LBL-27520
Preprint

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

To be submitted to Energy and Buildings

Performance of Radon Control Systems

B.H. Turk, J. Harrison, and R.G. Sextro

June 1989

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

To be submitted to *Energy and Buildings* LBL-27520

PERFORMANCE OF RADON CONTROL SYSTEMS

Bradley H. Turk, Jed Harrison,* and Richard G. Sextro

Indoor Environment Program
Applied Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

June 1989

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Buildings Systems Division, by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098, and by the U.S. Environmental Protection Agency (EPA) through Interagency Agreement DW89931876-01-0 with DOE.

*Current Address: Office of Radiation Programs, U.S. Environmental Protection Agency, 401 M. Street SW, Washington, D.C. 20460

ABSTRACT

Of five types of radon control techniques installed in seven New Jersey houses with basements, systems based on subsurface ventilation (SSV) by depressurization were the most effective and suitable for the long-term reduction of indoor radon levels. Small seasonal variations in substructure radon levels were observed in several houses while SSV systems were operating and may be due, in part, to changes in substructure ventilation rates from below 0.2 h^{-1} *to approximately 0.4* h^{-1}*. Effective permeabilities for near-house materials measured at SSV pipes were an order of magnitude larger (GM of* 4.1×10^{-9} m^2*) than the permeabilities of surrounding soils (GM of* 1.5×10^{-10} m^2*). Below-grade substructure surfaces appeared to have large air leakage areas as indicated by high entrainment fractions (0.41 to 0.92) of basement air in SSV exhausts. These leakage areas probably increased the effective permeabilities and influenced SSV flows and pressure field extensions. By sealing accessible leakage openings, greater depressurization below the slab during SSV operation was achieved in several houses, although indoor radon levels were not affected. In two houses, heating and cooling air distribution equipment caused additional substructure depressurizations ranging from 1.1 Pa to 5.4 Pa, but did not compromise radon reduction by SSV systems. Installation costs for SSV systems averaged $2270, while estimated annual energy costs to operate fan-driven radon control systems ranged from $85 for houses with oil heat to $250 for electrically-heated houses.*

1. INTRODUCTION

While a number of radon control techniques have been developed, tested and implemented [1, 2, 3, 4, 5, 6, 7], few studies have reported on the comparative and/or long-term performance of such systems [8, 9]. Radon entry into homes with elevated indoor radon concentrations is dominated by pressure-driven flow of radon-bearing soil gas. The pressure gradients are, in turn, driven by the effects of thermal differences, wind or mechanical systems; all of which may vary with time. Hence, the effectiveness of mitigation methods may also vary, due to daily or seasonal changes in environmental factors or in the operation of the building and mechanical systems within it. These mitigation methods usually lower indoor radon levels, however, the final time average concentration is not always below, or does not remain below, the U.S. Environmental Protection Agency's (EPA) guideline of 148 Bq m^{-3} (4 $pCil^{-1}$) for annual average concentrations [10, 11]. Therefore, this study was devised, as part of a larger research effort in seven New Jersey houses [12] to monitor the performance of various radon control strategies over an extended period. Continuous and periodic multi-parameter data were collected as mitigation systems were cycled on/off.

Periodic cycling of the mitigation systems allowed comparisons to be made between alternative mitigation systems at each house and observations of the relationships of system performance to several factors. These factors included indoor-outdoor temperature differences (ΔT), pressure differences (ΔP), ventilation rates, sealing of openings in the substructure surfaces, and operation of forced-air heating and cooling (HAC) equipment. In addition, seasonal changes in baseline (non-mitigated) radon levels could be monitored in order to provide a better means of evaluating system performance.

2. METHODS

Seven houses in north-central New Jersey were selected for the study on the basis of their elevated indoor radon levels, representative construction types, ease of access, and willing participation by the homeowners. All houses had basements with hollow block walls of concrete or cinder, while several houses also had slabs-on-grade or crawlspaces adjoining the basements. Except for two houses (LBL11 and LBL12*), all houses had an aggregate layer under the basement slab floor, while no aggregate was found under the slab-on-grade floor or slab floors in crawlspaces. A mitigation system was installed in the one control house (LBL14C) near the conclusion of the study. Generally, monitoring began in September 1986 and continued through September 1987. Residents were asked to keep basement doors and windows closed throughout the study, but occasionally opened windows on the upper floors during spring, summer and fall months. Additional information on the houses and radon control systems is presented in Table 1.

Control Techniques

Research diagnostic procedures were performed at each house to identify the significant source(s) of indoor radon and to assist in the selection and design of the radon control systems [13]. Examples of the procedures include blower door tests, subslab pressure field extension tests, and radon grab sampling. Radon entry with the pressure-driven convective flow of soil gas through cracks, openings and porous block walls in substructures was determined to be the most significant source of radon - as in most other houses with elevated levels of indoor radon.

Five basic radon control techniques, that were considered viable for reducing indoor radon concentrations below the 148 Bq m^{-3} objective, were installed and evaluated in at least one house (Table 1). Techniques were chosen for each house to be economical and suitable for effective control of radon, and for comparisons with competing systems in the same house. More detailed descriptions of these techniques can be found elsewhere [4, 5]. Following are the techniques that were evaluated.

Subsurface ventilation (SSV): A subsurface ventilation system, or a variant, was installed in every house to reverse the normal pressure gradient that encourages soil gas and radon to enter the building. Schedule 40, 7.6 cm (3") diameter PVC pipe was ducted to penetrations through the slab floors at one to three locations. Below the penetration, a 0.2 m^3 pit was usually

*The houses were numbered sequentially from LBL08 to LBL14.

excavated and filled with gravel to improve distribution of the pressure field. The pipes were connected to in-line fans capable of developing 13×10^{-2} m^3/s (270 CFM) of free air flow and 400 Pa pressure head. These SSV systems either depressurized the zone below the slab (SSD) and exhausted soil gas to the outside, or pressurized the subslab zone (SSP) with outside air. In two houses (LBL08 and LBL11), the SSV pipe was attached to a perimeter drain duct that had been created by plugging the top 2 to 4 cm of gap formed by an existing interior perimeter drain ("french drain") with foam rod and then sealing the plug against air leakage with flowable urethane caulk. (A perimeter drain is a 2 to 4 cm wide slot in the slab at the perimeter of basement floor that permits water and condensate to drain to the soil.) This procedure left an approximately 6 cm high and 2 to 4 cm wide open channel beneath the seal. At LBL09, one pipe of a three-pipe SSV system was connected to an existing subslab drainage pipe (footer drain) that paralleled the interior side of the footer. The length and configuration of this drainage pipe was unknown.

Block wall ventilation (BWV): The SSV systems in two houses (LBL10 and LBL12) were modified to ventilate the interior cavities of block walls by inserting pipes into the blocks and exhausting the air inside the cavities to outside. Large openings through the interior surfaces of the walls were also sealed to increase the effectiveness of the system.

Air-to-air heat exchanger (AAHX): A ducted air-to-air heat exchanger was installed in the basement/crawlspace of LBL09 to remove and supply air from those spaces, while minimizing the energy lost in the exhausted air. The unit was sized to provide approximately 0.5 air changes per hour of additional ventilation to the entire house and thereby dilute the concentrations of indoor radon.

Basement overpressurization: In two houses, a separate fan was used to pull conditioned air from the upstairs and exhaust this air into the basement to create a slight overpressurization of the substructure. An overpressurization (i.e., on average, a greater than zero pressure difference between basement and outside) was desired to reverse even the large pressure gradients at radon entry locations caused by extreme environmental conditions (indoor-outdoor temperature differences and wind). In one house (LBL12), the basement pressurization fan was attached to the return air duct of the forced-air furnace, while in the other house (LBL11 - with a baseboard hot water heating system), the upstairs air was pulled directly through a duct in the basement ceiling. Air leakage pathways to the upstairs and exterior were also sealed to reduce the fan flow rate necessary to achieve overpressurization.

Caulking of cracks and openings: After mitigation systems in the six houses had been operating for several months, accessible cracks and openings in substructure surfaces were caulked with urethane and silicone sealants to reduce the area available for soil gas entry. Openings found in the tops of block walls in two houses (LBL08 and LBL14C) were closed with expandable polyurethane foam or aluminum sheet.

