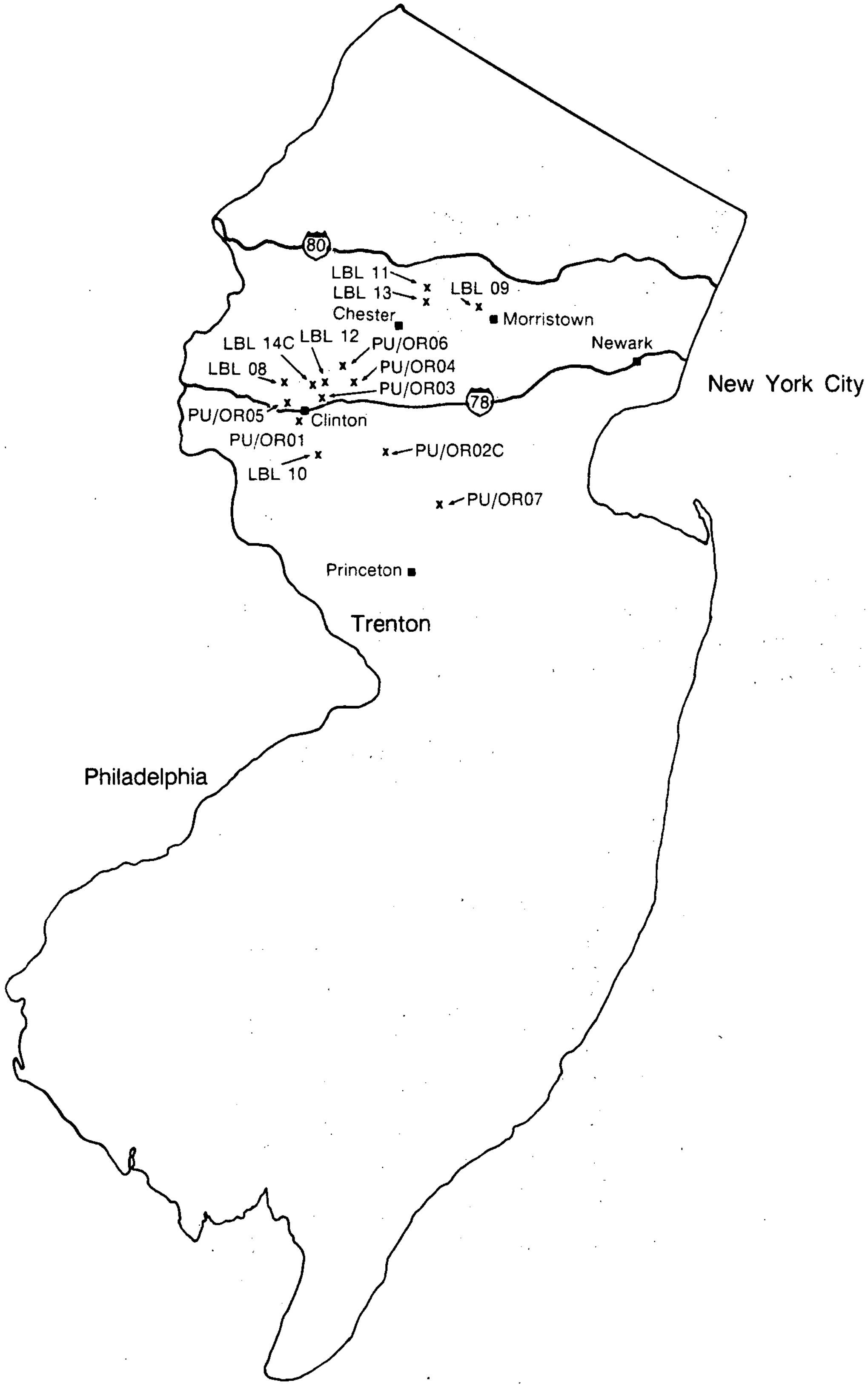

Figure 1. Location map of study homes in New Jersey. XBL 883-10103

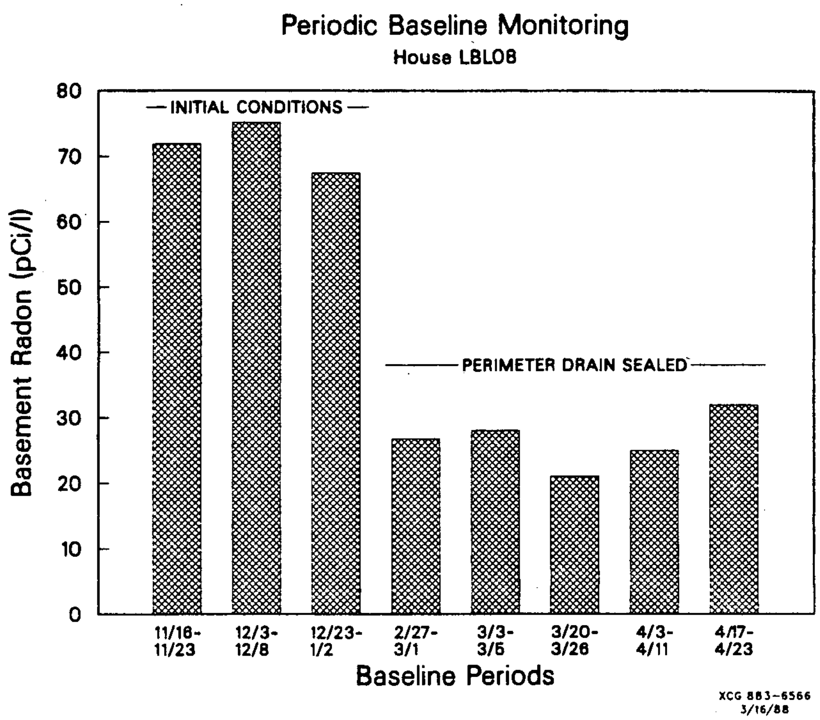

Figure 2. Baseline radon concentrations in the basement for LBL08. Note the decrease in the concentrations after the french drain was covered