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Session VIII:

Radon Prevention in New Construction

EVALUATION OF RADON RESISTANT NEW CONSTRUCTION TECHNIQUES

by : Terry Brennan
Mike Clarkin
Camroden Associates, Inc.
Oriskany, NY 13424

Michael C. Osborne
USEPA/AEERL
Research Triangle Park, NC 27711

Bill Brodhead
WPB Enterprises
Riegelsville, PA 18077

ABSTRACT

In 1989 a project to evaluate three approaches to radon resistant new construction was undertaken by the Radon Mitigation Branch of the EPA Air and Energy Engineering Research Laboratory. Test houses were selected. Indoor radon was measured to evaluate the effectiveness of foundation sealing and passive and active soil depressurization at preventing radon entry into the houses. Tracer gas methods were developed to estimate the fraction of air that was being drawn through the cracks and holes in the foundation by the soil depressurization system. Below grade leakage area was estimated using tracer gas data. It was found for the small number of houses in the study that a very small amount of below grade leakage can still result in elevated indoor radon levels. Passive soil depressurization systems were found to perform better than mechanical barriers alone, but did not keep radon levels as low as active systems. Active soil depressurization systems were found to perform very well.

KEY WORDS

Radon, Active Sub-slab Depressurization, Passive Sub-slab Depressurization, Barrier.

This paper has been reviewed in accordance with the U. S. Environmental Protection Agency peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

Growing concern about the health risks associated with indoor radon, a radioactive gas found in varying amounts in nearly all houses, has underscored the need for dependable radon-resistant residential construction techniques. In response to this public health exposure the United States Environmental Protection Agency (EPA) has developed and demonstrated a variety of methods that have been used to reduce indoor radon levels in existing houses. Many of these methods are being included in the design and construction of new houses. In an effort to determine whether a house built with radon resistant techniques would have had elevated radon levels if the radon resistant techniques had not been used and to evaluate the effectiveness of those techniques, EPA sponsored the Evaluation of Radon Resistant Construction Techniques project. This project addressed active versus passive sub-slab depressurization systems, investigated the effectiveness of using the foundation as a barrier, and assessed the energy penalties associated with the use of a sub-slab depressurization system. Because of the limited scope of this paper, the energy penalty issues will not be covered.

Two houses in Northern Virginia and two houses in Allentown, Pennsylvania, were selected for this project. All houses had sub-slab depressurization systems installed or provided for during construction. Careful attention was paid to foundation detail. Measurements made in these houses included continuous radon measurements with the sub-slab depressurization system operating under various conditions and, to some extent, monitoring of pressure differentials and airflows.

INVESTIGATION OF HOUSES -- RADON RESISTANT TECHNIQUES USED

The two Virginia houses, designated VA1 and VA2, are nearly identical 2-story frame houses built in a subdivision. The two houses are approximately 300 ft apart. Each house was constructed with radon resistant techniques including a layer of DOT #2 or ASTM #57 stone pebbles placed beneath the slab prior to pouring, a single-point sub-slab depressurization system, and perforated pipe placed within the stone layer. Additional techniques used were poured concrete foundation walls, sump holes capped and vented to the outdoors, and caulked floor/wall joints, form ties, and expansion joints.

The two Pennsylvania houses, designated PA1 and PA2, each has a layer of DOT #2 or ASTM #57 stone pebbles beneath the slab, a single-point sub-slab depressurization system, poured concrete foundation walls, capped sump holes, and caulked floor/wall joints and form ties. Both houses have perforated sub-slab interior footing drains connected to the sump holes. In House PA1, the sub-slab depressurization penetration is located approximately 18 in.* away from the footing drain. The House PA2 sub-slab depressurization system is connected directly to the sump hole.

RADON SOURCES

Sub-slab radon grab samples were taken at all houses. The two Virginia houses averaged less than 100 pCi/L beneath the slab. The two Pennsylvania houses averaged concentrations in excess of 1000 pCi/L beneath the slab.

ACTIVE VERSUS PASSIVE SUB-SLAB DEPRESSURIZATION SYSTEMS

Radon measurements were taken with the sub-slab system in the active and passive modes at Houses VA1, PA1, and PA2. The results of the radon measurements are illustrated in Figures 1,2, and 3, respectively. As can be seen, the radon concentrations in House VA1 are quite low. This was to be expected because the sub-slab radon grab samples indicated radon concentrations less than 100 pCi/L. For this reason it was decided that this house and House VA2 were not appropriate for this portion of the study. In order to determine the effectiveness of radon resistant construction techniques, it was felt that radon levels of at least 700 pCi/L (Br88) beneath the slab should be present.

(*) Readers more familiar with metric units may use the factors listed at the end of this paper.

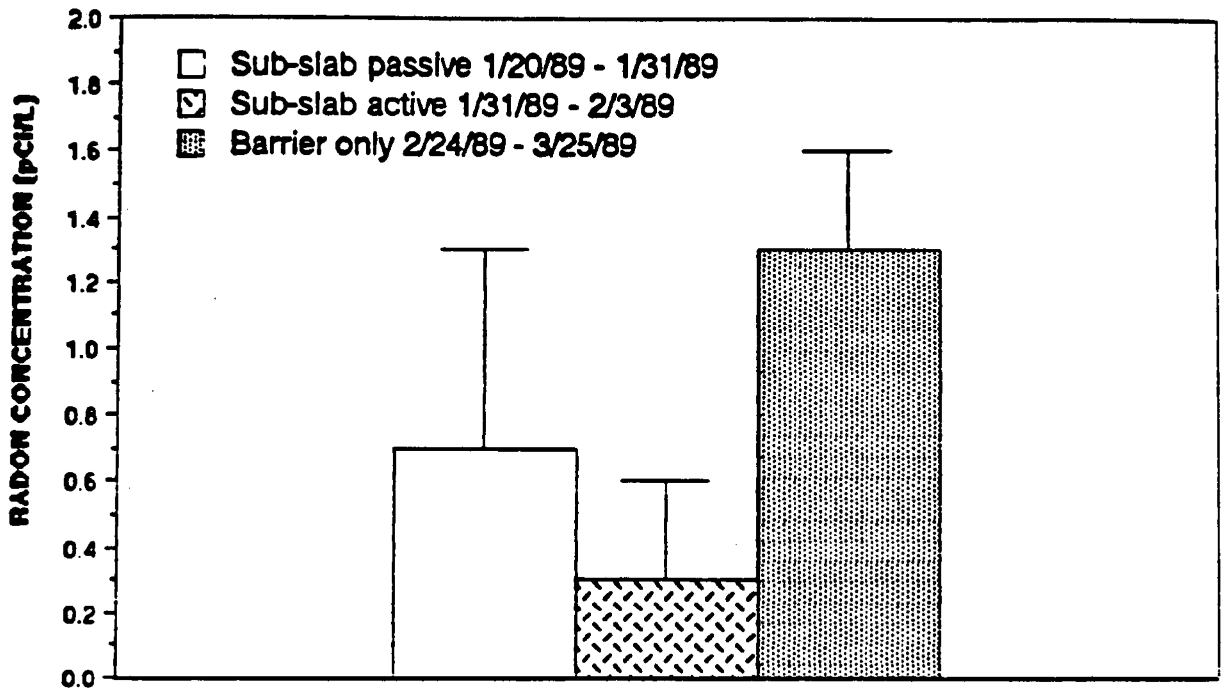

Figure 1. House VA1 basement radon concentrations with sub-slab system in the passive and active modes and with the exhaust pipe capped. (Error bars show 1 Standard Deviation)

