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INTENSIVE RADON MITIGATION RESEARCH: LESSONS LEARNED

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ABSTRACT

In the past three years, two intensive radon mitigation projects have been conducted on 15 houses in the Pacific Northwest and seven houses in New Jersey. Both studies collected extensive continuous and periodic data on important house and environmental parameters such as indoor and soil gas radon concentrations, indoor and outdoor temperatures, pressure differentials, ventilation rates, and mitigation system performance. Key findings indicate that soil temperatures can substantially influence the pressure difference that drives radon entry; forced air distribution systems can influence both substructure depressurization and the transport of radon to upper floors; air-to-air heat exchangers and basement overpressurization are successful control techniques in limited situations; subsurface ventilation is often an effective control measure; and resistance to flow for subsurface ventilation systems is greatly influenced by the leakiness of the substructure surfaces that are below grade. General guidance for future studies include an emphasis on research into the fundamentals of radon movement and mitigation.

INTRODUCTION

Public concern over the health risks associated with exposure to radon gas and our incomplete understanding of radon movement and accumulation in buildings has spurred a small number of intensive research projects on radon entry and control. The objectives of these projects include demonstration and evaluation of existing and innovative radon mitigation technologies; development of methods for problem diagnosis and selection of the proper mitigation system; and investigation of the basic radon entry processes and their relationship to building characteristics and dynamics, and to environmental variables. In these projects, collection of continuous, multi-parameter data was emphasized and often continued for extended periods.

Two such studies are discussed here. From October 1985 to April 1986 a study of 15 Pacific Northwest houses was conducted to provide alternatives to the air-to-air heat exchanger as the Bonneville Power Administration's (BPA) sole radon mitigation strategy. The homes had been identified during earlier surveys of indoor air quality as having elevated indoor radon levels. Fourteen were located east of Spokane, Washington, in the Spokane River Valley of eastern Washington and northern Idaho, while one was located in Vancouver, in western Washington. The Spokane River Valley is a region of glacial outwash with uniform soil characteristics of soil gas radon concentrations (100 to 700 pCi/L) and high air permeability (ranging from 10^{-10} to 10^{-13} m^2 with a geometric mean of 5.4×10^{-11} m^2 and geometric standard deviation of 4.9). The high permeability is an important factor in the elevated indoor radon levels in many area homes. Participating houses represented a variety of building and substructure types, except that 14 had poured concrete foundation walls while only one had foundation walls of stone and mortar. The study involved identifying the cause of high radon concentrations in each house, selecting and installing radon control systems by stages (sometimes with a competing system also installed), and then evaluating and modifying the control system to optimize performance. Some systems were cycled on and off to recover pre-mitigation baseline conditions. The following measurements were made during the course of the study: weekly average ventilation rates; continuous recording of indoor and outdoor temperatures, wind speeds and directions, and radon concentrations on one or two floors; periodic measurements of soil gas radon concentrations, building air leakage areas, and mitigation system operating parameters (duct air flow rates, pressure differences, and radon concentrations in air grab samples). Operating and installation cost data were also collected (1).

The second study of seven homes in north-central New Jersey was part of a larger project involving Oak Ridge National Laboratory, Princeton University, U.S. Department of Energy (U.S. DOE), U.S. Environmental Protection Agency (U.S. EPA), and the State of New Jersey Department of Environmental Protection (NJDEP). The work in the Pacific Northwest indicated that this second study should focus more extensively on appropriate diagnostic techniques; soils characterizations including moisture and temperature; relationships of radon entry to house and environmental parameters; seasonal effects; and post-mitigation system evaluations. Field measurements were made from September 1986 to October 1987 and data analysis is still in progress. The houses were selected from a group of 130 residences based primarily on how well they represented New Jersey house construction types, on their elevated radon levels, and their overall suitability for the study. All homes had foundation walls of hollow core concrete or cinder block. Six of the seven houses were located on hillsides. The local soils were variable in both permeability (ranging from 10^{-9} to 10^{-13} m^2 with a geometric mean of 4×10^{-11} m^2 and geometric standard deviation of 22.1) and soil gas radon concentrations (500 to 100,000 pCi/L), not only from house-to-house, but, more importantly, at the same house. Additional monitoring of precipitation, radon in other house zones, and pressure differences at different points of each structure was conducted. However, instrument failure hampered some of the originally intended measurements. Mitigation systems were also cycled on and off more routinely than in the Pacific Northwest study (2,3).

This paper presents some key findings to-date from the two studies that may affect studies under development or our understanding of mitigation system performance and radon movement into buildings.

SPECIFIC TECHNICAL AND SCIENTIFIC ISSUES

SOIL TEMPERATURE AND PRESSURE DIFFERENCES

In the vast majority of homes with elevated indoor radon concentrations, the primary cause is convective flow of soil gas containing radon into the substructure (4). The negative pressure differences that drive the soil gas movement are small (less than 0.1 to 10 Pascals) but persistent and can be created by operation of exhaust fans, heating, ventilation, air conditioning equipment, and vented combustion appliances; by certain wind conditions; and, most importantly, by the thermal stack effect. This stack effect results from warmer indoor temperatures (and thus less dense indoor air) that cause indoor absolute air pressures at the lower levels of the building to be smaller than those pressures on the outside surface at the same elevation within the soil.

Data from the control homes (not receiving mitigation until the end of the study) in the Spokane River Valley suggested that radon entry remained higher than expected as the outdoor temperatures moderated in March and April. We hypothesized that the soil temperatures outside of the basement walls at these homes lagged behind warming outdoor air temperatures and caused a negative pressure difference (ΔP) at the substructures to persist. Therefore, in New Jersey , soil temperatures were continuously monitored one meter from the structure at three depths on two sides of each house. We also observed, in these houses, higher than expected indoor radon levels during periods of warm and even hot (greater than 30 °C) outdoor air temperatures. At these times, the indoor-outdoor temperature difference was reversed and should have caused positive ΔP's and a reversed stack effect. However, ΔP measurements below grade were either either negative or very slightly positive. One house was built into the side of a hill with the downhill wall entirely above grade and the uphill wall mostly below grade. On a hot day, soil gas was observed to be flowing into the house through a test hole drilled through the basement floor near to the below-grade wall and flowing out of the house through a test hole near to the above-grade wall.