over. Each bar represents an average of approximately six days of continuous data.

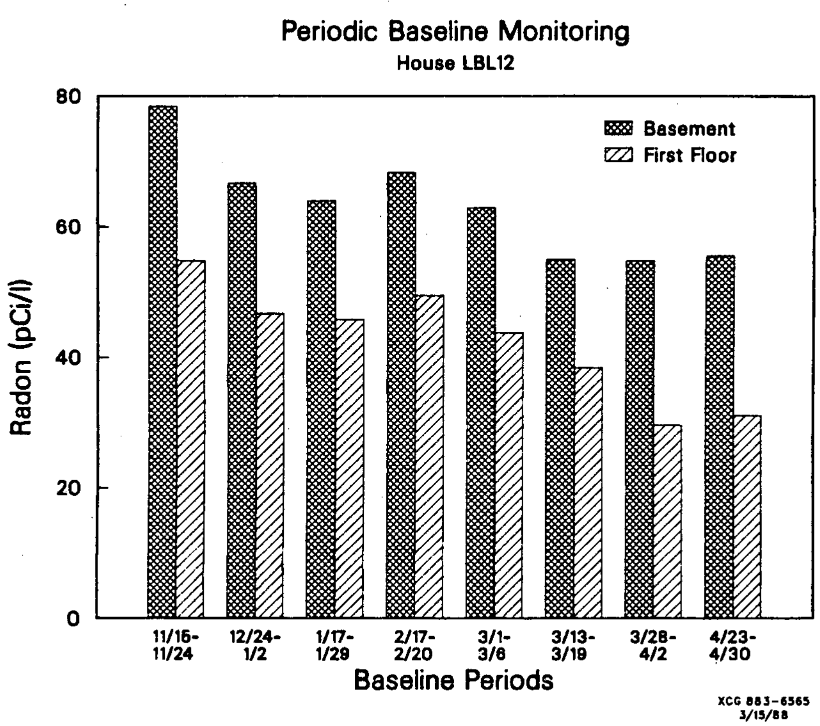

Figure 3. Baseline radon concentrations for LBL12. Falling radon levels throughout the heating season are typical, but not always the case, for the other homes.