More than one type of control system was installed in four houses (LBL09, LBL10, LBL11, and LBL12). For comparisons with unmitigated baseline conditions and to improve the intercomparison among the control methods, all systems were cycled on/off for periods of approximately seven days in a rotation that included seven-day baseline periods without mitigation system operation. This permitted the performance of the control systems to be assessed by comparisons to pre-mitigation indoor radon levels for similar environmental conditions throughout the year. Dampers were installed in ducts and pipes, and speed controllers were attached to all fans. These devices permitted flows and pressures to be modulated, and switching from one system to another (e.g., SSV to BWV, or vice versa). As the study progressed, systems were modified for experimental purposes and to improve their effectiveness at reducing indoor radon levels.

Measurement Procedures

Since the mitigation-related work in these seven houses was one part of a research project with multiple objectives, many variables were measured that were not directly related to the mitigation systems. These measurements are described by Sextro [12]. In all houses, indoor and outdoor temperatures, wind speed and direction, several pressure differences, and heating/air conditioning (HAC) blower operation were monitored every minute to produce 30-minute averages that were stored by an on-site data logger. Integrated circuit temperature sensors (LM35), accurate to within ± 1°C, were located on each floor of the buildings, in other unique zones (crawlspaces, garages, etc.), in the outside air at a height of approximately 3 m above grade, in the soil adjacent to the substructures, and in the SSV pits below the slab floors. Wind speed and direction were monitored at the top of a 10 m high meteorological tower at each house. Pressure differences were measured across the basement slab floors, between the basement and first floor (across the basement ceiling), and between the basement interior (at floor level) and 2 m from the exterior of the house approximately 10 cm below the soil surface (to dampen wind gusts). The differential pressure sensing device was a variable capacitance transducer (± 60 Pascal, Setra Model 264) with a minimum detection limit of 0.5 Pa and an accuracy of ± 1% of full scale. Measured pressure differences (ΔP) were corrected for the weight of columns of air in over the vertical sections of the tubes. A sail switch was placed in the supply air plenum of each forced-air HAC system to record blower on-time. Pulses from continuous radon monitors (CRM) were summed over the same 30-minute period and recorded by the data logger. These CRMs continuously passed filtered air through an alpha scintillation cell, and had an accuracy of ± 10%. Continuous samples were typically drawn from central locations at mid-height in the basement and on the first floor, and from a single location directly below the basement slab floor.

Other parameters were measured periodically throughout the study. As an indirect indicator of soil moisture, and therefore of permeability to air flow through the soil, precipitation was accumulated for approximately seven-day periods and continuously at one location throughout the study. Time-integrated water vapor concentrations in the air were measured outside and at several indoor locations for the same periods using passive diffusion sampler tubes. These samplers, which are analyzed gravimetrically, were accurate to within ± 10% [14]. Beginning in March, time-average ventilation rates were also measured (with an uncertainty of approximately 30%) over the seven-day periods using two-tracer (SF_6 and freon 13B1) constant injection and sampling systems for the separate zones represented by the substructures and upper floors. Only the substructure ventilation rates were measured during the summer when upstairs windows and doors were open. Energy consumption for the fans of mitigation systems was measured over two to seven-day periods with an inductive watt-hour meter. To assist in the evaluation of mitigation system performance, a series of measurements, similar to those conducted during diagnostics prior to mitigation [13], were made periodically following installation of the radon control systems. Approximately 30 test holes (approximately 9 mm in diameter) were drilled through slab floors and exterior walls, and into the cavities of hollow block walls at each house. At these holes, and in the ducts and pipes of the systems, (1) grab samples of air were collected in evacuated alpha scintillation cells to measure radon concentrations (± 25% uncertainty), (2) chemical smoke identified the direction of air flow through the holes, and (3) a hot wire anemometer with a flow adaptor quantified the air velocity during baseline periods and with the radon control systems turned on.

Since the study was completed, alpha track detectors have been periodically mailed to the homeowners for placement on different levels of each house. These detectors have been analyzed by a commercial laboratory with measurement uncertainties reported to range from a bias of 0.91 with a coefficient of variation (CV) of 16% [15] to a bias of 1.32 with a CV of 59% [16].

3. RESULTS

Reductions in Indoor Radon Levels

As illustrated in Figure 1a, indoor radon levels during baseline periods (mitigation systems off) exhibited significant seasonal differences that are probably related to changes in ventilation rates, pressure differences (due to variable temperature differences and wind), and soil conditions. Figure 1a also illustrates that sealing of minor cracks and openings in the substructure walls and floors often has little observable effect on baseline radon levels. Only when much larger areas of cracks and holes were sealed, as in Figure 1b (LBL08) where approximately 1.5 m^2 of open sump and perimeter drain were sealed (approximately 1% of basement floor area), were baseline radon levels significantly reduced.

The data in Table 2 have been aggregated to compare periods of mitigation with baseline periods of the same season(s) and of the same conditions of crack and opening sealing. In every instance, operation of the radon control systems reduced indoor radon levels. However, those techniques that provided the largest and most reliable reduction were the SSD and block wall ventilation systems. For houses where SSD and basement pressurization systems were operated at both low and high pressures (SSD - LBL08, LBL10, LBL12, LBL13; basement pressurization - LBL11 and LBL12), the higher pressures (except in the SSD systems at LBL12) caused greater drops in indoor radon levels. Connecting perimeter drain ducts to SSD systems also improved the effectiveness of the systems (LBL08 and LBL11) presumably by extending the pressure field to locations at the edge of the slab floor where soil gas was entering. SSD systems were more effective than comparable SSP systems (LBL08 through LBL13) and more effective than a competing AAHX (LBL09).

As seen in other studies, the effectiveness of basement overpressurization is related to the level of overpressurization. For example, in LBL11 only after a larger fan (15×10^{-2} m^3/s) was installed that was capable of developing overpressures of approximately +5 Pa, were indoor radon levels reduced below the target concentration. In contrast, this technique was not effective in LBL12 because overpressurization was never achieved (indoor-outdoor ΔP = -0.6 Pa) due to air leakage between the first floor and basement through the existing HAC ductwork.

The AAHX reduced radon levels by an amount expected from the additional ventilation. However, to achieve our target concentrations, it was necessary to subsequently install an SSD system. Long-term reductions in indoor radon levels are shown on Table 3. Unfortunately there is considerable uncertainty inherent in the alpha track detectors used in the follow-up study, especially at the low concentrations after successful mitigation. Therefore, increases in indoor radon levels above our objective in three houses (LBL08, LBL11, LBL12) during the two follow-up heating season periods may not be statistically significant. Because of design flaws in LBL11, shifting and settling of the foundation is causing new and repaired cracks in substructure surfaces to open up. These openings could impair the performance of the mitigations system and could be responsible for the increase in indoor radon levels. In all cases, indoor radon concentrations remain far below pre-mitigation levels.

Relating SSV Performance to Other Factors

Since SSV is usually the most successful system in controlling indoor radon, we examined the interaction of its operation and performance with several environmental parameters and house characteristics in more detail. The flows and pressure fields developed by an SSV system depend on the "effective" permeability of soils and aggregate near the substructure, and to a lesser extent on the permeability of undisturbed soils surrounding the house. Materials near the below-grade exterior surfaces of the substructure often have higher permeability to soil gas flow because of: (1) the material size (e.g., aggregate), (2) less tight packing (e.g., loosely compacted backfills), and (3) the presence of air gaps caused by expansion/contraction cycles and settling of soil. By applying the equation used to calculate *in-situ* soil permeability at small soil probes [17], to the flow and pressure data collected at the SSV pipes, "effective" permeabilities were calculated for the near-house region

$$k = 2.5 \times 10^{-11} \frac{Q}{rP} \text{, where} \quad (1)$$

k = effective soil air permeability (m^2),
Q = flow rate ($l\ min^{-1}$),
r = pipe radius (0.04 m), and
P = pipe pressure (Pa).

This equation is based on the assumption of a spherical cavity of radius *r* at the end of the pipe or probe surrounded by homogeneous material with a spatially uniform permeability and, thus, does not account for nearby floors and walls. The geometric mean (GM) of the average effective permeabilities for below-slab SSV pipes at each of the houses was 4.4×10^{-9} m^2, or an order of magnitude higher than the GM permeability of the soils around these houses (approximately 1.5×10^{-10} m^2). For two SSV pipes which terminated immediately external to a hollow block wall (LBL10), the GM effective permeability was even higher, 16×10^{-9} m^2. This is consistent with other observations that hollow-block wall building materials have high permeabilities to air flow, and, thus, provide a possible low resistance entry path for soil air entering the substructure [18, 19].