Using measured soil temperatures, inside-outside temperature differences can be corrected, and a modified total pressure difference can be calculated and pressure profile derived from the following simplified expression:

$$\Delta P = g\ (h_1(\rho_1 - \rho_o) + h_b(\rho_b - \rho_o) + h_s(\rho_s - \rho_s)\ ) \qquad (1)$$

where:

ΔP = total pressure difference (indoor minus outdoor) at basement floor a distance, h_s, below grade (Pa),
g = gravitational constant (9.81 m/s^2),
h_1, h_b, h_s = vertical distances between neutral pressure level and bottom of first floor, between top of basement and soil surface, and between soil surface and basement floor below grade, respectively, and
$\rho_1, \rho_o, \rho_b, \rho_s$ = densities of air for first floor, outside, basement, and soil, respectively.

The neutral pressure level used to define distance h_1 in Equation 1 is the level where indoor and outdoor air pressures are equal when the wind speed is zero and is a commonly used parameter in models of air infiltration.

Substituting temperatures,

$$\Delta P = g\ \rho_{STD}\ T_{STD}\ (h_1(1/T_1 - 1/T_o) + h_b(1/T_b - 1/T_o) + h_s(1/T_b - 1/T_s)), \quad (2)$$

where:

T_1, T_o, T_b, T_s = average T (°K) for first floor, outside, basement, and soil, respectively, and
ρ_{STD}, T_{STD} = standard sea level air density, $\rho_{STD} = 1.225\ kg/m^3$, at standard temperature, $T_{STD} = 288.2$ °K.

Predicted pressure differences for New Jersey house LBL08 are displayed in Figure 1 using data from Table 1. The neutral pressure level was assumed to be near the house ceiling and we also assumed that the floor between the basement and first floor was not tightly sealed so that there were no substantial discontinuities in the indoor pressure. A linear soil temperature profile was assumed, thus, an average soil temperature can be used in equation 2, although this assumption may not always be valid.

The winter profile shows the damping effect of the soil temperatures causing the negative ΔP to be reduced (note the change in slope of the pressure curve). Likewise, the soil temperatures in summer cause the ΔP to be less positive (~1Pa) than indicated by a calculation using only the outdoor air temperature. In homes with higher basement temperatures, the ΔP during some periods of the summer will actually become negative, thereby drawing soil gas into the building. Figures 2a,b compare measured ΔP's (30-minute intervals) at the basement floor of LBL08 with values calculated using Equation 2. Calculations with both the corrections for soil temperature and without the corrections are shown. The diurnal change in ΔP is evident in both winter and summer and is due to the daily cycle of outdoor air temperature change. The greatest differences between the values calculated with and without the soil temperature corrections occur at the times of largest excursion from the outdoor daily mean temperature, typically afternoon and early morning. This is because the slowly responding soil temperatures have the greatest difference from the more rapidly changing outside air temperatures at these times.

While not exactly correspondent, the calculation of ΔP's corrected for soil temperatures more closely predict the measured ΔP's than does the calculation without soil temperatures, especially in the summer. Coupled with the impact of cool soil temperatures, is the fact that the house structure retains the higher daytime temperatures longer than the outdoor air, thus making the ΔP's more negative at the substructure soil gas entry points. Daily pulsing of soil gas entry into the structure during periods of negative ΔP may account for the observed indoor radon levels during the summer. Figure 2 also displays the periodic spikes of measured ΔP that are usually caused by high winds, but occasionally by operation of the mechanical systems. The periods shown here were selected to exclude most instances of high wind and mechanical system operation.

This continuous data set clearly shows the value of correctly measuring ΔP during studies of radon behavior and the effects of remedial action. Stable and sensitive (±0.25 Pa) differential pressure measuring devices should be located as close as possible to the measurement location to avoid the necessity of height and temperature corrections. Frequent checks of the response of the measurement device at zero ΔP should be made to permit compensation for drift at the important ΔP's of less than 1.0 Pa. These checks are essential to detect the transitions between pressurization and depressurization of the substructure with respect to the soil. Key ΔP's to monitor include the ΔP across the substructure floor, between the interior of the basement and the hollow cores of exterior block walls, the ΔP across exterior substructure walls, the total ΔP between a point at the level of the substructure floor and outside (which will require height and temperature corrections for below-grade floors), and, of secondary importance, the ΔP across substructure surfaces adjoining other heated zones.

INFLUENCE OF FORCED AIR DISTRIBUTION SYSTEMS

The forced air distribution system of many residential heating and cooling units can influence indoor radon in at least two ways, particularly if the system passes through a substructure. First, leaky return air ducts or return plenums in the substructure have been observed to depressurize the substructure as much as 10 Pa (for example, this was observed when the central air conditioner blower was operating in LBL13). Other homes with less severe leakage problems have had up to 3 Pa additional depressurization in the substructure with the furnace blower operating. While a radon problem already existed without this additional depressurization, the forced air system exacerbated the problem and made it more difficult to mitigate.

Second, forced air distribution systems can transfer large amounts of substructure radon to the upper floors. In a modeling study of the New Jersey data, Revzan (5) found that the duration of operation of the furnace blower was one of the most important parameters that influenced the variations in radon levels on the upper floors (the furnaces were always located in the basement). Figure 3 shows the average time-of-day radon concentration for approximately 120 days during the heating season at Spokane River Valley house ESP108C. The standard deviation for main floor data points was approximately 5 pCi/L and approximately 3.5 to 4.5 pCi/L for the basement data. The furnace is controlled by a set-back thermostat that requested increased house temperatures and furnace operation after approximately 7:30 each morning. Declining basement and increasing first floor radon levels show that the house air is being mixed until about 13:00 when the higher outdoor temperatures place less demand on the furnace and the basement radon levels rise slightly above first floor levels. In the evening, falling outdoor temperatures cause greater furnace activity and better house air mixing. At 22:00, the thermostat sets back the required house temperature, furnace operation decreases, and basement radon levels begin to climb as the first floor levels begin to decline.