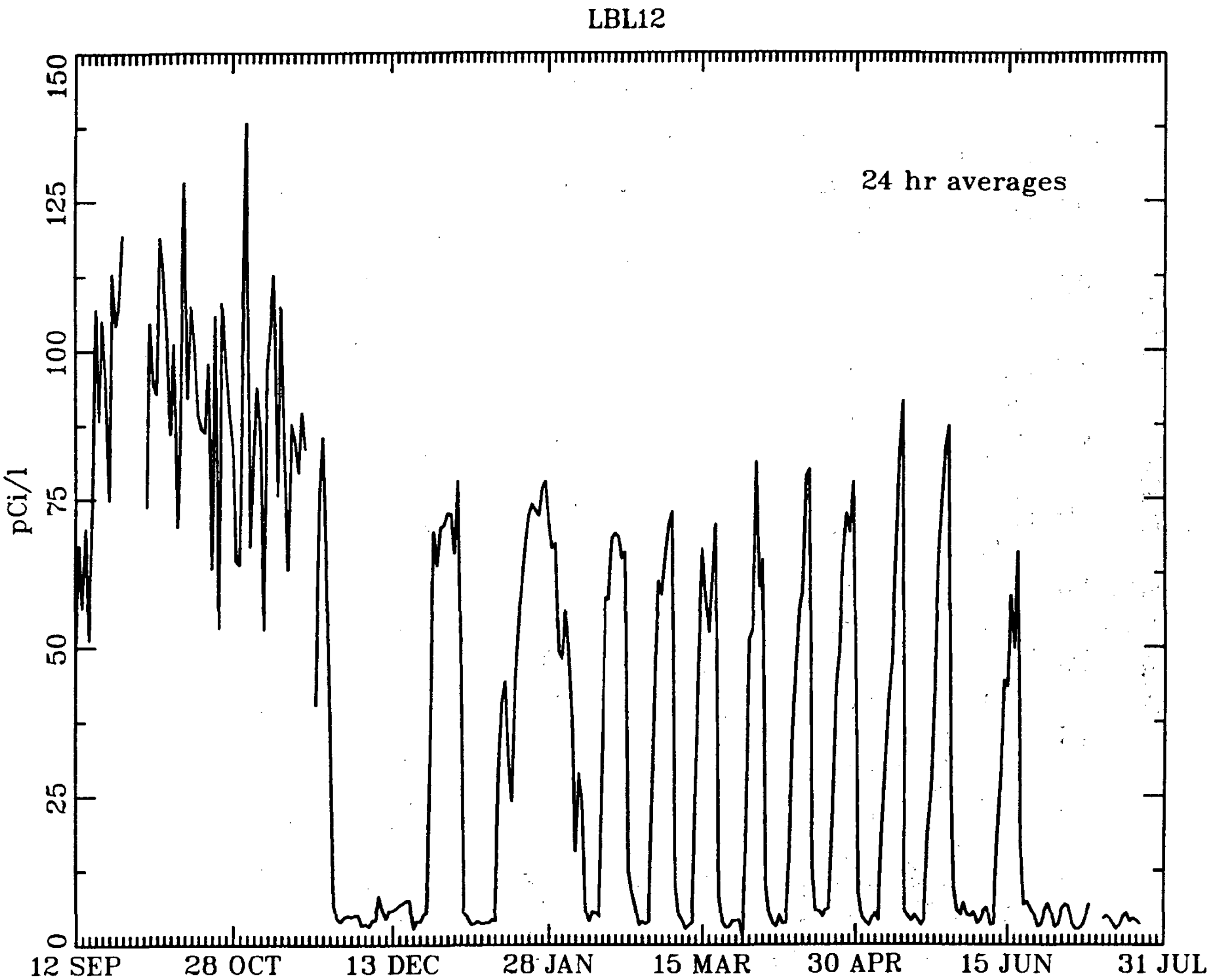

Figure 4. Basement radon levels from September 12, 1986 through July 1987 for house LBL12. The data have been averaged over 24 hours. The periodic spikes are due to the weekly cycling of the SSV mitigation system which began February 23 and continued through June 25, 1987.