House PA1 averaged 1.1 ± 0.2 pCi/L in the active mode from March 31 to April 5, 1989. During this same period, the sub-slab depressurization system was maintaining an average pressure difference between the basement and the sub-slab air of -210 Pa. The system was placed in the passive mode on April 7, 1989, and allowed to run passively until April 13. During this period, the basement radon concentration averaged 8.2 ± 2.4 pCi/L. Unfortunately, equipment malfunctions resulted in the loss of the pressure differentials during this period; however, for the period between April 5 and 7, the sub-slab system maintained an average pressure differential of -1 Pa in the passive mode. While this should not be considered the pressure differential that the system was developing during the April 7 to 13 period, it does represent the pressure differential that the passive system can develop. A pressure differential of 1 Pa is very small and can be easily overcome. In fact the pressure differential switched from negative to positive during the April 5 to 7 monitoring period. On April 13, 1989, all radon monitoring equipment was removed from the field for calibration checks, and not placed back in the field until May 5. The system was again placed in the passive mode on May 5, and allowed to run passively until May 11. Basement radon concentrations during this period averaged 9.9 ± 3.6 pCi/L. In order to determine how the active system would perform under stress, the basement was depressurized to an average of -10 Pa during the period from June 6 to 27, 1989. During this period basement radon concentrations averaged 1.5 ± 0.6 pCi/L. This is not significantly different from the non-stressed test.

While it is obvious that active soil depressurization has a dramatic impact on indoor radon concentrations the case is much less clear for passive soil depressurization. During the two periods in April and May that passive soil depressurization was monitored the radon concentrations were 8 to 10 pCi/L. However in the barrier-only testing in May immediately following the passive test the radon concentration was 9.4 ± 2.8 pCi/L (see Figure 4). This implies that the passive soil depressurization had little effect on the basement radon concentrations, but is not conclusive. Later the barrier-only method resulted in indoor radon levels of 20 ± 8 pCi/L.

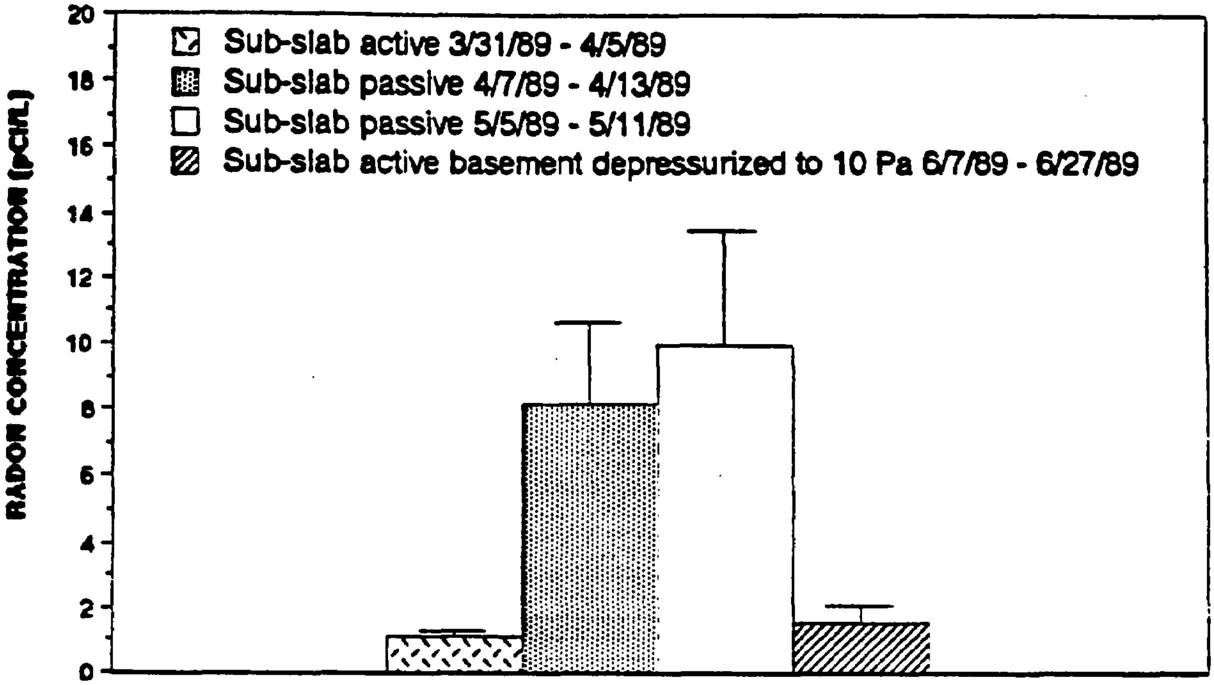

Figure 2. House PA1 basement radon concentrations with sub-slab system in the active and passive modes and active mode with basement depressurized to 10 Pa.

House PA2 was also subjected to cycling between active and passive sub-slab depressurization systems. From February 6 to 8, 1989 (admittedly a very short period), the basement radon concentration averaged 0.4 ± 0.3 pCi/L with the system in the active mode. From February 8 to 11, the basement averaged 3.5 ± 3.4 pCi/L with the system in the passive mode. On March 3, the system was placed in the active mode and run until April 1. Basement radon concentrations over this period averaged 0.6 ± 0.7 pCi/L. The system was again placed in the passive mode on May 5 and run passively until May 18. Basement radon concentrations averaged 1.5 ± 0.5 pCi/L over this time period. After a series of experiments that involved the testing of the barrier in this house, the system was again run passively from July 24 to August 18. Basement radon concentrations over this period averaged 2.23 ± 0.7 pCi/L.

Note that, in this house, passive soil depressurization worked better than barrier-only in consecutive tests in May [1.5 ± 0.5 pCi/L passive and 5.2 ± 2 pCi/L barrier-only (see Figure 5)]. Another interesting bit of data for the passive soil depressurization in this house was that it kept radon levels at 5.2 ± 5.1 pCi/L when a 16 sq in. hole in the slab was resulting in 36.7 ± 8.9 pCi/L with barrier-only technique. This is rather encouraging for passive soil depressurization in some cases.