These data suggest the importance of additional research on the flow of radon within buildings and the effects of air distribution systems.

AIR-TO-AIR HEAT EXCHANGERS

Three houses in the Spokane River Valley and one in New Jersey had an air-to-air heat exchanger (AAHX) installed. Radon levels in three of the homes (ESP109, ESP121, and LBL09) responded as predicted by being inversely proportional to total house ventilation rates. Figure 4 shows the baseline and post-AAHX ventilation rates and radon levels, and the curves of the expected response to the additional ventilation. These data also imply a constant radon entry rate. Only in house NSP204, where an AAHX had been incorrectly installed prior to our study and was operated during the baseline period, was performance greater than anticipated. In this instance, the very large drop in house radon levels was caused by improvements made to the air distribution system of the AAHX.

Overall, results suggest that the practical use of AAHX is limited to those houses (or zones of houses) whose initial radon levels or ventilation rates are low to moderate. If initial radon levels are high and ventilation rates are also high, then the final ventilation rates necessary to achieve radon levels below guidelines will be excessive. The AAHX may also be successful in those houses (such as NSP204) where more efficient radon removal is possible through properly installed air distribution systems.

BASEMENT OVERPRESSURIZATION

Basement overpressurization systems were installed and evaluated in five Spokane River Valley houses and two New Jersey houses. The systems utilized a fan which pulled air from the upstairs and blew it into the basement. The basements were also air leak-tightened as much as practical.

In all Spokane River Valley homes and one New Jersey home, sufficient overpressurization was achieved to reduce indoor radon levels below 4 pCi/L. Because of leaky forced air furnace ductwork in LBL12, the average basement depressurization was reduced from --4 Pa to --1 Pa at a maximum fan flow rate of 0.17^{-2} m^3/s (360 cfm), but was not sufficient to overcome the natural depressurization due to the stack effect. Consequently, basement radon levels were only reduced to 37% of their baseline level of 64 pCi/L. In the other homes, the ability to achieve average winter-time pressures in the basement that were more than 2 to 3 Pa greater than the outside pressure resulted in indoor levels below EPA's guideline of 4 pCi/L. It was noted that as the overpressurization was increased, radon entry rates (i.e., indoor radon concentrations multiplied by ventilation rates) decreased (see Figure 5 for the Spokane River Valley homes). The necessity of a slight average overpressure (above zero) to overcome the diurnal and weather-related periods of negative pressure differences can be seen in Figure 2. By examining the figure, we can imagine that basement overpressurization offsets the midline of the plot to above zero. If the mean overpressurization is not sufficient to eliminate pressure difference excursions to below zero, radon entry by convective flow will continue. Indoor levels will be elevated if the substructure is subjected to negative pressures for a sufficient percentage of the time.

Therefore, basement overpressurization will only be practical in those homes whose substructure can easily be maintained air leak-tight so that a fan with a reasonable flow (less than 0.14 m^3/s - 300cfm) can be used. In two houses, basement overpressurization was installed as a competing system to subsurface ventilation (SSV). Although both techniques successfully reduced radon levels, both homeowners preferred the SSV systems as being quieter and less drafty. Other long-term problems with basement overpressurization are addressed by Prill (6).

AIR FLOW NEAR SUBSURFACE VENTILATION SYSTEMS

For the majority of homes in these two studies, regardless of house or soil type, subsurface ventilation (SSV) was the most appropriate and effective mitigation strategy. This result may be surprising because most Spokane River Valley houses had poured foundation walls, no gravel beneath the slabs, and surrounding soils that were highly permeable, while the New Jersey homes had hollow block foundation walls, gravel beneath the slabs, and soils that were variable in permeability. To find some common characteristic between the houses and regions, it is useful to consider the effect of the soils and aggregates very near to the substructure and the effect of the substructure materials themselves on SSV operating parameters.

For several reasons, it is expected that air permeabilities very near to houses could be higher than those for the "undisturbed" soil further than one meter away. The backfill material placed next to foundation walls may be less tightly packed, while air gaps and channels between the building walls, footers, slabs, and the surrounding material are frequently observed . Also increasing the near-house permeability are the gravel fill frequently placed below slabs, and the leakage pathways penetrating walls and floors of the substructure itself. As a result, an SSV pipe located adjacent to or below the slab will "see" an overall or effective permeability that depends on the undisturbed soil, the soil or aggregate or gaps near to the foundation, and the amount of leakage between the foundation and the soil. The flow and pressure measurements from the SSV pipes in these two studies were used to calculate effective permeability from a derivation of Darcy's law used for smaller soil probes (7):

$$K = 2.5 \times 10^{-11} \frac{Q}{rP}, \qquad (3)$$

where:

K = soil air permeability (m^2),

2.5×10^{-11} = a lumped, unitless constant,

Q = flow rate (L/min),

r = pipe radius (0.04 m),

P = pipe pressure (Pa),

The data are presented in Table 2. This equation assumes an unobstructed sphere of material around the pipe and thus doesn't account for the proximity of walls and floors. However, results should be within a factor of two to three of the actual value.

From the table, we note that 1) the average effective permeabilities are similar for both regions of the country (2.0×10^{-9} m^2 vs. 2.7×10^{-9} m^2), 2) effective permeabilities are higher than permeabilities typical of the surrounding soil, 3) in this small sample of houses and soils, the presence of gravel below the slab, attachment to a drain tile system, or attachment to a perimeter drain duct was observed to have a very small impact on the effective permeability even though these measures tend to extend the SSV pressure field, and 4) the two pipes immediately external to a hollow block wall (LBL10) had effective permeabilities a factor of five to ten higher than other SSV systems. In fact, the effective permeability based on air flows into (or out of) hollow block walls for a competing block wall ventilation system in this same house was identical, suggesting that the porous block dominated the flow paths to both systems.