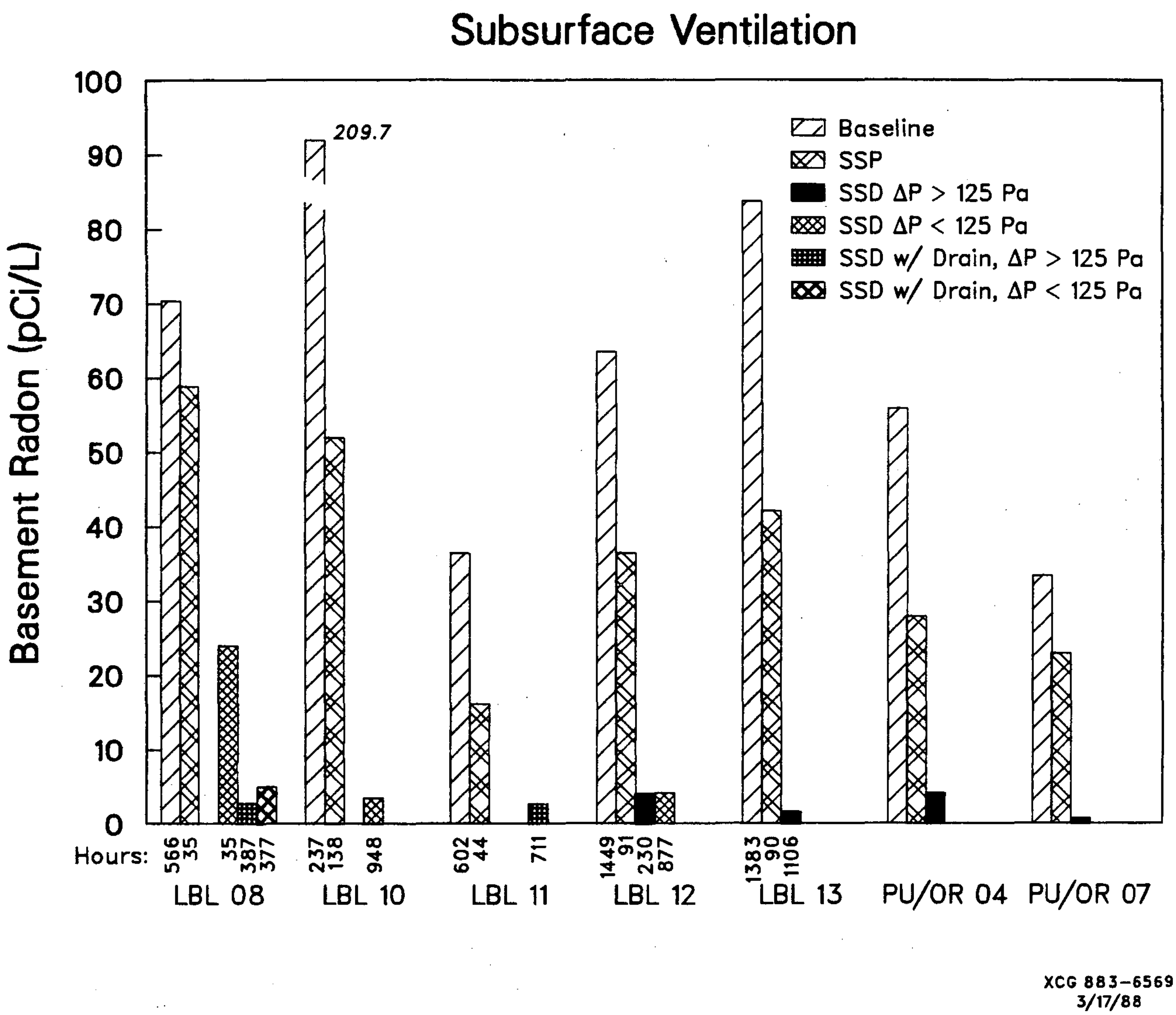

Figure 5. Reductions in basement radon levels following mitigation with subsurface ventilation. Subsurface depressurization (SSD) was always more effective than subsurface pressurization (SSP). Increasing the pressure difference tended to lower levels, but attaching the system to a sealed perimeter drain (french) duct was even more effective.