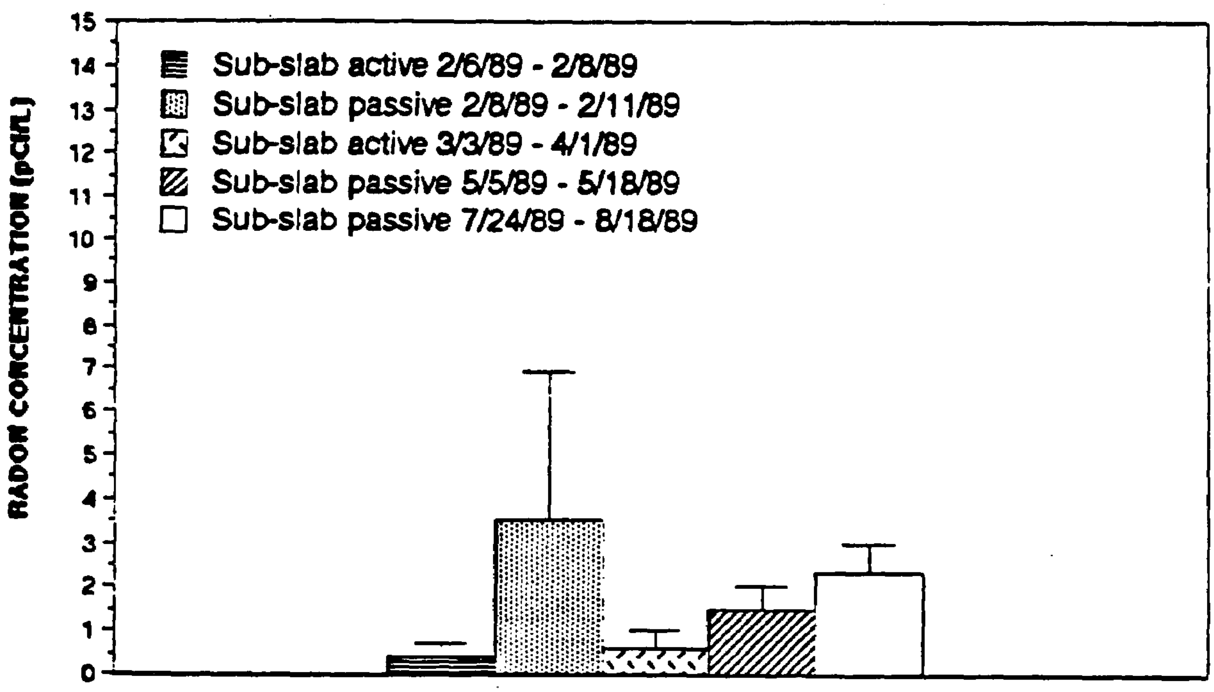

Figure 3. House PA2 basement radon concentrations with sub-slab system in the active and passive modes.

EFFECTIVENESS OF BARRIERS

Although the radon source at House VA1 was considered too low to include the house in this portion of the study, measurements were made to see how effective the barrier was. The basement radon concentration was continuously monitored from February 24 to March 25, 1989. Basement radon concentrations during this period averaged 1.3 ± 0.3 pCi/L.

House PA1 was subjected to a series of experiments designed to determine both the effectiveness of a barrier and the effect various size holes in the barrier have on the indoor radon concentration. As can be seen in Figure 4, even the best laid plans of the most conscientious researchers often go awry. Radon concentrations in the basement varied greatly with no regard for hole size even when radon source strengths were similar. One would have expected that increasing the size of the hole would have resulted in higher radon concentrations.

It is hypothesized that the leakage area already present is large enough so that increasing the area and allowing more air to be drawn in through the soil is diluting the soil air and lowering the soil air concentration faster than the production and transport of radon can replenish it.

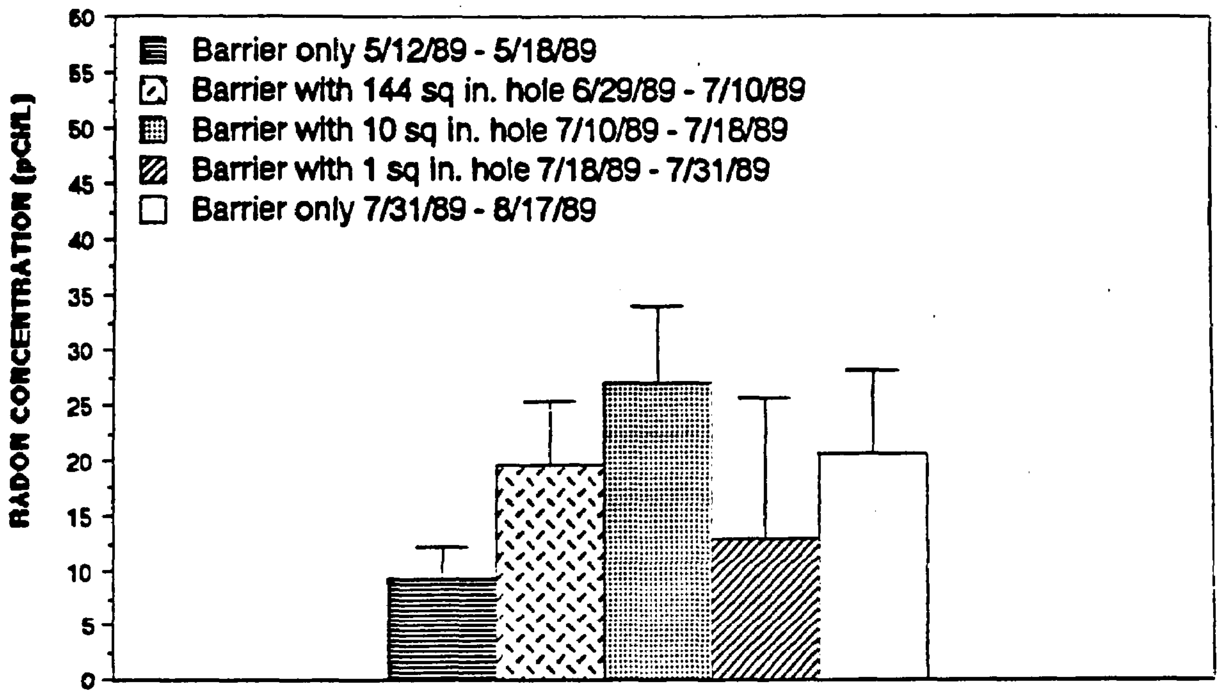

Figure 4. House PA1 basement radon concentrations during barrier-only tests.

The effectiveness of the barrier in House PA2 was also tested. This house followed the idea that increasing the below-grade leakage area should result in an increase in basement air radon concentrations. As seen on Figure 5, a 16 sq in. hole in the barrier resulted in increased concentrations, compared to the intact barrier. Radon concentrations with the 16 sq in. hole increased rapidly to an average of 36.7 ± 9 pCi/L. From July 13 to 24, the sub-slab system was operated in the passive mode with the same 16 sq in. hole in the barrier as in the previous period. The passive sub-slab system maintained the basement radon concentration at 5.2 ± 5 pCi/L. Because of this behavior it is believed that the amount of below-grade leakage area is smaller than the critical size at which soil air dilution puts a cap on the basement air concentration. This hypothesized phenomenon would be very dependent on the strength of radon sources and their geometry with respect to low airflow resistance pathways beneath the house and through the foundation.