The porous block walls in the New Jersey houses and the extensively cracked slab floors in the Spokane River Valley homes (and poorly sealed stone and mortar wall in ESP120) may have been the primary air movement pathways to the SSV systems.

Tracer gas tests in seven houses (on eight systems) indicate that a very large part (40 to 92%) of the air exhausted to the outside by the SSV systems originated in the substructure (Figure 6). This air was drawn through cracks, holes, and porous surfaces in the substructure walls and floors. The tests show the effectiveness of the subsurface depressurization (SSD) systems in reversing the pressure field in the below-grade space around the substructure. When these data for SSD air entrainment are compared with the average effective permeability at each house (Figure 6), we see that the entrainment fraction generally increases along with the effective permeability. This can be interpreted to mean that, for these houses, the resistance to flow for the SSV systems is largely influenced by the leakiness of the substructure surfaces that are below grade. [It remains that radon depleted near to the substructure would be more quickly replenished by surrounding soils of high permeability than by low permeability soils.]

In both studies, very large openings were sealed just prior to, during, or after installation of the SSV systems and in some cases improved SSV performance. Since later sealing of other visible cracks and holes had little or no observable effect on SSV performance or effective permeability, we must assume that the majority of the remaining substructure air leakage area is due to a large number of very small surface defects, to undiscovered large openings or cracks that were not sealed, or to porous surfaces of significant size. Therefore, after large openings are sealed, extensive effort would be required to seal the remaining leakage paths so that SSV pressure fields would be extended and performance enhanced. Because slab floors in the New Jersey homes were generally in good condition without cracking or webbing, the high permeability and entrainment fraction are probably due to leakage paths involving the block foundation walls. Since this analysis involves relatively few homes, more research should be specifically directed towards study of air movement into and out of block walls and on the effect of small defects in poured foundation walls and slab floors. It is encouraging that recent diagnostic tests using a vacuum cleaner to depressurize below the slab emphasize the importance of permeability of materials very near to the substructure and the extent of the pressure fields developed through this material.

SUGGESTIONS FOR FUTURE RESEARCH

The field of radon mitigation is relatively new to the U.S., and has only received substantial attention since the discovery of extremely high indoor radon levels in eastern U.S. homes. As a result, most radon investigations have stressed development and demonstration of remedial measures to satisfy public demand for effective and economical solutions. A number of measures have been found to meet that demand.

However, it is essential that future studies place more emphasis on better understanding and characterization of the important variables that control radon entry, movement, and accumulation within buildings so that we can more efficiently select and design radon mitigation systems. It is also important to investigate the detailed processes that cause mitigation systems to succeed or fail and to understand their operating limitations through a range of environmental conditions.

FIELD MEASUREMENTS AND MODELING

Future studies should be designed to support validation of existing models and the development of new models that incorporate key variables for predicting indoor radon levels and the performance of radon control systems. Successful models will, in turn, more effectively guide the design and implementation of field measurement experiments.

These field measurements require carefully planned experimental procedures that include collection of reliable data on the important parameters, yet maintain enough flexibility so that unusual or interesting phenomena can be investigated. Continuous monitoring (requiring more expensive instrumentation) is recommended so that relationships between factors can be evaluated. Data collection should begin at least several weeks before mitigation to establish baseline conditions (preferably beginning before the heating or cooling seasons), and continue through a 12-month period, if possible, while mitigation systems are cycled on and off. In this way, any seasonal or short-term changes in radon entry and mitigation system behavior can be observed. As much as possible, commonly measured data should be reported in a standard format and all data should be fully annotated. The last recommendation is vital for other users to interpret and compare data sets.

In all homes that participate in a research or demonstration project, data collection should continue after mitigation in the form of long-term follow-up monitoring. Currently, there is not enough experience or data on the long-term performance and reliability of the various mitigation systems being installed. As a minimum, exposure and analysis of annual alpha track detectors should continue for several years, and preferably longer, after radon control systems have been installed. Additional periodic inspections of systems and measurements of operating parameters would provide useful data on occupant acceptance, system and material performance, component life, and other unexpected problems.

DIAGNOSTICS

Our experience with research-based diagnostics to determine the source of a building's radon problem and potential solutions began in the Spokane River Valley study and was expanded in the New Jersey work. These diagnostic procedures are time-consuming, labor-intensive, and require considerable instrumentation (8). They are not appropriate for the practicing private mitigation contractor, since it is often more economical and equally effective to overdesign a system than to invest in comprehensive diagnostics. However, for those complex situations in homes that are difficult to mitigate, a full diagnostic effort may be required before a successful system can be selected and installed. Studies that further refine the techniques and advance the interpretation of results should continue.

SUMMARY

Findings from a study of 15 homes in the Pacific Northwest and one of seven homes in New Jersey have highlighted several important technical and programmatic issues.

- The temperature of soils surrounding substructures substantially influences (positively and negatively) the pressure differences that drive radon into buildings.
- Forced air distribution systems with leaky return air ductwork or plenums located in the substructure can both add to the natural depressurization of the substructure and transport significant amounts of radon from substructures to upper floors.
- Air-to-air heat exchangers are practical for radon control only in those houses or zones of houses that have low to moderate initial radon levels and ventilation rates or where very efficient ventilation or radon removal can be established with the AAHX air distribution system.
- The success of basement overpressurization depends on achieving a pressure in the basement that is at least 2 to 3 Pa greater than the average natural depressurization of the basement. Incremental increases in the degree of overpressurization result in decreases in the percent of time that the basement is subjected to negative pressure differences and thus, decreases the time-average radon entry rate. Only basements that can easily be maintained air leak-tight are suitable.
- Calculations of effective air permeability for SSV systems and measurements of the large fraction of basement air that is entrained in the exhausted SSV air, suggest that the leakiness of the below-grade substructure surfaces greatly influences the flow resistance to an SSV system.
- Future projects on radon entry and radon mitigation should include research components that further our understanding of the basic processes of radon gas movement and radon control systems. This research should be founded on careful experimental plans that collect continuously measured data of high quality over a sufficiently long period before and after mitigation. Research and demonstration projects should be followed by long-term monitoring to evaluate the reliability of mitigation systems.
- Research diagnostics have limited usefulness by private mitigation contractors, but may still be necessary for those houses that are difficult to mitigate or as a basis for formulating simpler, more effective approaches.