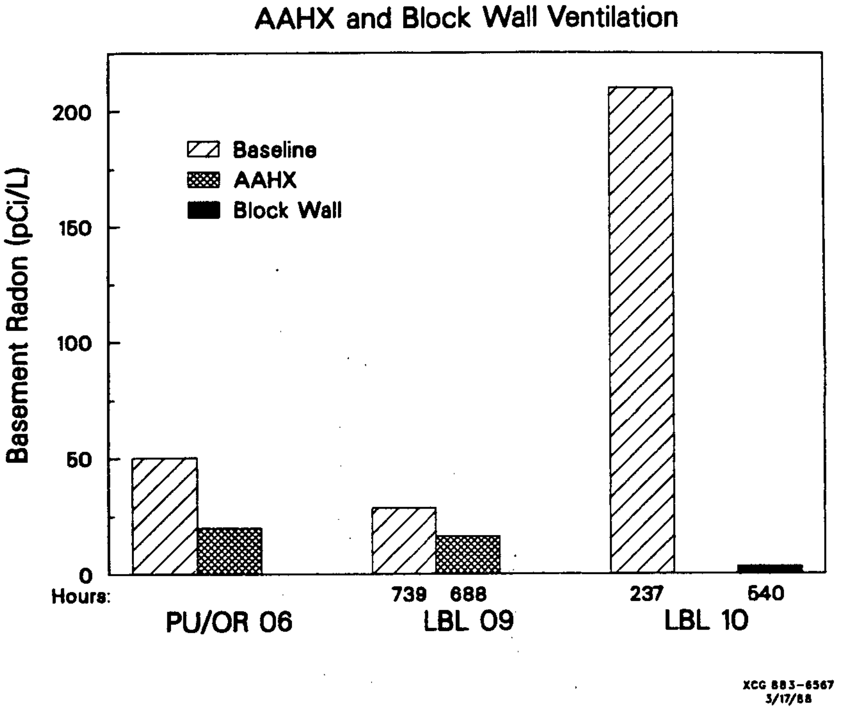

Figure 6. Reductions in basement radon concentrations due to operation of an AAHX in LBL09 and PU/OR06 and block wall ventilation in LBL10. The AAHX performed as expected, with levels reduced by an amount expected from the additional ventilation, but still higher than the target concentration. The block wall ventilation was as effective in reducing radon concentrations as an SSD system (see Figure 5).

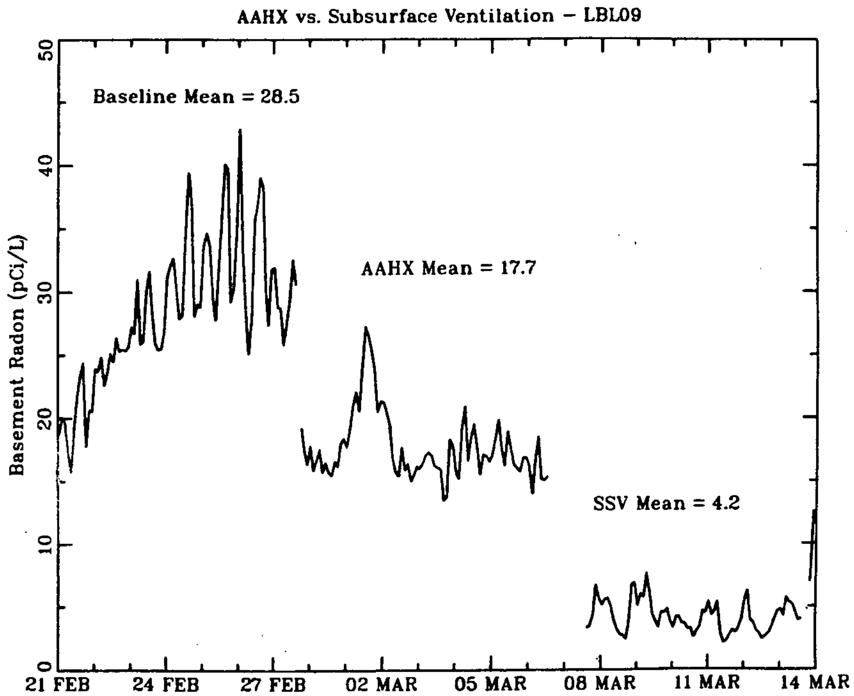

Figure 7. Comparison of the performance of AAHX and basement SSD systems in LBL09. A SSD system was also added to the crawlspace to bring final concentrations below 4 pCi/L.