To determine the amount of basement air that was entrained into SSD systems and exhausted to the outside, the concentration of ventilation measurement tracer gas in the SSD exhaust ducts was measured and compared to the tracer concentration in the basement air. These data, collected in five houses after caulking and sealing, indicate that approximately 40% (LBL12) to 90% (LBL11) of the air exhausted by these systems originated in the basement. When the data from similar tests in two Spokane, WA houses are included (40% and 80% [6]) the mean percentage for the seven houses is approximately 70%. Evidently a substantial area of air leakage exists in the below-grade substructure surfaces. This leakage area should have a significant effect on the flow resistance or effective permeability "seen" by the SSV systems. Figure 2 illustrates that the fraction of air in the SSD ducts that originated in the basement generally increases with effective permeability. The routine sealing of cracks and openings in the substructure surfaces at these houses had no significant impact on the effective permeability as shown for LBL12 in Figure 3. This suggests that we sealed only a small fraction of the leakage area between basement and soil (where the permeable block walls may have been responsible for much of the unsealed leakage area). In addition, a two-tailed T-test performed on data collected at eight SSV pipes at six houses showed no significant difference in the effective permeability before and after sealing of cracks and holes. With the exception of the large openings sealed at LBL08, there was also no significant change observed in indoor radon levels during SSD operation after crack sealing (Table 2). However, after crack sealing the ΔP across the basement slab floors increased significantly during SSV operation in three of the five houses where data were available (ΔP increases: LBL09 ~ 4 Pa, LBL12 ~ 11 Pa, LBL13 ~ 15 Pa). There were no large changes in SSV pipe pressures during this period, but it is possible that changes other than crack sealing (e.g., decreased permeability of the soil) could have caused the ΔP across the slab to increase. Although other workers have observed that periods of precipitation correlate with higher pressures and lower flows in the SSV pipes, and brief increases in indoor radon levels [20], we observed no correlation between effective permeability and daily average precipitation (calculated from weekly total precipitation) for six of these houses.

Radon levels in the basement and SSD exhaust air were compared with ΔT and ΔP data at several houses while the SSD systems were operating (Figure 4). SSV exhaust radon levels usually correlated with the diurnal changes in ΔT and indoor-outdoor ΔP. For example, the correlation coefficients for the 147 measurement periods in Figure 4 were significant at $P << .01$; $R = 0.57$ and $R = -0.66$, respectively, but these correlations are not explained. If basement radon levels demonstrated cyclic changes, these were also usually in step with the variations in ΔT and ΔP.

It has been suspected that SSD systems lower indoor humidity levels by reducing the entry rate of water vapor carried along with soil gas. In a multiple linear regression, basement water vapor concentrations were regressed on outdoor water concentrations and SSD operation for 210 measurement periods in all houses. The results [$C_{bsmt} = 0.66 (C_{out}) - 0.13 (SSD) + 2.49$; where C_{bsmt} = basement water vapor concentrations (g-H_2O vapor/kg-air), C_{out} = outside water vapor concentrations, and SSD = SSD systems on/off] showed that SSD operation had a statistically insignificant effect ($t = 0.8$, $p = 0.40$) on basement water vapor concentrations. Variations in outdoor water vapor concentrations explained 84% of the variation in indoor levels, while occupant activities presumably accounted for most of the remaining variation. A simple psychrometric calculation corroborates these findings. By stopping the entry of 10 m^3h^{-1} of soil gas at 15°C and 100% relative humidity (RH) into a 600 m^3 house at 20°C and 40% RH, the indoor water vapor concentration is reduced by on approximately 0.18 g kg^{-1} and the RH by 2%.

Where HAC air distribution equipment and/or HAC ductwork is located in the substructure, radon from the substructure is more readily distributed throughout the upper floors of the house, and additional depressurization of the substructure can occur during operation of the HAC blower [21, 22, 6]. Substructure pressures can become more negative because of leaks in the substructure return-air ducts and plenum, or because of unbalanced air distribution caused by closed supply-air diffusers in the basement. During initial diagnostic tests, two houses were identified where HAC blower operation created significant additional basement depressurization [14]. To determine the effect of this blower operation on the pressure differences driving soil gas entry, multiple linear regressions were run on continuous data for approximately one-week periods in the winter and summer. The regression model variables were ΔT, basement-outside ΔP, slab floor ΔP, and blower on-time (%). The data include periods when the doors to the basements were open. Table 4 shows that these models are often uncertain, having low coefficients of determination (R^2). However, they do suggest (as a best, but uncertain estimate) that if the HAC blowers were on continuously (100%), additional depressurizations of 0.4 Pa to 1.1 Pa and 0.3 Pa to 2.3 Pa would be developed across the slab floors of LBL09 and LBL13, respectively. The greater additional depressurization in the summer for LBL13 resulted from removing the cover of the return air plenum of the air conditioner in the basement. The total additional basement-outside ΔP ranged from 1.1 Pa to 5.4 Pa and compares to the additional depressurization measured during the diagnostic test with the basement door closed (3.5 Pa to 4.8 Pa in LBL09 and 0.3 Pa to 8.0 Pa - for air conditioning in LBL13). The HAC blowers did not threaten the reversed pressure gradient developed by the SSD systems at the pressure measurement point on the floors in either of these houses. However, at the edges of the basement floors or in buildings where the SSD pressure field is smaller, the persistent additional depressurization of the HAC blower could cause radon entry into the structure. In the six houses with a forced-air HAC system, blowers operated approximately 20% to 30% of the heating season. Thus, these HAC systems would increase the time-average ΔP by only 20% to 30% of the values given above.

Slight increases (approximately 20%) in substructure radon levels from below to above 148 Bq m^{-3} were observed in two houses (LBL09 and LBL12) during SSD mitigation in late spring and summer. Substructure radon levels during these periods exhibited strong diurnal variations, with concentrations peaking at 220 Bq m^{-3} to 370 Bq m^{-3} between the hours of 0400 and 0700. Radon levels during the remainder of the day usually were well below 148 Bq m^{-3}. Since the best correlations of average substructure ventilation rates with average indoor-outdoor temperature difference were also at these two houses LBL09 ($R = 0.83$, $P < 0.01$); LBL12 ($R = 0.84$, $P < 0.01$), the increased indoor radon concentrations may have, in part, resulted from the reduced ventilation rates during the spring and summer. The substructure ventilation rates included infiltration of outside air directly into the substructures and mechanical ventilation from HAC blowers that mixed upstairs air into the substructure. The average on-time of the HAC blower also correlated with average ventilation rates for LBL09 ($R = 0.92$, $P < 0.01$), and LBL12 ($R = 0.83$, $P < 0.01$).

Ventilation rates in the substructures were quite low for periods with small ΔT, but varied considerably over time. For LBL09, the GM ventilation rate was 0.38 h^{-1} (with a minimum of 0.27 h^{-1}) for ΔT less than 5°C, and 0.83 h^{-1} for ΔT greater than or equal to 5°C. For LBL12, the GM ventilation rates were 0.22 h^{-1} (with a minimum of 0.12 h^{-1}) and 0.39 h^{-1}, respectively. For six of the houses (including LBL09 and LBL12), the GM substructure ventilation rate was 0.41 h^{-1} for periods when the average ΔT was less than 5°C and 0.60 h^{-1} for periods when the average ΔT was greater than or equal to 5°C. Substructure ventilation rates were less than or equal to 0.20 h^{-1} for approximately 50% of the measurement periods at LBL11 and approximately 40% of the periods at LBL12.

In general, correlations between substructure ventilation rates and radon levels were poor, but may also be in error because the measurement uncertainties are large in comparison with the values being measured. Nonetheless, these data illustrate the potential pitfall of short-term measurements of post-mitigation radon levels if the ventilation rates may be substantially different than at other times of the year.

Attempts to identify other key parameters that substantially influence SSV performance were not successful. Flows, ΔPs, and radon concentrations at test holes, precipitation, and snow cover did not exhibit significant relationships to radon concentrations in the indoor air or SSV pipes, or to flows and pressures in the SSV pipes. However, because the measured values of some of these parameters were very small (near to the lower detection limits) and uncertain, the impact on SSV performance may have been difficult to establish.

<u>Installation and Energy Costs</u>

From detailed cost sheets that were completed by the mitigation contractors, the installation costs for each primary control technique were summarized in Table 5. The research perspective of this study may have resulted in slightly higher total costs because of additional modifications, and more demanding specifications for assembly and materials. The average total cost of $2270 for the SSV systems was higher than for other techniques, but resulted in more effective radon control. The cost per unit of treated floor area (total cost divided by the floor area of the substructure zone affected by the control technique) averaged $27 m^{-2} for the SSV systems.