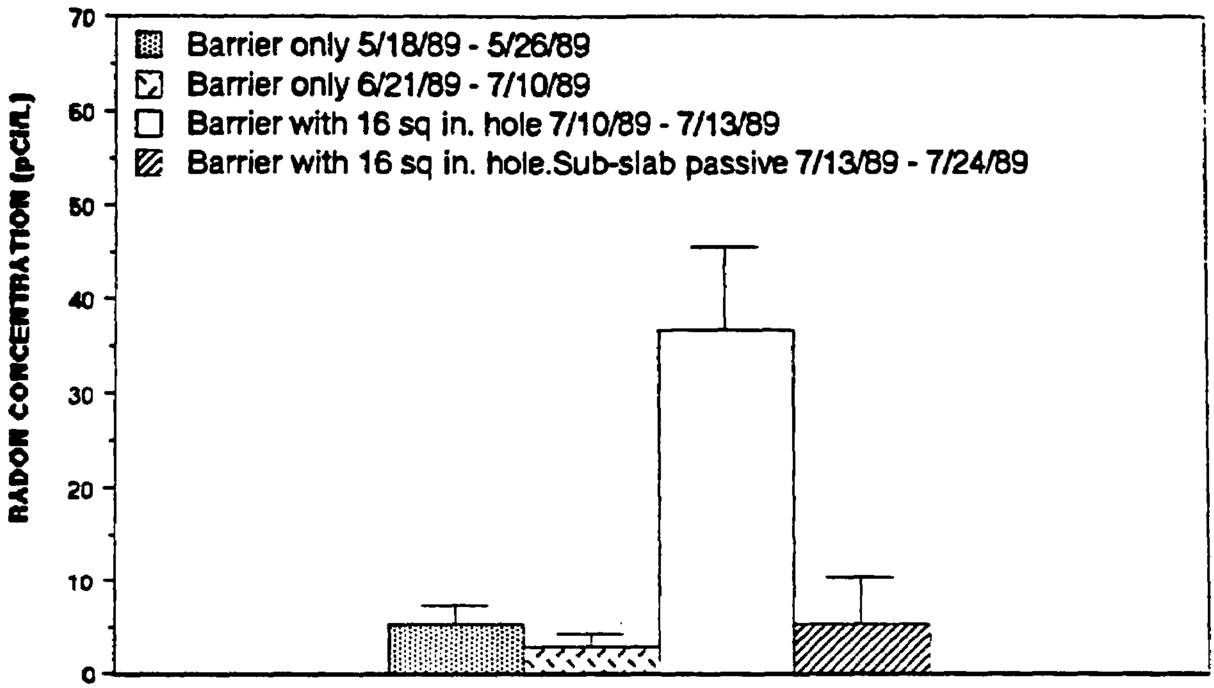

Figure 5. House PA2 basement radon concentration during barrier-only tests.

BELOW GRADE LEAKAGE AREA (BGLA)

The BGLA was estimated in three of the houses (VA1, VA2, and PA1). The measurement was not made in House PA2 because it was occupied and access was limited. This is unfortunate because it seems to have had the best results for the mechanical-barrier-only technique. The technique used to estimate the BGLA is as follows. The total airflow out of the active sub-slab stack and the fraction of that exhaust air coming from the basement was estimated using a tracer gas technique (described in detail in a poster paper (Cl 90). The air pressure differential between the sub-slab air and the basement air was measured using a micromanometer at several test holes. Because of the tightness of the foundation and the surrounding low-permeability soil it was found that the layer of stone pebbles beneath the slab acted like an air plenum. That is, there was very little difference in pressure differences (DPs) measured at different locations (all DPs were within 3% of each other from one end of the basement to the other in all three houses). Given this special case it is possible to calculate the leakage area of a sharp-edged orifice (Sa89) that would give the same airflows at the same DPs as was measured in each house. Figure 6 summarizes the measurements and the calculated BGLAs.

House ID	Average DP (in. WC)	Total Stack Airflow (cfm)	Basement Airflow(cfm)	BGLA (sq in.)
VA1	0.44	78	34	3
VA2	0.22	24	11	1.4
PA1	0.78	16	3	0.2

Notice that the BGLAs are a few square inches or less. In fact, for one of the houses it is only 0.2 sq in. As a check on the BGLA soil gas concentrations, basement infiltration rates and the airflow characteristics of the BGLAs were used to estimate basement radon concentrations if the basements were depressurized by 1 to 2 Pa. The results for Houses VA2 and PA1 compared well with actual radon measurements made in them (an estimated range of 20 to 30 pCi/L compared to 9 to 20 pCi/L measured for PA1 and an estimated 1 to 2 pCi/L compared to <1 pCi/L measured for VA2). However, the estimated concentration for VA1 was 20 to 30 pCi/L and the measured indoor radon concentration in VA1 was 1.3 ± 0.3 pCi/L. It is hypothesized that the BGLA in VA1 actually is close to the 3 sq in. estimate: the explanation for the much lower measured indoor radon concentrations than would be predicted is the result of outdoor air leaking under the slab at the corner of the basement with a walkout door. Air leaking in at this site would not pass through much soil and could be diluting the air beneath the slab. The exterior door was tightly sealed.

The remarkable thing about these BGLA measurements is that under some circumstances it takes only a tiny leakage area to result in elevated indoor radon. The implications are not encouraging for depending on a mechanical barrier technique to control indoor radon.

CONCLUSIONS

The conclusions of this study must be considered as representing only a few houses, located in specific soils and climates, and (except for PA2) unoccupied. Because all of these houses had tight foundations and relatively tight soils, they also represent only one of four possibilities (tight soil - tight foundation, loose soil - loose foundation, tight soil - loose foundation, and loose soil - tight foundation).

The limited sample studied shows that making mechanical barriers that can prevent soil air entry may be impractical with the ordinary amount of quality control found in the construction of most houses. This study includes an example of a house with a very tight foundation (10 to 100 times tighter than the tightest of building shells) that still has elevated indoor radon levels. Additionally it was found that enlarging the leakage area in this foundation had no dramatic impact on the indoor radon concentrations, implying that tightening efforts had little impact on the radon levels observed in the barrier-only mode in this particular house.

Passive soil depressurization seemed to work fairly well in House PA2, but did not seem to work at all in PA1. This result is not unexpected considering the wide variety of environmental and site specific variables that impact on indoor radon concentrations. The question that remains to be answered is how often or under what circumstances is passive soil depressurization a viable option? Both houses meet a goal of radon levels as low as possible using active soil depressurization.

Active soil depressurization proved to be extremely effective in all houses tested. In PA1 indoor radon levels averaged 0.57 pCi/L and never got above 3 pCi/L in the active mode, and in PA2 indoor radon averaged 1.4 pCi/L and was never above 2 pCi/L in the active mode. Both houses spent a good deal of time below 1 pCi/L of radon. At these low levels, uncertainty due to measurement accuracy begins to become an important source of error in hourly measurements.