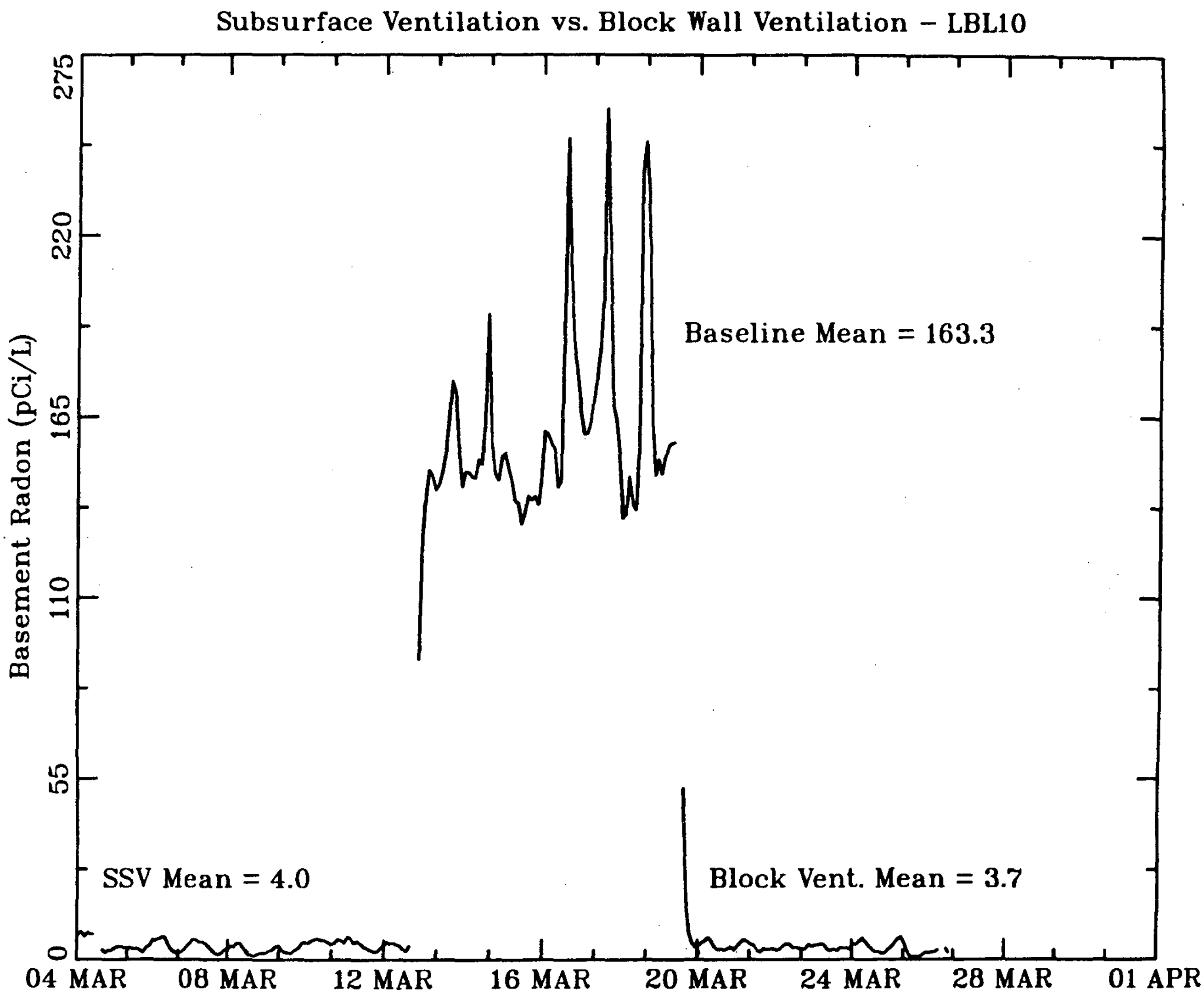

Figure 8. Comparison of block wall and SSD systems in house LBL10 during a four-week period. Performance of the two systems is almost identical.