Energy costs to operate the control systems were estimated for five houses based on the energy usage of the fans, calculations of the energy lost due to the additional ventilation caused by the systems, and climatological data and current costs of electricity and heating oil. The additional ventilation was calculated from the air flow rates in the systems and the fractions of air in the SSD exhaust ducts that originated in the basement. These cost estimates are shown in Table 6. The power for eight SSV system fans ranged from 61 to 84 watts and averaged 72 watts. At high speed, the fan power was 122 watts for the AAHX and 137 watts for the basement pressurization system at LBL11. We assumed that the fans operated throughout the entire year, while the energy penalty associated with additional ventilation would increase costs during only a September - May heating season. Although four of the houses had central air conditioning systems, the systems were used infrequently - therefore, additional cooling costs were not calculated. Total estimated additional energy costs ranged from $85 y^{-1} to $170 y^{-1} for houses with oil heat and $130 y^{-1} to $250 y^{-1} for all-electric houses. Energy costs for the house with the AAHX were competitive with energy costs in houses with SSD systems, due partly to the high energy exchange (recovery) efficiency (0.72) calculated from the measured flows and temperatures in the AAHX. Energy costs were not calculated for the basement pressurization systems, because of uncertainty in estimating any additional ventilation.

4. DISCUSSION AND SUMMARY

This study adds to the growing evidence that subsurface ventilation is often the most effective technique to reduce indoor radon levels. In general, these systems have continued to be effective for the 2 1/2 year period after completion of the initial research. In the depressurization mode, these systems reverse the natural pressure gradient across the substructure surfaces by creating lower pressures in the soils and aggregate surrounding the structure. Consequently, a greater vacuum in the SSD pipe or connection to distribution channels (perimeter drain ducts) extends the pressure field so that radon enters the interior space at fewer locations and/or less frequently. Sealing openings in the substructure surfaces below grade tends to increase the magnitude and spatial range of depressurization beneath the slab, although, with only one exception, no changes in indoor radon levels were observed during SSD operation, presumably because the pressure fields were sufficiently robust to control most of the radon entry before sealing.

The correlation between effective permeability and the fraction of air in SSD exhausts that originates in the basement indicates that the resistance to flow for SSV systems may depend, substantially, on the leakiness of below-grade substructure surfaces, and on the location of leaks and the permeability of materials near the exterior of these surfaces. Sealing of visible minor cracks and holes had no measurable effect on effective permeability possibly because: 1) the majority of the remaining substructure air leakage area is due to large areas of porous surfaces (e.g. block walls); to a large number of very small cracks and penetrations; or to undiscovered large openings that were not sealed; or because 2) the effective permeability is only affected substantially by the permeability of materials near to the SSV pipe and the presence of nearby cracks. If the situations in (1) are the explanation, considerable sealing effort would be required to cause significant improvements in SSV performance. More research on air movement through block walls and small cracks and openings in poured concrete surfaces is required along with a better understanding of the dependence of effective permeability on various factors.

In contrast with a study in Spokane, WA [7], subsurface pressurization proved to be much less effective than SSD in these NJ houses. A possible explanation for the difference is that radon concentrations in the soil gas around the NJ houses were much higher (ranging from 19,000 Bq m^{-3} to 3.7×10^6 Bq m^{-3}) than those in Spokane (ranging from 3700 Bq m^{-3} to

26,000 Bq m^{-3}). Thus, only in Spokane were SSP systems able to reduce radon concentrations in entering soil gas sufficiently for effective radon control.

Low ventilation rates were measured in substructures during periods of small indoor-outdoor ΔT in the spring and summer. These low ventilation rates may have been partly responsible for slight increases in basement radon levels during SSD operation in two houses. Therefore, ventilation rate is another variable that can significantly affect the results of short-term measurements of post-mitigation radon levels.

The operation of HAC system blowers can create significant additional depressurization in the substructures of some buildings. Since this additional depressurization could overcome the pressure gradient developed by an SSD system, SSD systems should be designed and tested with consideration given to HAC operation, or the HAC system should be modified to minimize the additional depressurization.

No relationships were observed in this study between operation of SSV systems and indoor water vapor concentrations, precipitation, snow cover, and flows, ΔPs and radon concentrations at test holes. However, with the exception of water vapor concentrations, physical models may be necessary to explain the subtle and complex relationships among these parameters and their effect on SSV operation.

Other radon control techniques were successfully applied in special circumstances. Block wall ventilation was as effective at lowering indoor radon concentrations as a competing SSD system in a house with block walls where large openings into the wall cavities were sealed. Basement pressurization was also effective where the basement was overpressurized by approximately 6 Pa, although satisfactory results have been achieved with a 3 Pa overpressurization [7]. This technique is recommended only for houses with relatively air leak-tight substructures without forced-air HAC systems and vented combustion appliances upstairs, and where SSV is not suitable. Poor appearance, excessive noise, the necessity of maintaining the air-tightness of the substructure, and increased air movement in the house (the average substructure ventilation rate increased from 0.22 h^{-1} to 1.7 h^{-1}) were important drawbacks to this technique.

Costs to install these mitigation systems were, on average, slightly higher than in other studies and surveys [10, 7] and within the range of costs for other house maintenance and repairs (roofing, painting, remodeling, etc.). The annual cost of energy to operate the fans and heat additional ventilation air is not prohibitive ($85 to $250), but can be significant over the life of the house. Development of more effective passive control techniques [23], even if they have higher installation costs, might result in lower life-time costs by reducing the energy costs.

ACKNOWLEDGMENTS

The authors thank co-workers Jacques Hill, Tim Nuzum, Ken Revzan, Ellen Saegebarth, and Greg San Martin for collection, handling and analysis of data; and Rich Prill for assistance in selection and design of radon control systems; Ken Gadsby and Dave Harrje at Princeton University for contributing data on long-term follow-up measurements; Mary Cahill at the New Jersey DEP for on-site logistical support; David Sanchez at the AEERL of the U.S. EPA for program support and management; and the homeowners for their past and continuing participation.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Buildings Systems Division, by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098, and by the U.S. Environmental Protection Agency (EPA) through Interagency Agreement DW89931876-01-0 with DOE.

REFERENCES

1. Scott, A.G. and Findlay, W.O., Demonstration of Remedial Techniques Against Radon in Houses on Florida Phosphate Lands, EPA-520/5-83-009, NTIS PB84-156157 (1983), U.S. EPA, Washington, D.C.
2. Erickson, S.-O., Schmieo, H., and Clavensto, B., Modified Technology in New Constructions, and Cost Effective Remedial Action in Existing Structures, to Prevent Infiltration of Soil Gas Carrying Radon, *Radiation Protection Dosimetry, 7* (1984) 223.
3. Henschel, D.B. and Scott, A.G., The EPA Program to Demonstrate Mitigation Measures for Indoor Radon: Initial Results, in Indoor Radon, *Proceedings of an APCA International Specialty Conference* (1986), Pittsburgh, PA: Air Pollution Control Association, pp. 110-121.
4. Scott, A.G., Preventing Radon Entry, Chapter X. Radon and Its Decay Products in Indoor Air (1988), Eds. W.W. Nazaroff and A.V. Nero (NY: Wiley-Interscience).
5. Turk, B.H., Harrison, J., Sextro, R.G., Hubbard, L.M., Gadsby, K.J., Matthews, T.G., Dudney, C.S., and Sanchez, D.C., Evaluation of Radon Reduction Techniques in Fourteen Basement Houses: Preliminary Results, *Proceedings of the 81st Annual Meeting of the Air Pollution Control Association. Dallas, TX* (1988), 88-107.2.
6. Turk, B.H., Harrison, J., Prill, R.J., and Sextro, R.G.,Intensive Radon Mitigation Research: Lessons Learned, *Proceedings of the Symposium on Radon and Radon Reduction Technology* (1988), Paper VI-3, U.S. EPA, Denver, CO.
7. Turk, B.H., Prill, R.J., Fisk, W.J., Grimsrud, D.T., and Sextro, R.G., Effectiveness of Radon Control Techniques in 15 Homes, submitted to the *Journal of the Air Pollution Control Association* (1989), LBL-26961, Lawrence Berkeley Laboratory, Berkeley, CA.

8. Nitschke, I.A., Wadach, J.B., Clarke, W.A., Traynor, G.W., Adams, G.P., and Rizzuto, J.E., A Detailed Study of Inexpensive Radon Control Techniques in New York State Houses, Eds. B. Berglund, T. Lindvall, and J. Sundell, Indoor Air, Vol. 5: Buildings, Ventilation and Thermal Climate (1984), Swedish Council for Building Research, Stockholm, p. 111.