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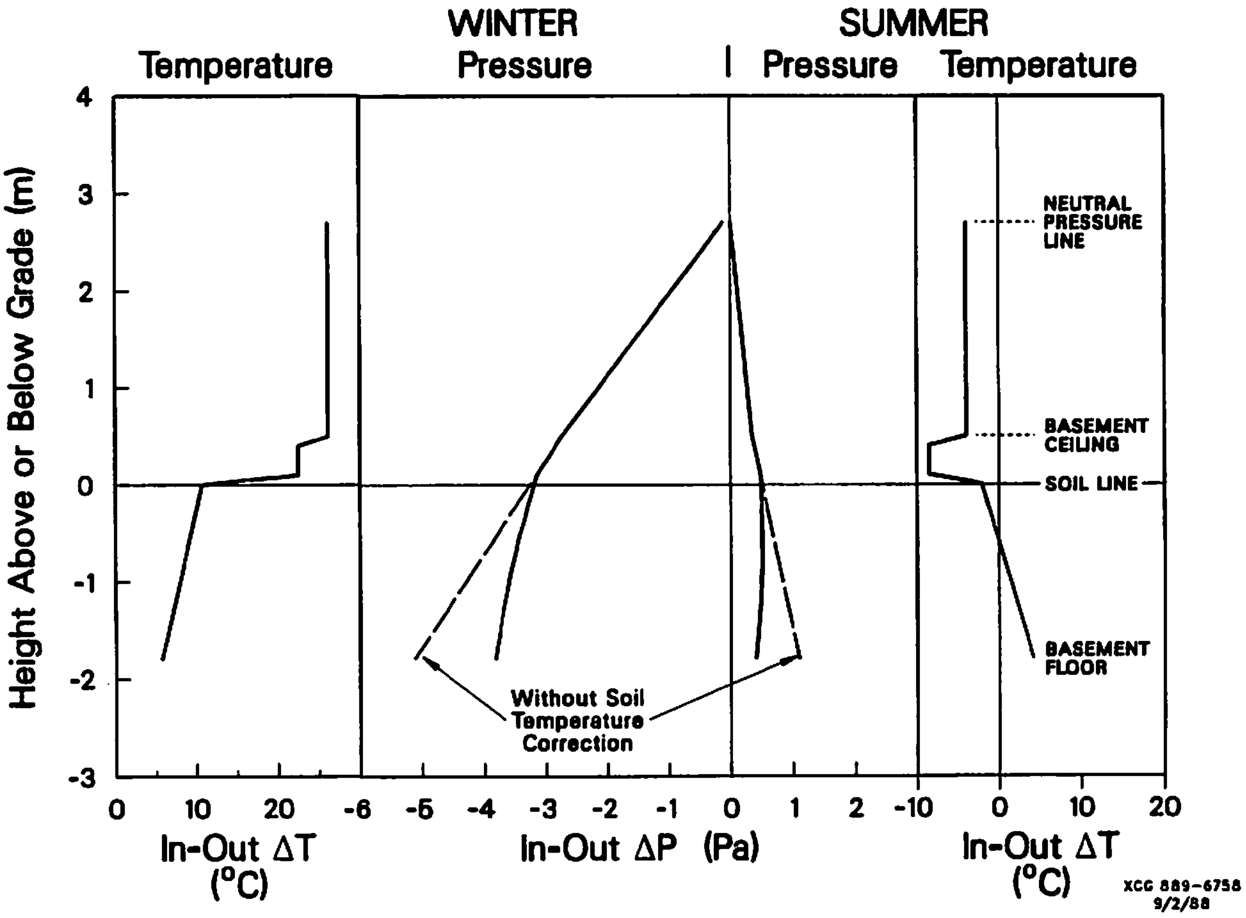

Figure 1 Predicted pressure and measured temperature difference profiles for New Jersey house LBL08 during winter and summer conditions. Pressure differences are calculated over the vertical distance of the building using measured temperatures (from Table 1) in a form of Equation 2. Note that soil temperatures tend to cause pressure differences below grade to be less negative during winter and less positive during summer than if only outdoor temperatures were used.