METRIC CONVERSION FACTORS

Readers more familiar with metric units may use the following to convert to that system:

Nonmetric	Multiply by	Yield Metric
ft^3/min	0.00047	m^3/sec
ft	0.305	m
ft^3	0.028	m^3
in.	2.54	cm
$in.^2$	6.45	cm^2
in. WC	0.249	kPa

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Radon Mitigation Performance of Passive Stacks In Residential New Construction

By: David W. Saum
Infiltec
Falls Church, VA 22041

and Michael C. Osborne
U.S. EPA, AEERL
Research Triangle Park, NC 27711

ABSTRACT

Passive stacks have been proposed and installed as a radon resistant measure in new houses, but little quantitative data on their performance has been collected. This study involved continuously monitoring several houses that were recently built with radon resistant features including crack sealing, porous subslab aggregate, and a stubbed off pipe penetrating the slab for use in installing a radon mitigation system. For this project, the pipe systems were completed so that they exited from the roof, and half of the houses had radon mitigation fans installed on the pipes. Houses were continuously monitored with the pipes sealed, then with the pipes open but no fans operating, and finally with the fans (if installed) operating. The results show significant radon mitigation performance by the passive stack systems in most cases, and excellent mitigation by the active systems. Failures by the passive stack systems appear to be due to basement depressurization by heating, ventilation, and air-conditioning (HVAC) duct leakage, poor installation of subslab piping, and poor communication between multilevel slabs.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

A passive stack (PS) radon mitigation system is a type of subslab depressurization (SSD) system where the source of exhaust power in the stack is buoyant air rather than an electric fan. The buoyant force is generated whenever the air in the pipe is at a higher temperature than the outdoor air. Since the major cause of radon entry into houses is thought to be pressure driven flow of radon into the house that is primarily caused by temperature differentials, the PS has been suggested as an inexpensive, low energy solution to radon problems that automatically compensates for changes in temperature.

Several problems with PS radon mitigation have been suggested: reverse pressures from wind, pressure losses under the slab, reverse pressures during the summer, and reverse pressures due to mechanical and heating appliances. Although some mitigators report installing PS systems, there is little quantitative data on their performance. This paper reports on a study of PS in 16 new houses constructed by Ryan Homes in Maryland and Virginia. These houses had basement radon levels between 4 and 20 pCi/L before the stacks were installed. During construction, a pipe stub was imbedded in the slabs, 4 in. (10 cm) of clean coarse aggregate was installed beneath the slabs, and the floor-wall cracks were sealed with polyurethane caulk. In half of these houses the passive stack performance was compared to conventional fan powered SSD performance. This paper contains a discussion of the passive stack theory, a summary of results, and conclusions.

PASSIVE STACK THEORY

The term stack effect is commonly used to describe the pressures and flows that are generated when buoyant warm air is enclosed in a building. The ASHRAE Handbook of Fundamentals[1] contains an extensive discussion of building stack effect. Figure 1 is a schematic diagram of the stack pressures that would be expected in a house when there is no wind and the inside temperature is higher than the outdoors. In order to understand the stack effect, two terms -- column pressure and neutral pressure level -- must be defined.

Column Pressure

Column pressure is the maximum differential pressure that can be induced across any point on the building shell by an inside-outdoor temperature difference. The column pressure is proportional to the building height and the temperature difference between inside and outdoors. For example, a 45°F (25°C) temperature difference and an 8 ft (2.4 m) building height will induce a column pressure of 0.01 in. (0.025 cm) wc pressure across the building envelope. In Figure 1 the column pressure is the sum of the top and bottom pressures. Note that the column pressure is not affected by the airtightness of the building.

Neutral Pressure Level

The neutral pressure level (NPL) is the imaginary line around the enclosure where the differential pressure inside-outdoors is zero. In Figure 1 the top pressure is shown to be equal in magnitude to the bottom pressure. This results in a NPL that is half way up the side of the enclosure. The NPL location and stack pressure distribution across the building envelope are determined by the building airflow resistance, including the resistance of both the building shell and any internal partitions. In houses, there are generally large openings (doors) or leaks between floors, and the internal airflow resistance is assumed to be small relative to the shell airflow resistance. Therefore, the shell openings determine the location of the NPL and the pressures across the top and bottom of the shell. Note that the NPL and the pressures on the enclosure are determined by the distribution of leaks on the enclosure surface, and not by the overall airtightness or leakiness of the enclosure. Leakier enclosures will require more heat to maintain the inside-outdoor temperature difference, but the column pressure will be independent of the airtightness. If the majority of leaks are near the top of the enclosure, then the NPL will be near the top, but the maximum pressures will be at the bottom. When top and bottom openings are equal in size, the NPL is midway up the side of the enclosure.

Effects of Sealing

Sealing leaks in the enclosure will not change the column pressure, but the NPL will be shifted if leaks near the top or bottom of the enclosure are sealed. Since radon entry may be proportional to the depressurization of the slab, sealing the upper part of the shell should be beneficial since it will reduce this depressurization, but sealing leaks in the lower part of the shell should be detrimental since it will increase the depressurization of the lower part of the enclosure. If a house could be sealed as completely as a hot air balloon, with all remaining leaks concentrated at the bottom, then there would be no stack induced depressurization on the slab that would pull radon into the house. Appendix A contains a calculation which relates shell leakage distribution to pressure on the lower surface of the enclosure.

Figure 2 shows the changes in pressure on the upper and lower surfaces of an enclosure under a variety of leakage configurations. Figures 2.A and 2.B have already been discussed, Figure 2.C shows the effect of sealing half the leaks in the bottom, while Figure 2.D shows the effect of sealing half the leaks in the top. As a general rule for radon control, air sealing should be limited to the upper surfaces of the house in order to minimize depressurization of the slab. Since a PS system does not have much suction power, the reduction of stack effect in the building may be necessary to maximize its performance.

Passive Stack System

A PS radon mitigation system is shown schematically in Figure 3, and its performance is determined by the interaction of two stacks. The house acts as a stack which creates depressurization above the slab, and the PS pipe generates a counteracting depressurization below the slab. For the PS to operate successfully, the PS must induce slightly more depressurization beneath the slab than the house induces above. For best performance of the PS five conditions must be met.

Raise the column pressure of the PS

The PS depressurization beneath the slab should be maximized by keeping the temperature of the stack as high as possible relative to the outdoor air temperature. Most important, the PS should not be run though unheated spaces, such as garages.

Raise the NPL of the stack

The flow though the stack should be minimized by sealing the slab to keep the NPL of the PS as high as possible which will increase the depressurization below the slab. A PS that is open at both ends will have a NPL at its midpoint, and a PS that is connected to an airtight subslab cavity will have a NPL at its top.

Lower the NPL of the house

The house stack depressurization above the slab should be minimized by air-sealing of the house envelope to lower the NPL of the house as much as possible. Air-sealing of the upper surfaces of the house will lower the house NPL, but sealing the lower part of the house will raise the NPL and increase the stack depressurization above the slab. Lowering the temperature of the house would decrease house stack depressurization, but it is not generally practical, and would also result in a lower stack temperature. Note that if the house NPL is below the stack NPL, then the PS will not provide radon mitigation.