9. Nitschke, I.A., Clarkin, M., Brennan, T. Rizzuto, J., and Osborne, M., Preliminary Results from the New York State Radon-Reduction Demonstration Program, *Proceedings of the Symposium on Radon and Radon Reduction Technology* (1988), Paper VII-3, U.S. EPA, Denver, CO.

10. De Pierro, N. and Cahill, M., Radon Reduction Efforts in New Jersey, *Proceedings of the Symposium on Radon and Radon Reduction Technology* (1988), Paper VII-2, U.S. EPA, Denver, CO.

11. Prill, R.J., Fisk, W.J., and Turk, B.H., Evaluation of Radon Mitigation Systems in 14 Houses over a Two-Year Period, submitted to the *Journal of the Air Pollution Control Association* (1989), LBL-26959, Lawrence Berkeley Laboratory, Berkeley, CA.

12. Sextro, R.G., Turk, B.H., Harrison, J., Revzan, K.L., and Nero, A.V., Radon Entry and Control in Seven Houses with Basements, submitted to *Radiation Protection Dosimetry* (1988), LBL-25292, Lawrence Berkeley Laboratory, Berkeley, CA.

13. Turk, B.H., Harrison, J., Prill, R.J., and Sextro, R.G., Developing Soil Gas and Radon Entry Potentials for Substructure Surfaces and Assessing Radon Control Diagnostic Techniques, submitted to *Health Physics* (1989), LBL-27319, Lawrence Berkeley Laboratory, Berkeley, CA.

14. Girman, J.R., Allen, J.R., Lee, A.Y., A Passive Sampler for Water Vapor, *Environment International, 12* (1986) 461-465.

15. Oswald, R.A., Experience with Alpha Track Detectors, *Proceedings of the 81st Annual Meetings of the Air Pollution Control Association, Dallas, TX* (1988), Paper no. 88-107.8, Air Pollution Control Association, Pittsburgh, PA.

16. Pearson, M.D., A Comparison of Four Types of Alpha-Track Radon Monitors, *Proceedings of the Technical Exchange Meeting on Passive Radon Monitoring*, Grand Junction, CO (1988), available from the National Technical Information Service, Springfield, VA.

17. DSMA Atcon Ltd., Review of Existing Instrumentation and Evaluation of Possibilities for Research and Development of Instrumentation to Determine Future Levels of Radon at a Proposed Building Site, Report INFO-0096 (1983), Ottawa, Canada: Atomic Energy Control Board.

18. Garbesi, K. and Sextro, R.G., Modeling and Field Evidence of Pressure-Driven Entry of Soil Gas Into a House Through Permeable Below-Grade Walls, submitted to *Environmental Science and Technology* (1989), LBL-26980, Lawrence Berkeley Laboratory, Berkeley, CA.

19. Harris, D.B., Ruppersberger, J.S., and Walton, M., Radon Wall Coatings Test Facility: Design and Development Phase, *Proceedings of the Symposium on Radon and Radon Reduction Technology, Vol. 2, Symposium Poster Papers* (1988), pp. 4-65 to 4-80, U.S. EPA, Denver, CO.

20. Hubbard, L.M., personal communication, 1988.

21. Harrje, D.T., Hubbard, L.M., Gadsby, K.J., Bolker, B., and Bohac, D.L., The Effect of Radon Mitigation Systems on Ventilation in Buildings, ASHRAE Transactions (1989), Vol. 95, Part 1.

22. Revzan, K.L., Turk, B.H., Harrison, J., Nero, A.V., Sextro, R.G., Parametric Modeling of Temporal Variations in Radon Concentrations in Homes, *IEEE Transactions on Nuclear Science, 35* (1) (1987) 550-555.

23. Tappan, J.T., Passive Radon Reduction Techniques for Existing and New Structures, *Proceedings of the Symposium on Radon and Radon Reduction Technology* (1988), Paper VII-4, U.S. EPA, Denver, CO.

TABLE 1

Description of houses and significant mitigation techniques

House ID	Stories Above Grade	Heating/Cooling Systems	Substructure Description[a]	Mitigation Techniques in order of evaluation
LBL08	1	Oil FAF[b] & DHW[c] whole house fan	Full basement, walls, partially painted, perimeter drain duct with sump	1. SSV Depressurization 2. SSV Pressurization 3. Seal-Perimeter Drain Duct 4. Low-Pressure SSV Depressurization with Drain Duct △ 5. Seal Cracks and Holes △ 6. High-Pressure SSV Depressurization with Drain Duct
LBL09	2	Gas FAF & DHW whole house fan and AC[d] (after 8/5/87)	Basement w/two attached unvented slab floor crawlspaces, basement walls painted perimeter floor/wall crack (~1 mm)	1. AAHX Ventilating Both Basement and Crawlspace 2. AAHX Ventilating Crawlspace Only △ 3. AAHX Ventilating Basement Only 4. SSV Depressurization (Basement) △ 5. SSV Depressurization (Basement) and Interior Footer Drain Ventilation △ 6. Seal Cracks and Holes △ 7. SSV Depressurization (Basement/Crawlspace) and Interior Footer Drain Ventilation
LBL10	2	Gas FAF & DHW whole house fan and AC	Basement w/attached slab-on-grade, walls mostly painted, heating system ducting runs below slab-on-grade	△ 1. SSV Depressurization of Slab-on-Grade 2. SSV Pressurization of Slab-On-Grade △ 3. Block Wall Ventilation △ 4. Seal Cracks and Holes
LBL11	2	Oil BBHW[e] & DHW whole house fan	Daylight basement w/one wall entirely below grade, walls unpainted, perimeter drain duct, built over loose fill	1. SSV Depressurization 2. SSV Pressurization 3. Seal Perimeter Drain Duct △ 4. SSV Depressurization with Drain Duct 5. Low-Pressure Basement Overpressurization △ 6. High-Pressure Basement Overpressurization △ 7. Seal Cracks and Holes
LBL12	2	Elec. FAF & DHW attic fan and AC	Basement w/attached, unvented slab floor crawlspace, painted walls	△ 1. SSV Depressurization 2. SSV Pressurization 3. Low-Pressure Basement Overpressurization △ 4. Seal Cracks and Holes △ 5. SSV Depressurization and Block Wall Ventilation (Crawlspace)
LBL13	2	Oil FAF, elec. DHW attic fan and AC	Full basement, walls unpainted, perimeter floor/wall crack (~1 mm)	△ 1. SSV Depressurization 2. SSV Pressurization △ 3. Seal Cracks and Holes
LBL14C (control)	2	Propane FAF & DHW attic fan	Full basement, painted walls	1. Seal Open Block Wall Cavities △ 2. SSV Depressurization

[a]All substructure walls are concrete or cinder block.
[b]FAF = Forced Air Furnace
[c]DHW = Domestic Hot Water
[d]AC = Whole House, Forced-air, Air Conditioning
[e]BBHW = Baseboard Hot Water
△ Those mitigiation techniques involved in routine system cycling.

TABLE 2

Summary of basement radon reductions due to control system operation* (arith. mean ($Bq\ m^{-3}$) - no. hours)