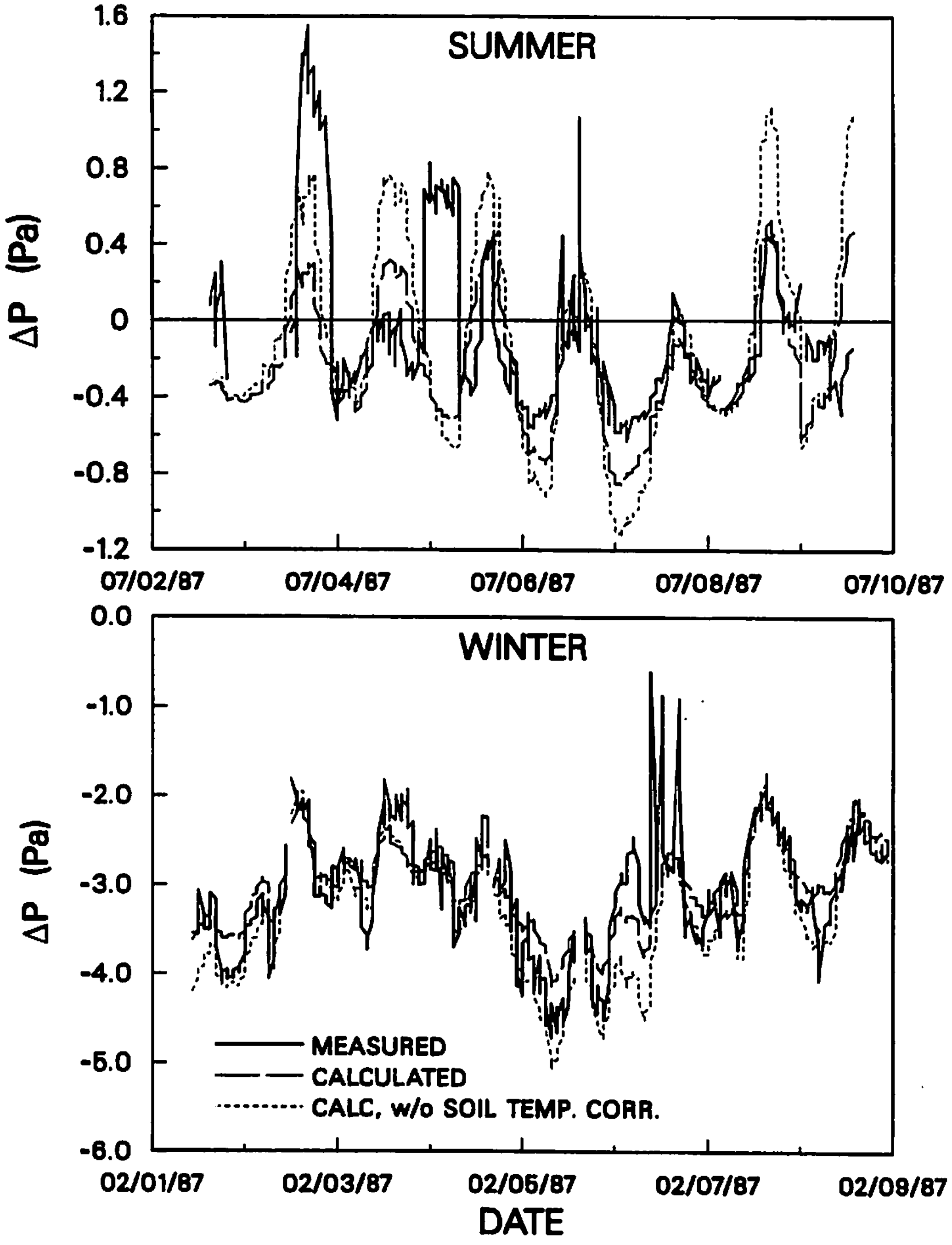

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Figure 2 Summer (a) and winter (b) plots of pressure differences between the basement at the floor and outside in the soil at the same elevation for New Jersey house LBL08. Measured ΔP are represented by a solid line, calculated ΔP that are corrected for soil temperature by a dashed line, and calculated ΔP without correction for soil temperatures by a dotted line. The calculated values using soil temperatures more closely predict measured values, while calculations without soil temperatures tend to overpredict pressure differences. Anomalous ΔP spikes are due to wind or mechanical system operation.