Maximize air-flow communication under the slab

If there is any airflow into the stack, there will be a pressure drop in the aggregate that will reduce the depressurization of some areas of the subslab. Good airflow communication by using clean coarse aggregate and laying perforated pipe under the slab may minimize this problem.

Minimize any mechanical source of house depressurization

Any negative pressure in the house will add to house depressurization above the slab. Examples of this problem include imbalances in forced air distribution systems, fireplaces, exhaust fans such as dryers, and combustion air exhausted from the house by fossil fuel heating systems.

SUMMARY OF RESULTS

An Example of Passive System Performance

Figures 4 and 5 show the radon mitigation performance of a typical house (#MIL) in which a PS was installed. This house was built in 1987 and has 1600 sq ft (149 m^2) of finished space with 800 sq ft (74 m^2) of unfinished basement area. The basement has poured concrete walls, is about 4 ft (1.2 m) below ground, and has a sump connected to an external footing drain. The passive stack goes up about 12 ft (3.7 m) through a chase inside the house and exits about 2 ft (0.6 m) below the roof line. During construction, a perforated pipe was laid in the 4 in. (10 cm) deep gravel bed beneath the slab and was run diagonally across the basement to provide communication. One end of the perforated pipe is connected to the sealed sump, and a T fitting was used to bring a 4 in. (10 cm) diameter pipe stub up through the slab for possible connection to a future radon control system. All visible slab cracks were sealed with polyurethane caulk. When the passive stack was installed in late 1988, a long twisted run of 4 in. (10 cm) pipe was necessary to connect the pipe stub at one side of the basement to the chase located in the center. The heating system is a heat pump with a fan system located in the basement, and the distribution ductwork is contained within the shell of the building. Blower door measurements showed about 5 air changes per hour (ACH) at 20 in. wc (50 Pa) which is relatively airtight for the Maryland climate.

Winter performance

Figure 4 shows the winter performance of the passive stack. Although the radon mitigation performance is significant (85%), the radon spikes suggested that some unknown depressurization source in the house was occasionally overcoming the PS system. When the basement was reexamined, it was found that the homeowner had sealed off all the supply ducts in the unfinished basement to save energy, but he had neglected to seal a large return vent. Therefore any time the basement door was closed, the basement was depressurized by about 0.030 in. (0.076 cm) wc. This counterpressure overcame the passive stack system and brought in radon but only when the basement door was closed.

Summer performance

Figure 5 shows the summer performance in house #MIL after the air return vent in the basement was sealed in order to prevent basement depressurization by the heat pump fan. Although the summer radon levels were much lower than the winter levels in this house, the PS radon reduction was still substantial (70%). There is no sign of the spikes that were seen in the winter, and the pressures measured under the basement door were less than 0.004 in. (0.01 cm) wc. During the period shown in Figure 5, the house was air conditioned, and there were several periods when the outdoor air temperature was higher than indoors. These data do not indicate that passive system performance decreases when the temperature differentials are reversed.

PS performance conclusions

In several of the PS houses, the stack provided radon mitigation well below 1 pCi/L during all seasons of the year. Performance did not seem to be affected by pipe straightness, position of the vent on the roof, or wind conditions. Houses with poorer mitigation performance seemed to have four main problems: 1) depressurization of the basement because of large leaks in the return ducts in the basement, 2) multilevel slabs that were not connected to the PS pipe system, 3) stack pipes run through unheated spaces, and 4) improperly connected stack pipes that were blocked by debris during construction. Even in houses where there was a combination of problems, the PS generally gave mitigation performance of at least 50%.

Passive Versus Active System Performance

In half the houses, SSD systems with fans were installed: these houses were studied to compare the performance of the PSs with the active systems. The stack was sealed for several days to approximate premitigation conditions, the stack was opened without fan operation to approximate a PS system, and finally the fan was turned on to demonstrate fan assisted SSD performance. The resistance of the fan in the pipe was assumed to be small enough to ignore because of the small airflows in the pipes under passive conditions. House #TIN had some of the highest radon levels in this study, but it was otherwise quite typical of the active houses. This house had 2000 sq ft (186 m^2) of finished floor area on two floors, and an unfinished 800 sq ft (74 m^2) walk-out basement below. The basement has poured concrete walls with the same crack sealing and stubbed off pipe described in the passive house. There was no sump and the pipe stub was connected only to a perforated pipe in the aggregate beneath the slab. The blower door measurement showed that this house was about 4 ACH at 20 in. wc (50 Pa) which is quite tight.

Winter performance

When the fan was on, the radon levels were well below 1 pCi/L, but they quickly rose to about 30 pCi/L when the fan was turned off and the pipe was sealed. When the passive stack was simulated by opening the stack without turning on the fan, the radon levels were significantly depressed, but there were occasional large spikes that could not be explained. Even so, the radon reduction due to the PS was about 75% (Figure 6).

Summer performance

The house was retested during warm weather in September: the radon levels during the PS test were lower than for the comparable winter levels. Since the measurements did not include a test period when the stack was sealed, it is not possible to determine the absolute mitigation performance. There were some spikes in the radon levels but not as many as the winter data showed. After this monitoring was concluded, a reexamination of the heat pump fan system showed that a construction defect had left a large hole in the return duct in the basement. The hole generated a depressurization of 0.050 in. (0.13 cm) wc in the basement every time the fan came on and the basement door was closed. The September PS data may be low for this house because the mild weather did not require much heat pump operation (Figure 7).

Active versus passive

The conventional active SSD system is a very reliable solution to radon problems in new construction houses because it will overcome most of the inadequacies of PSs highlighted in this study. Even the severe depressurization that was found in this house was negligible compared to the pressures of about 0.75 in. (1.9 cm) wc that are commonly generated under the slab by most SSD fans. The only problem in the test houses that this excess fan power could not overcome is the lack of communication between multilevel slabs that was seen in several houses.

CONCLUSIONS

This study suggests that PS systems in new house construction can provide radon mitigation that is comparable to the performance of active systems if there are no interfering sources of house depressurization. However, the study also suggests that forced air heating systems are major sources of house depressurization due to duct leakage. Since PS systems are very sensitive to pressure imbalances in the house, they provide a sensitive tool for studying the interaction of the other systems in the house.

Duct Leakage

The pressure imbalances in houses due to duct leakage and flow imbalance were recently studied in Florida houses by Cummings[2]. That study indicated that Florida houses typically have heat pumps in the attic outside the house envelope, and that duct leakage can cause depressurization or pressurization of the entire house. Since the houses in this study had no ductwork outside the conditioned space, the leakage could only cause room to room variations in pressure rather than changes in whole house pressure. However, when the HVAC fans are in the basement, as they were for all of the houses in this study, the probability of significant pressures in the basement is quite high. All of the houses in this study had pressurization of the upstairs bedrooms when the doors were shut because of the lack of returns in the rooms. This problem does not seem to produce significant basement depressurization. It seems to be more of an energy conservation problem than a contributor to the radon problem. Cummings[2] reports a similar problem in Florida.