Description of Control System	LBL08			LBL09			LBL10			LBL11			LBL12			LBL13			LBL14C	
	mean		hrs.	mean		hrs.	mean		hrs.	mean		hrs.	mean		hrs.	mean		hrs.	mean	hrs.
[A] Subsurface Ventilation (Depress.):																				
Baseline	2700		424	--		--	5900		571	1200		382	2500		897	2900		776	--	--
1) Post-SSD (low ΔP)	1400		152	--		--	310		46	160		140	140		545	56		23	--	--
2) Post-SSD (high ΔP)	--		--	--		--	140		559	--		--	140		202	38		832	--	--
[B] SSD after Sealing:																				
Baseline	860		1049	--		--	--		--	--		--	2500		620	--		--	--	--
1) Post-SSD (low ΔP)	550		115	--		--	--		--	--		--	170		571	--		--	--	--
Baseline	--		--	--		--	4400		1099	--		--	2200		264	1400		1809	**58	219
2) Post-SSD (high ΔP)	--		--	--		--	64		941	--		--	180		289	+50		1611	+**<37	382
[C] SSD & Drain Duct Vent.:																				
Baseline	860		1049	--		--	--		--	--		--	--		--	--		--	--	--
1) Post-SSD & DDV (low ΔP)	140		336	--		--	--		--	--		--	--		--	--		--	--	--
Baseline	920		1871	--		--	--		--	520		502	--		--	--		--	--	--
2) Post-SSD & DDV (high ΔP)	+24		1201	--		--	--		--	+23		458	--		--	--		--	--	--
[D] Subsurface Vent. (Pressurization):																				
Baseline	2700		424	**910		222	5900		571	1100		685	2500		897	2900		776	--	--
Post-SSP (Compare to SSD Code)	2300	[A1]	21	**740	[E]	44	1600	[A2]	51	610	[C2]	29	1500	[A2]	68	1400	[A2]	99		
[E] Footer Drain Ventilation:																				
Baseline	--		--	980		581	--		--	--		--	--		--	--		--	--	--
Post-FDV	--		--	150		882	--		--	--		--	--		--	--		--	--	--
[F] Block Wall Ventilation:																				
Baseline	--		--	--		--	4400		1099	--		--	--		--	--		--	--	--
Post-BWV	--		--	--		--	+75		819	--		--	--		--	--		--	--	--
[G] Air-Air Heat Exchanger:																				
Baseline	--		--	1000		2657	--		--	--		--	--		--	--		--	--	--
Post-AAHX	--		--	560		1572	--		--	--		--	--		--	--		--	--	--
[H] Basement Pressurization:																				
Baseline	--		--	--		--	--		--	1100		685	2500		897	--		--	--	--
1) Post-BP (low ΔP)	--		--	--		--	--		--	250		303	2000		119	--		--	--	--
Baseline	--		--	--		--	--		--	520		502	2500		897	--		--	--	--
2) Post-BP (high ΔP)	--		--	--		--	--		--	19		390	1100		45	--		--	--	--
[I] Sealing:																				
Baseline	2500		1323	1000		1271	7200		1329	1500		1496	3500		1369	5100		1187	**490	218
Post-Sealing	860		1049	1200		290	5600		457	840		197	2300		526	1900		547	**58	219
[J] Multiple Systems:																				
Baseline	--		--	1100		330	3500		349	805		237	1700		435	--		--	--	--
Post-Mitigation (using systems as coded)	--		--	+90	[B2]+[E]	338	61	[B2]+[F]	218	11	[C2]+[H2]	121	+84	[B1]+[F]	429	--		--	--	--

+Denotes final mitigation system configuration

*Standard error of mean is less than instrument uncertainty (10%) for all measurements

**All monitoring conducted during summer (June - August)

TABLE 3

Long-term follow-up measurements of indoor radon [Bq m^{-3} (no. of measurements)]

House ID	Location	Pre-Mitig. Baseline+	Final Post-Mitig++	Oct. '87 - May '87	May '88 - Sept. '88	Sept. '88 - May '89
LBL08	basement	2500	24	210	33*	130**
	1st floor	940	36	130	41*	160**
LBL09	crawlspace	--	--	--	85	110
	basement	1000	90	67	72(2)	110(2)
	1st & 2nd floor	780	39	--	35(2)	67(2)
LBL10	basement	7200	75	90	67*	96**
	1st & 2nd floor	2000	57	70	63*	100**
LBL11	basement	1500	23	160(2)	44(2)	230(2)
	1st & 2nd floor	560	13	44	13(2)	87(2)
LBL12	crawlspace	--	--	--	67	110
	basement	3500	84	100	65(2)	110(2)
	1st & 2nd floor	1700	39	220	48(2)	94(2)
LBL13	basement	5100	50	35(2)	59(2)	43(2)
	1st & 2nd floor	1700	18	37	30(2)	30(2)
LBL14C	basement	690	<37	--	--	28(2)
	1st & 2nd floor	370	7	--	--	26(2)

+Average radon concentrations for periods before any mitigation, typically September through November (LBL08 - LBL13) and September through June (LBL14C). Data from continuous radon monitors in basement and on first floor only.

++Average radon concentrations for final mitigation system configuration, from continuous radon monitors in basement and on first floor only. See Table 2.

*Detectors removed 11/88.

**Detectors exposed from 11/88 to 3/89.

TABLE 4

Effect of forced-air HAC blower operation and indoor-outdoor Δ T on wall and floor pressure differences during SSD operation using equation of form, Δ P = A (blower % on) + B (Δ T, °C) + C.

house ID	season	number of measurements	SLAB-FLOOR Δ P					BASEMENT-OUTSIDE Δ P				
			blower coeff. (A)	Δ T coeff. (B)	constant (C)	R^2	F-value	blower coeff. (A)	Δ T coeff. (B)	constant (C)	R^2	F-value
LBL09	winter (2/8 - 2/13)	115	-0.011	0.007⁺	10.3	0.13	8.2***	-0.022	-0.163	0.43	0.37	33***
	summer (8/10 - 8/17)	174	-0.004	-0.035	15.5	0.38	52***	-0.011	-0.080	-0.53	0.41	61***
LBL13	winter (2/28 - 3/8)	196	-0.003	0.009	2.2	0.37	38***	-0.019	-0.142	-0.55	0.79	365***
	summer (6/13 - 6/19)	139	-0.023	0.012	18.3	0.67	138***	-0.054	-0.061	-0.47	0.74	194***

***Significance level (P) of Fisher statistic (F) is ≤ 0.001

⁺Unstable parameter (T = 0.3, P = 0.75)

TABLE 5

Mitigation system installation costs

SYSTEM TYPE	labor effort (man-hours)	labor cost ($)	materials & equip. ($)	misc. ($)	overhead & profit ($)	total ($)	cost per unit of treated floor area ($/m^2)
SSV							
LBL08:	84	1280	440	260	880	2860	16
LBL09: basement [(a)]	84	1240	210	140	700	2290	43
crawlspace	31	460	260	--	320	1040	16
LBL10:[(b)]	73	1180	380	380	850	2790	14
LBL11:	60	1040	360	310	750	2460	31
LBL12:	52	850	300	160	590	1900	24
LBL13:[(c)]	107	1620	440	290	1050	3400	56
LBL14C:	37	610	220	140	460	1430	15
SEAL PERIMETER DRAIN							
LBL08:[(d)]	19	340	330	15	320	1010	6
LBL11:[(d)]	34	540	--	75	270	890	11
AAHX							
LBL09:	30	550	470	50	480	1550	30
CAULK CRACKS & OPENINGS							
5-house average	6	100	25	15	65	210	3
BLOCK WALL VENTILATION							
LBL10:[(e)]	11	160	70	60	130	420	2
LBL12:[(e)]	19	310	60	90	210	670	35
BASEMENT PRESSURIZATION							
LBL11:	20	290	230	30	240	790	10
LBL12:	26	450	310	10	360	1130	14

(a) connected into interior drain tile

(b) subsequently down-graded form 3-pipe to 2-pipe

(c) subsequently down-graded from 3-pipe to 1-pipe

(d) was an essential part of successful SSV system

(e) was incorporated into existing SSV system

TABLE 6

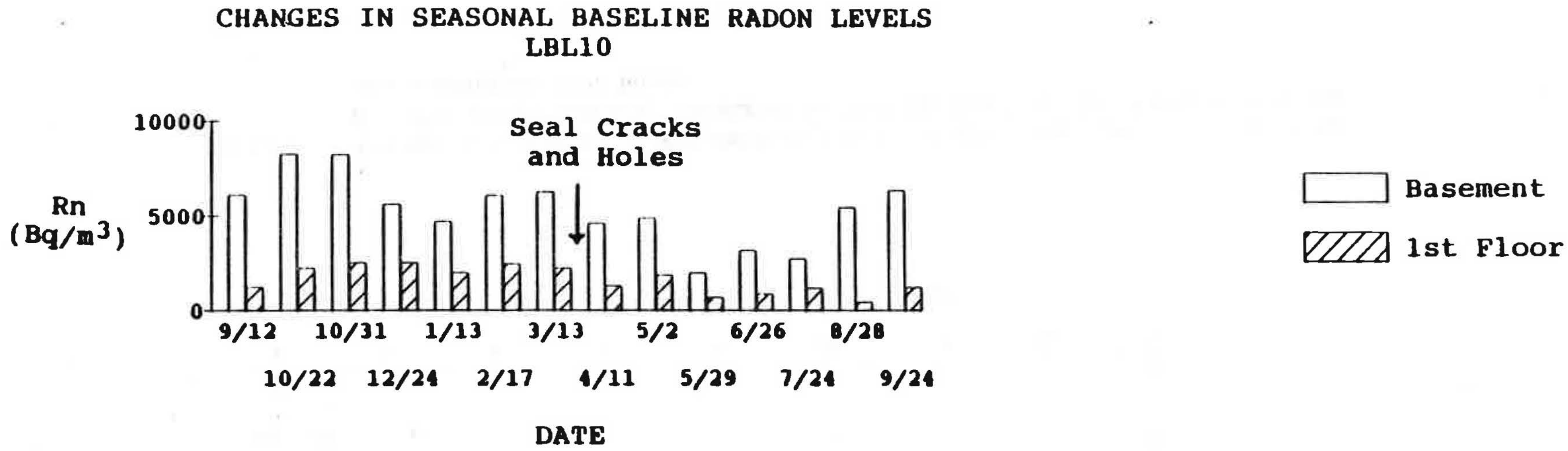
Estimated operating costs for radon control systems