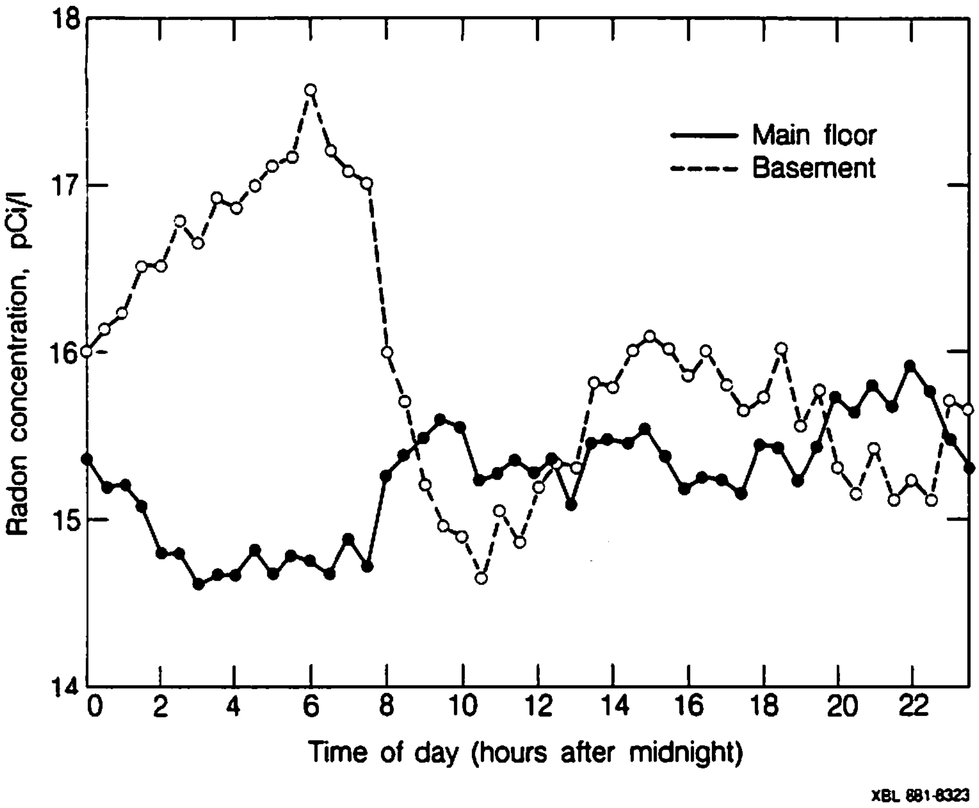
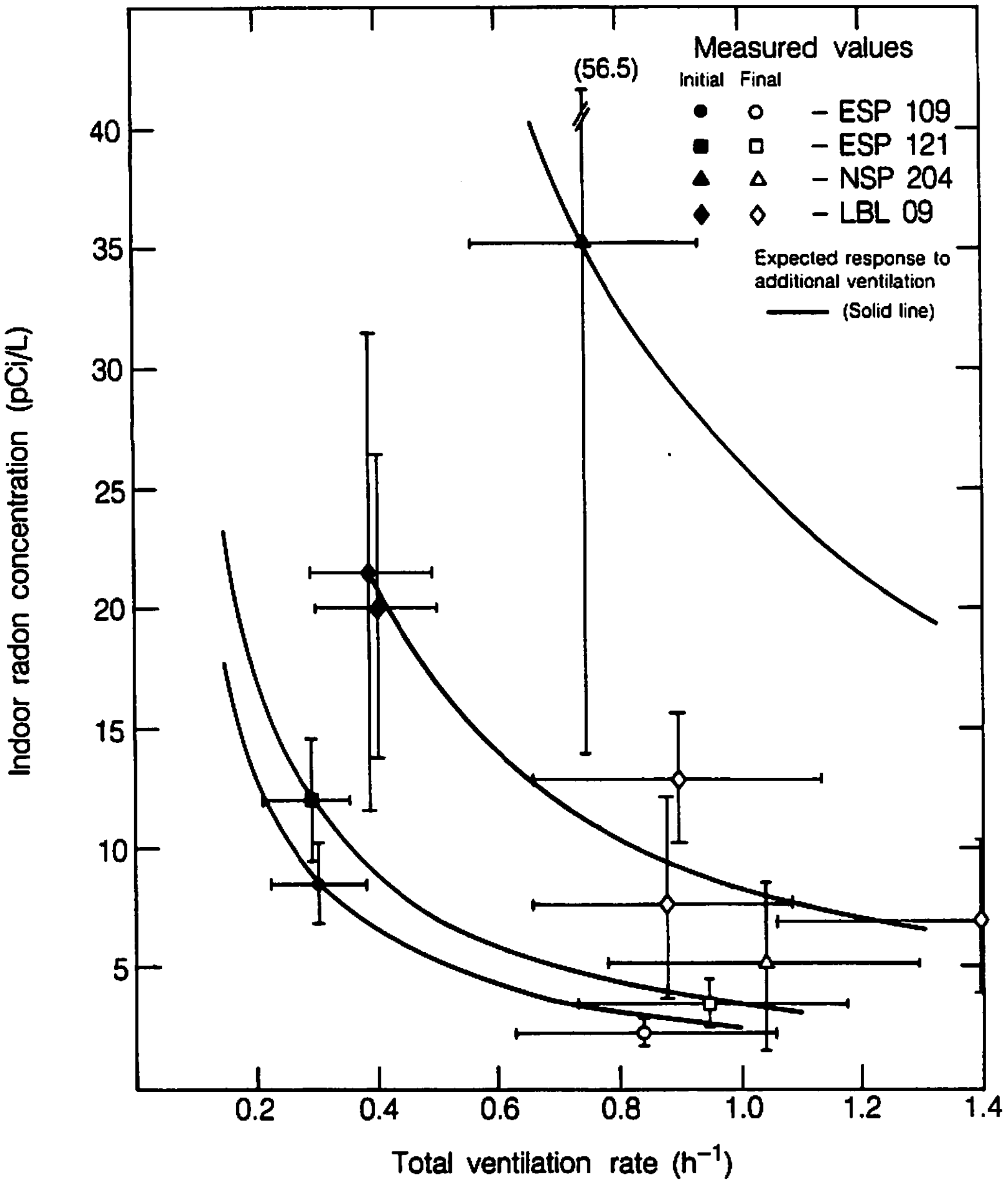


Figure 3 Average time-of-day basement and first floor radon concentrations for 120 days during the heating season for Spokane River Valley house ESP108C. When the thermostat requests higher indoor air temperatures, mixing of house air by the forced air furnace blower causes radon concentrations to become more equal between levels.



XBL 8710-11268

Figure 4 **Actual vs. expected reduction in indoor radon due to additional ventilation from AAHX's in four houses. Because of improved radon removal by a modified air distribution system, concentrations in house NSP204 do not respond in a manner that is inversely proportional to the additional ventilation.**