Adequate Ventilation

The houses in this study were found to be almost airtight. If they did not have forced air heating and cooling systems, and the pressure or leakage problems previously discussed, then they might be under-ventilated when compared to ASHRAE recommendations[3]. If the duct leakage and imbalances were corrected for reasons of energy conservation or radon mitigation, then the ventilation impact should be considered.

Limitations and Suggestions for Further Work

This study was very limited in the housing stock studied since it only dealt with heat pump houses within a limited area. Future studies might look at Florida or Minnesota houses with their different climates and HVAC systems. All of the stacks in this study were 4 in. (10 cm) schedule 40 PVC pipe. It would be useful to study 3 in. (7.6 cm) pipe since it would be simpler and cheaper to run smaller pipe through the house.

Recommendations to Builders

Passive stacks appear to be the most effective passive radon mitigation technique for new construction. This study suggests that the stack should be run through the warm part of the house, excellent subslab communication can be provided with 4 in. (10 cm) of clean coarse aggregate, and the stack pipe should be run up to the roof line. Additional guidance should include avoidance of duct leakage that depressurizes the basement and connecting stack pipes to each level of multilevel slabs. Things that can be ignored include wind caps for the stack, multiple bends in the pipe, and failures due to cooling situations.

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1. ASHRAE Handbook of Fundamentals, Chapter 23 Infiltration and Ventilation, Section 23.2 Driving Mechanisms, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., Atlanta, Georgia, 1989.

2. Personal communication with J. B. Cummings, Florida Solar Energy Center, 300 State Road 401, Cape Canaveral, Florida, Sept. 13, 1989.

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APPENDIX A

CALCULATIONS

Column pressure P_{col} can be computed from barometric pressure P_b, enclosure height H, inside temperature T_{in}, and outdoor temperature T_{out}:

$$P_{col} = 0.52P_bH(1/T_{out} - 1/T_{in}) \quad (1)$$

where H = height of building in ft
P_b = ambient (barometric) pressure in psia (14.7 at sea level)
T = Rankine temperature (459 + Fahrenheit temperature)

The stack pressures can be computed in the case of an enclosure with sharp edged holes in the top and bottom with areas A_{hi} and A_{lo}. The equation for air flow Q under standard conditions through a sharp edged hole is given by:

$$Q = 16.9AP^{0.5} \quad (2)$$

where Q = flow in cfm
A = Area in sq in.
P = Pressure in in. wc

If air flows through an enclosure because of stack effect, then flow rate in Q_{lo} must equal flow rate out Q_{hi}:

$$Q_{lo} = Q_{hi} \quad (3)$$

or

$$16.9A_{lo}P_{lo}^{0.5} = 16.9A_{hi}P_{hi}^{0.5} \quad (4)$$

Rearranging, $P_{lo} = P_{hi}(A_{hi}/A_{lo})^2$ (5)

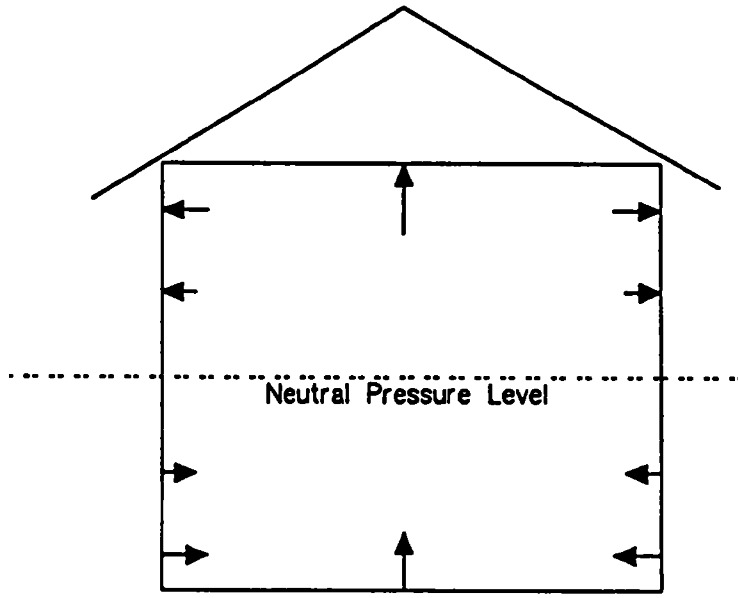
But column pressure P_{col} is the sum of the high P_{hi} and low P_{lo} pressures:

$$P_{col} = P_{hi} + P_{lo} \quad (6)$$

Combining 5 with 6:

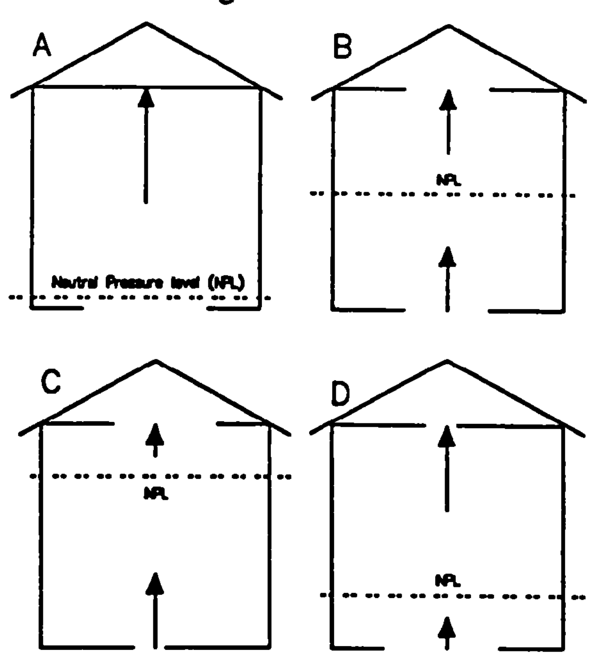
$$P_{lo} = P_{col}/[(A_{lo}/A_{hi})^2 + 1] \quad (7)$$

Note that lower pressure P_{lo} is determined by the ratio of upper A_{hi} and lower A_{lo} leaks and not by total leakage A.