house ID	mitigation system	est. additional ventilation (m^3/sec)	est. additional heating season energy loss by vent. (kWh)+	FAN OPERATION: rating (watt)	FAN OPERATION: 12 mo. energy usage (kWh)	est. total additional annual energy usage (kWh)	EST. ADDITIONAL ANNUAL ENERGY COST: electrical heat ($)	EST. ADDITIONAL ANNUAL ENERGY COST: oil heat ($)++
LBL09:	air-air heat exchanger*	0.082	2200	122	270	2500	250	95
	2-fan SSD w/footer drain	0.013	1200	150	1300	2500	250	170
LBL10:	SSD	0.015	1500	66	580	2100	210	100
	block wall ventilation	0.015	1400	68	600	2000	200	100
LBL11:	SSD w/drain duct vent.	0.019	1900	68	600	2500	250	120
LBL12:	SSD	0.069	680	74	650	1300	130	85
LBL13:	SSD	0.010	1000	68	600	1600	160	90

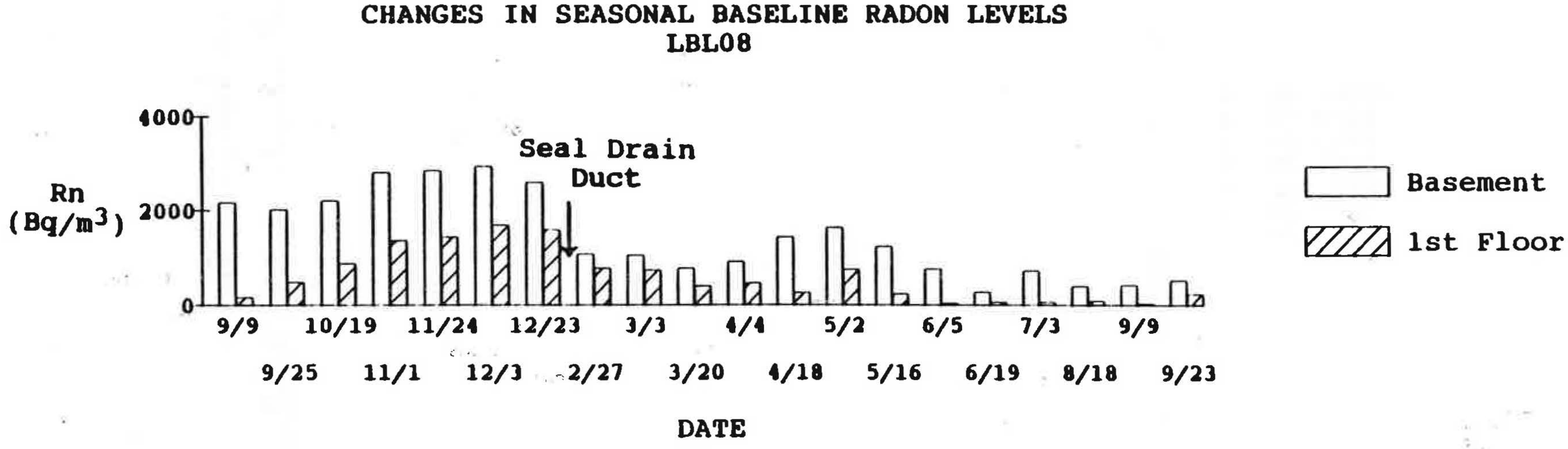
+Based on 18.3° C average indoor balance-point temperature and monthly average outdoor temperatures for a heating seaseon from September - May.

++Includes electrical cost of fan operation (@ $0.10/kWh) and fuel oil cost of furnace operation (@ $0.85/gal.; 1.57 x 10^8 J/gal.; 75% efficiency).

*Using an energy exchange efficiency of 0.72 for heating season plus fan operation for summer months.



(a)



(b)

Figure 1. Seasonal changes in indoor radon levels under baseline or unmitigated conditions are shown for houses LBL10 (a) and LBL08 (b). Radon levels have been significantly reduced in (b) because a very large area of leakage through the substructure surface was sealed.

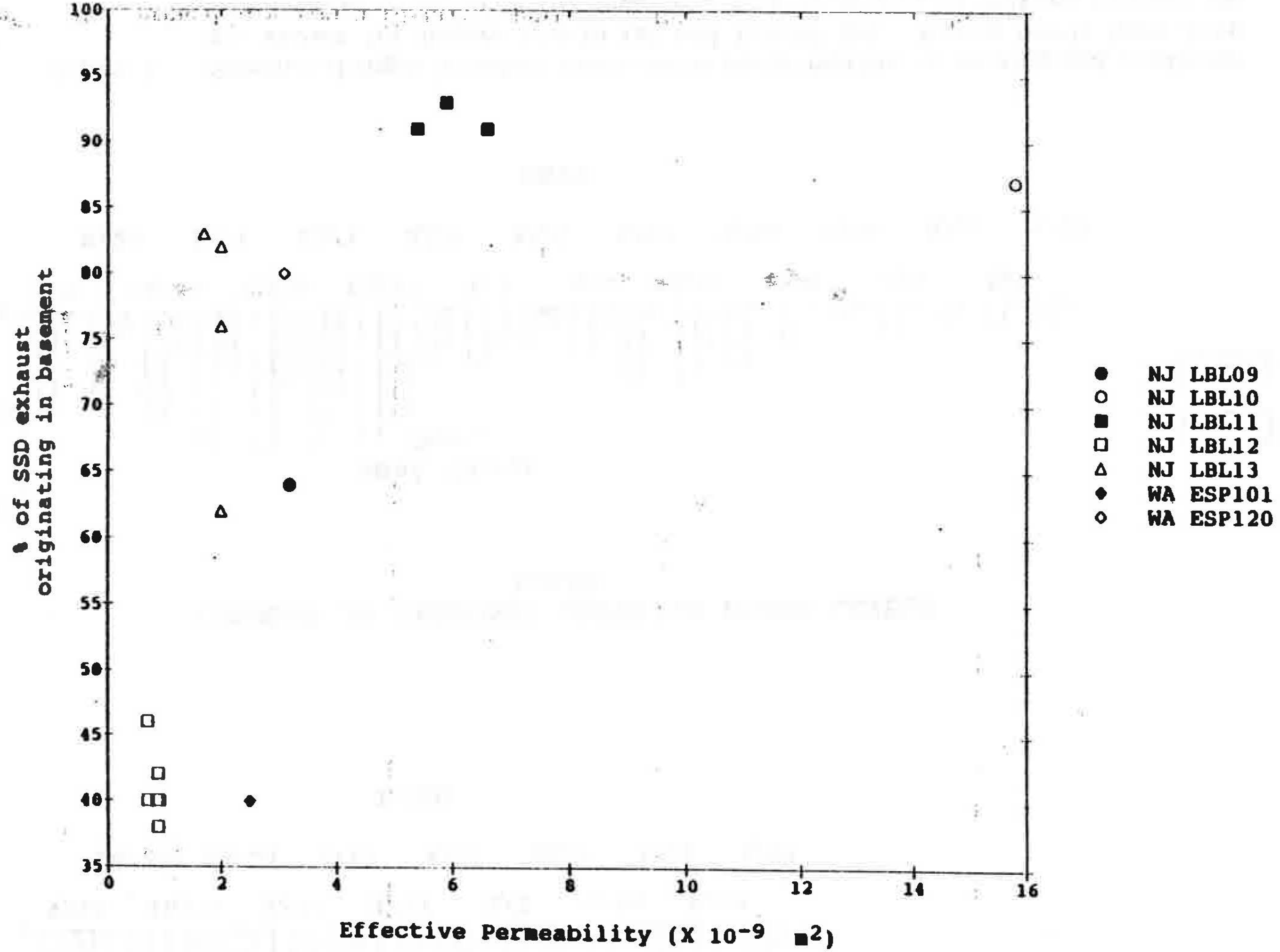


Figure 2. The percentage of air in SSD exhausts that originated in the basement is related to the effective permeability calculated for SSD pipes in five New Jersey houses and two Washington State houses.