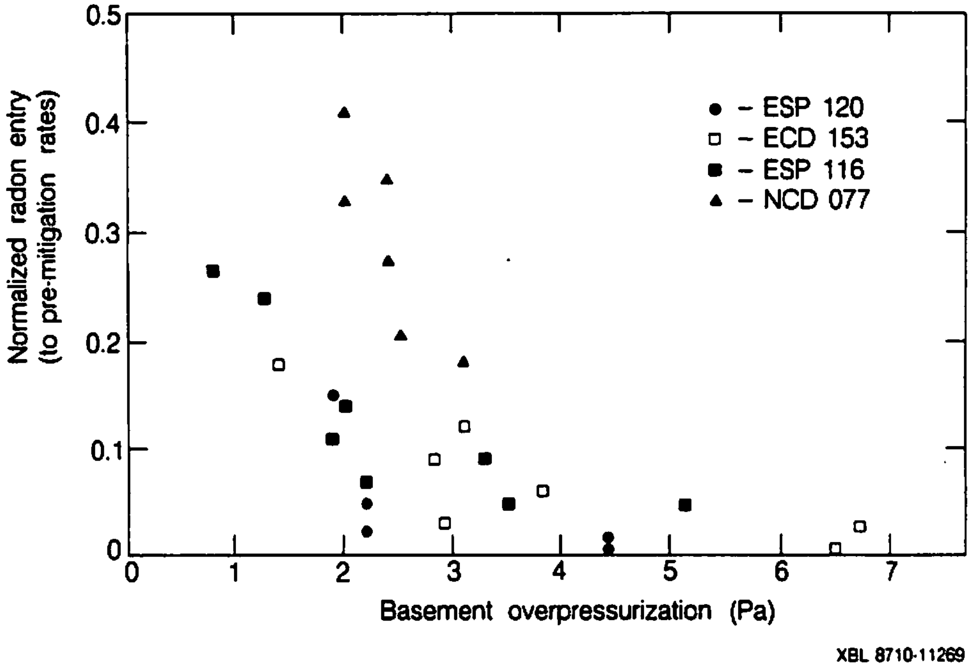
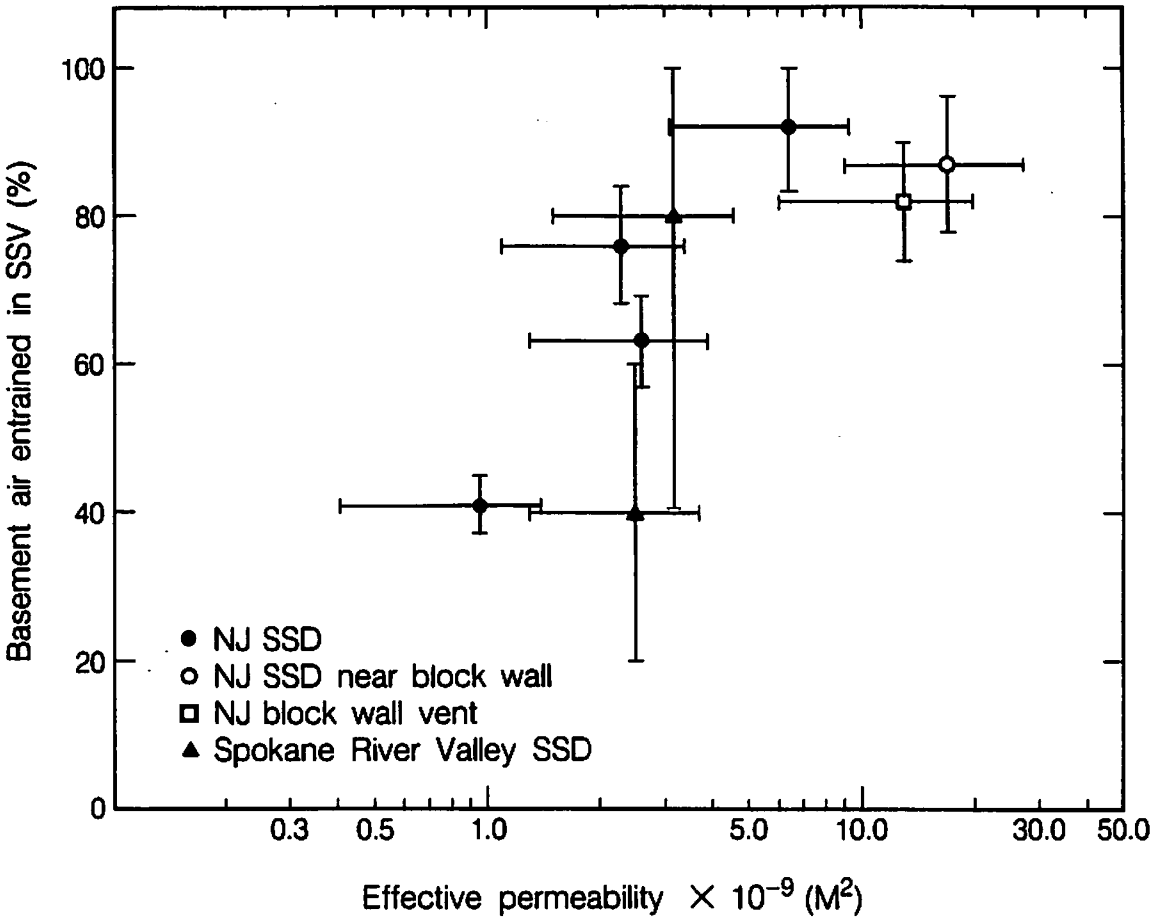


Figure 5 Incremental increases in basement overpressurization reduced radon entry rates in four Spokane River Valley houses by decreasing the amount of time that the basement experiences negative pressure differences.



XBL 889-8953

Figure 6 Percent of basement air entrained in SSV exhaust increases along with effective permeability calculated for SSV pipes. These data imply that leakage pathways through the below grade surfaces of the substructure greatly influence flow resistance to SSV systems.

Table 1. ENVIRONMENTAL TEMPERATURES (°C) AT LBL08 USED FOR FIGURE 1

		WINTER 2/9/87 @ 2100	SUMMER 7/8/87 @ 1630
Soil temperatures (depth):			
	(08.15 m)	1.3	23.7
	(0.76 m)	4.0	20.6
	(1.98 m)	6.9	16.8
Outside		-10.3	30.1
Basement		12.2	21.5
First floor		15.8	26.0

Table 2. EFFECTIVE AIR PERMEABILITY AT SSV PIPES

			Effective Permeability (m^2)			
Description	No. Houses	No. Pipes	Geometric Mean	Maximum	Minimum	Geometric Mean Soil Permeability near House(s) (m^2)
<u>Spokane River Valley</u>:						
All SSV	6	16	2.0×10^{-9}	5.4×10^{-9}	6.2×10^{-10}	5.4×10^{-11}
a) SSV w/gravel below slab	1	1	2.1×10^{-9}	-	-	4.3×10^{-11}
<u>New Jersey</u>:						
All SSV	7	9	4.1×10^{-9}	2.3×10^{-8}	9.6×10^{-10}	4.0×10^{-11}
All SSV, except a), below	6	7	2.7×10^{-9}	6.2×10^{-9}	9.6×10^{-10}	4.8×10^{-11}
a) SSV external to block wall	1	2	1.7×10^{-8}	2.3×10^{-8}	1.2×10^{-8}	9.9×10^{-12}
b) SSV attached to drain tile	1	1	2.6×10^{-9}	-	-	1.0×10^{-11}
c) SSV attached to perimeter drain duct	2	2	3.6×10^{-9}	6.2×10^{-9}	2.1×10^{-9}	9.7×10^{-11}
d) SSV w/o gravel below slab	1	1	4.2×10^{-9}	-	-	5.1×10^{-11}
Block Wall Ventilation	1	2	1.3×10^{-8}	1.4×10^{-8}	1.2×10^{-8}	9.9×10^{-12}