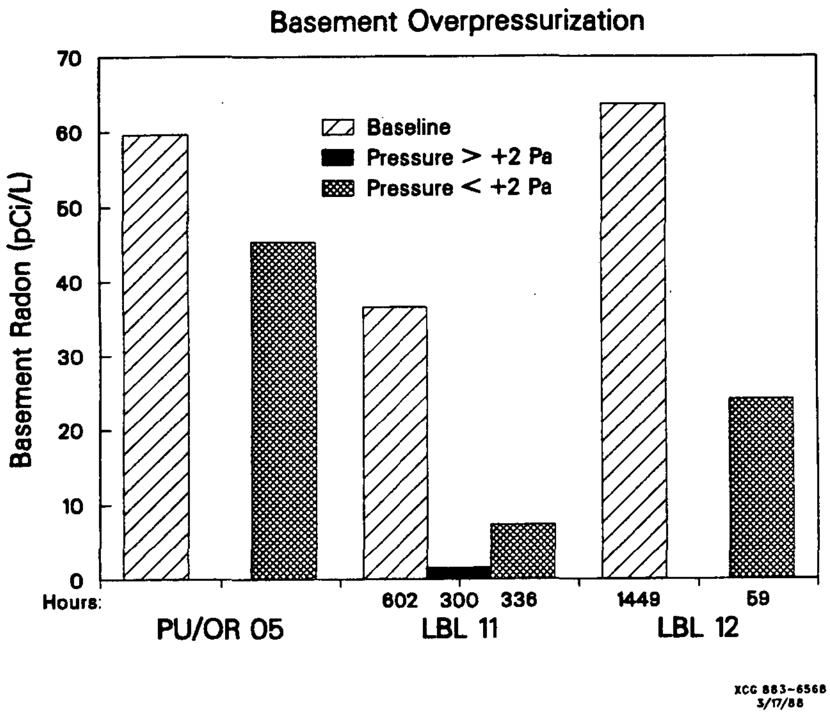

Figure 9. Reductions in basement radon levels due to basement overpressurization in three homes. Only when sufficient overpressures were achieved, did radon concentrations fall below target levels, as in the case of LBL11.

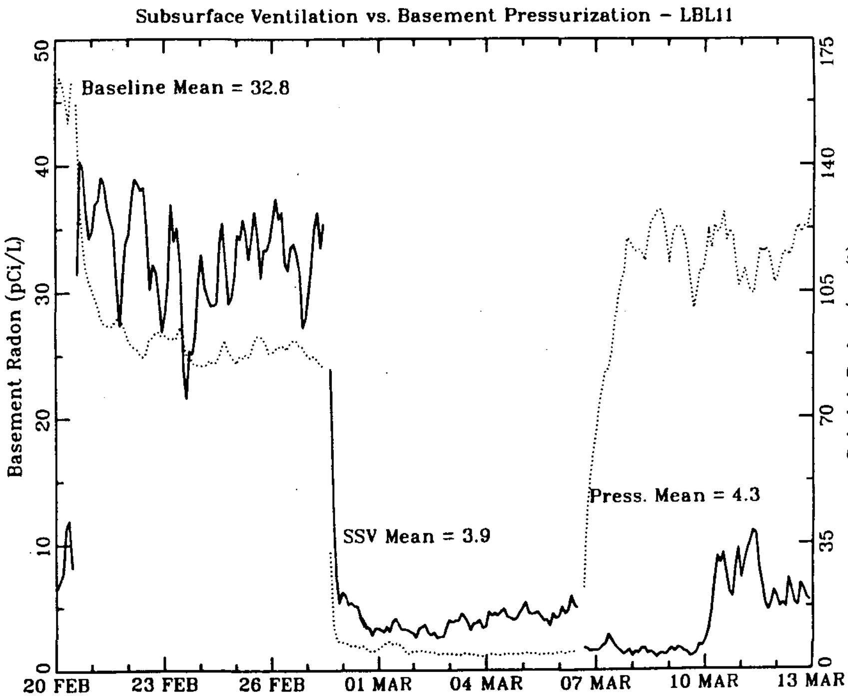

Figure 10. A comparison of the effectiveness of subsurface depressurization and basement pressurization in LBL11. Note that although indoor radon levels are low with both systems, the subslab soil gas radon concentrations (dotted line) remains high during basement pressurization. The average basement overpressure was approximately +1.2 Pa. The greater variability in radon levels during basement overpressurization result from the sensitivity of radon entry rates to basement pressures, which are, in turn sensitive to ΔT and windspeed.

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