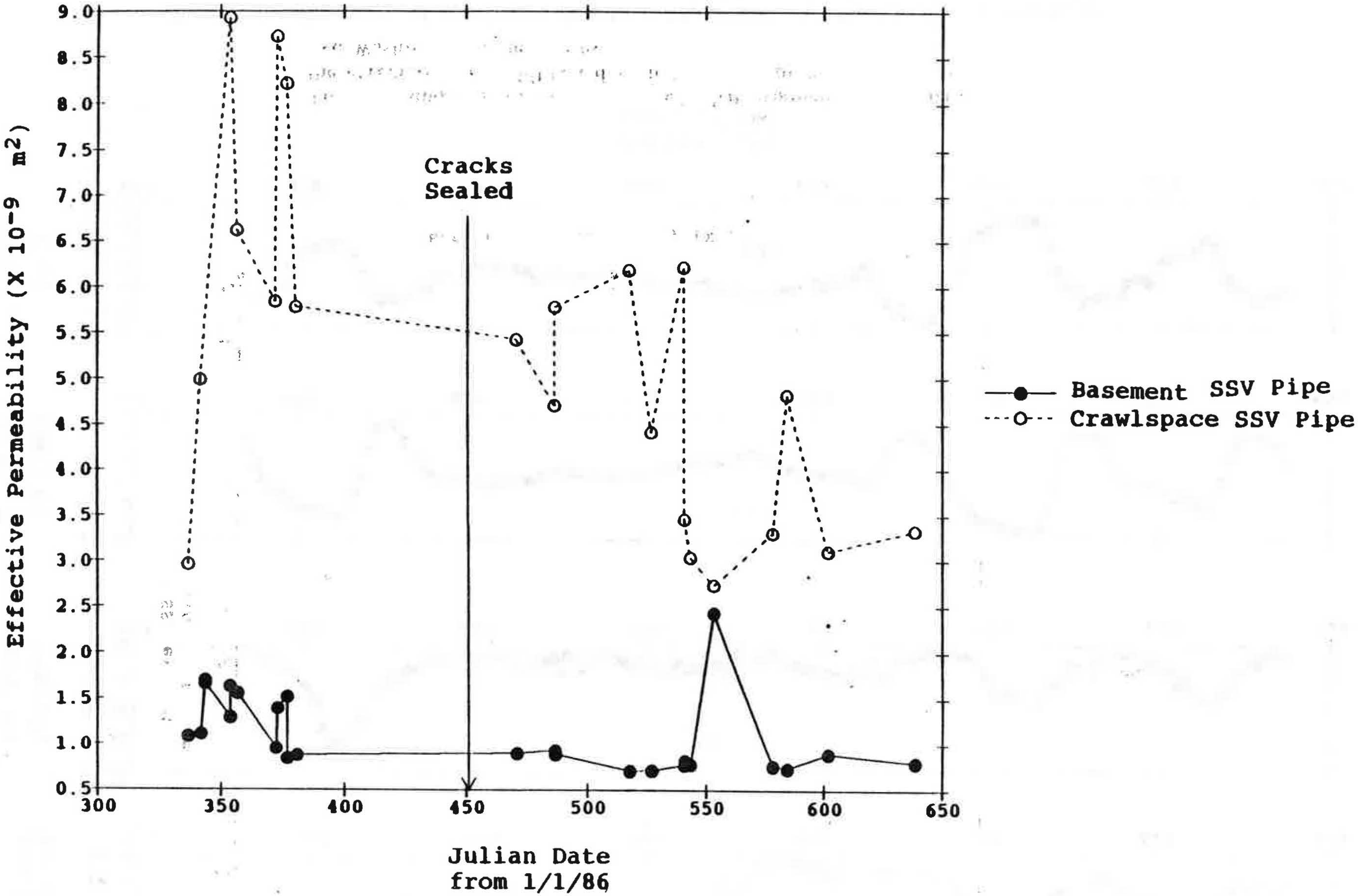


Figure 3. SSV effective permeability over a 10-month period for two pipes at LBL12. No effect is observed after sealing of visible and accessible substructure cracks and openings.

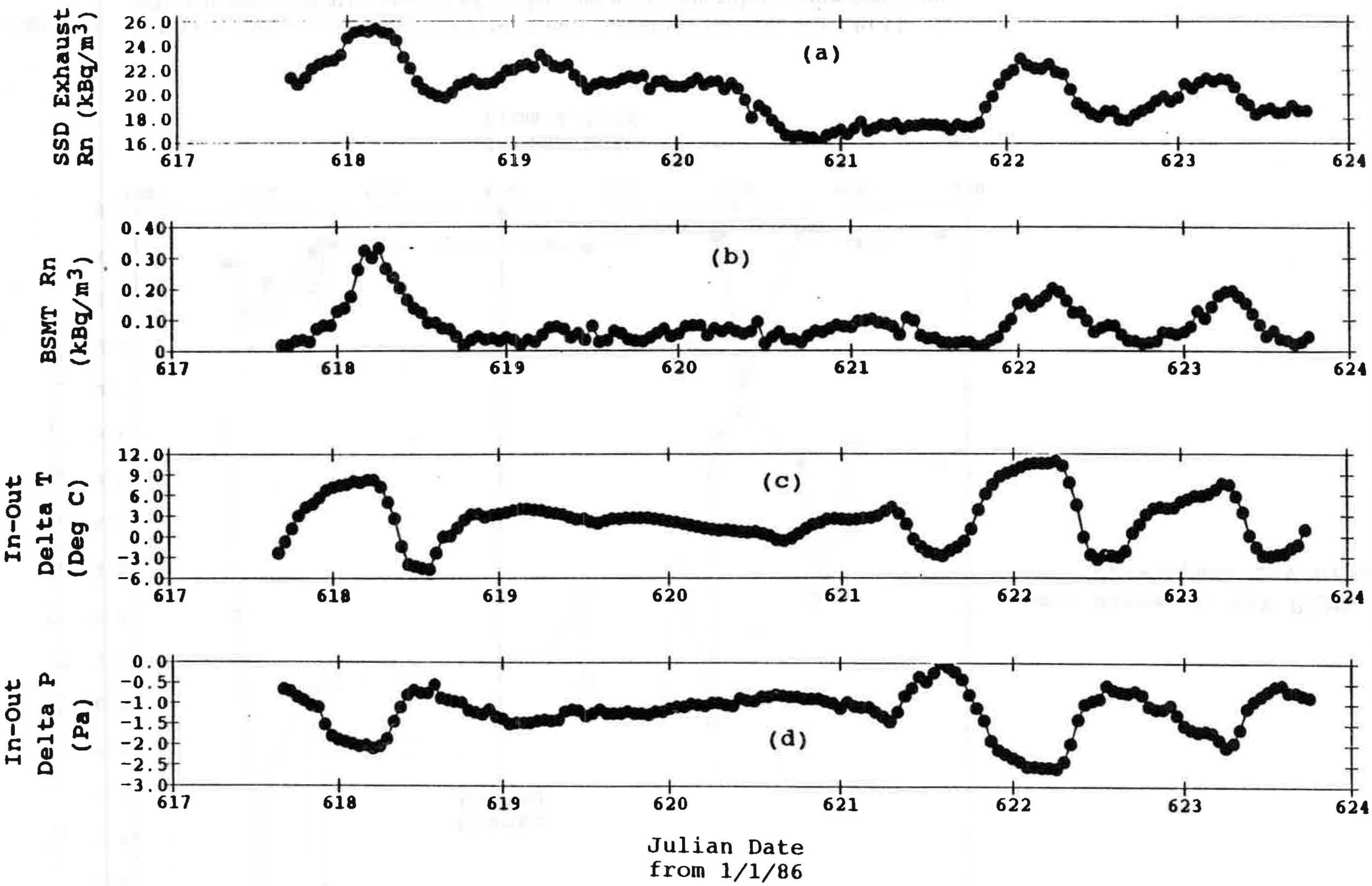


Figure 4. One week of continuous data from September 1987 for LBL10 that relates radon concentrations in the SSV exhaust (a) and basement (b) to indoor-outdoor ΔT (c) and ΔP (d).