Assume no wind and warmer indoors than outdoors
Arrow length represents pressure magnitude

FIGURE 1 Schematic Diagram of Stack Effect Pressures in a House



Arrow length represents pressure magnitude
Assume houses are warmer indoors than outdoors

FIGURE 2 Stack Pressures for Several Leakage Configurations

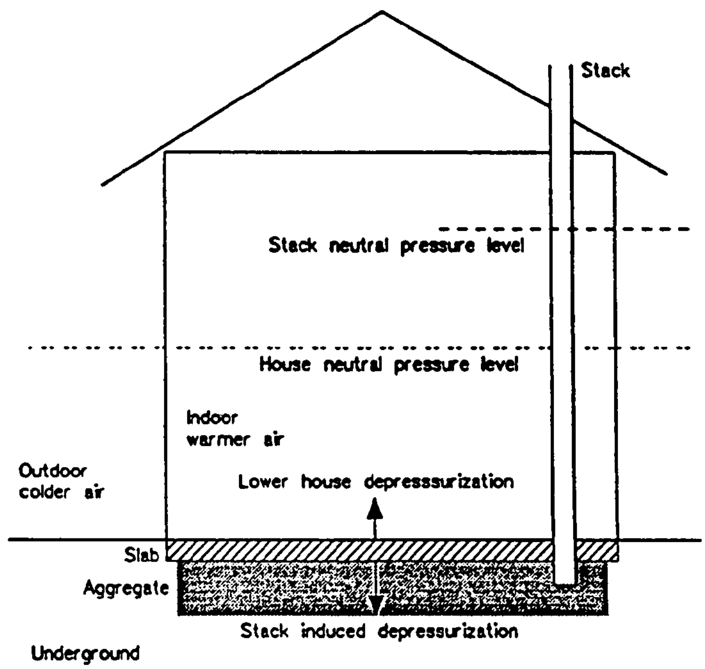


FIGURE 3 Schematic Diagram of Passive Stack Radon Mitigation System

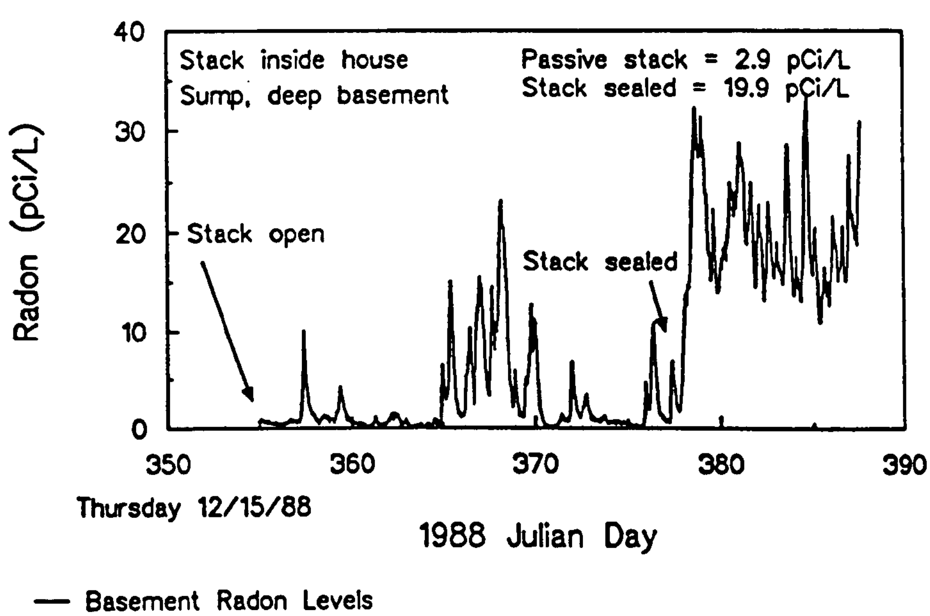


Figure 4 Winter Performance of Passive Stack System

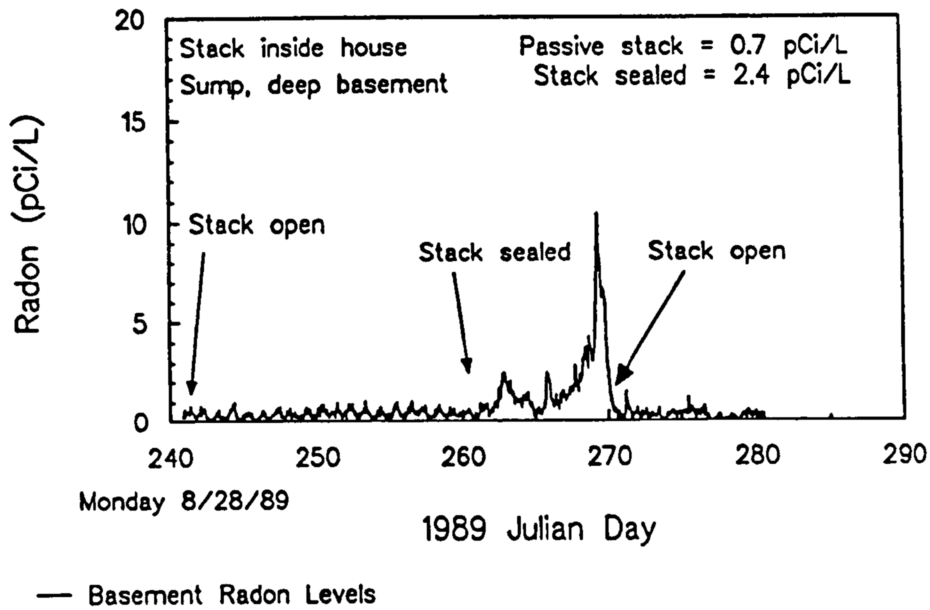


FIGURE 5 Summer Performance of Passive Stack System

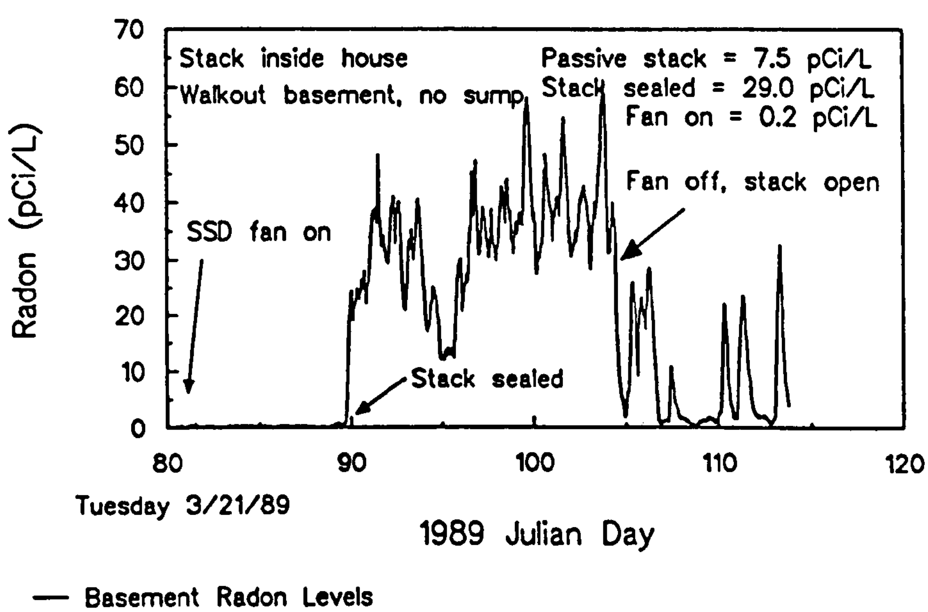


FIGURE 6 Winter Performance of Active and Passive Stack Systems

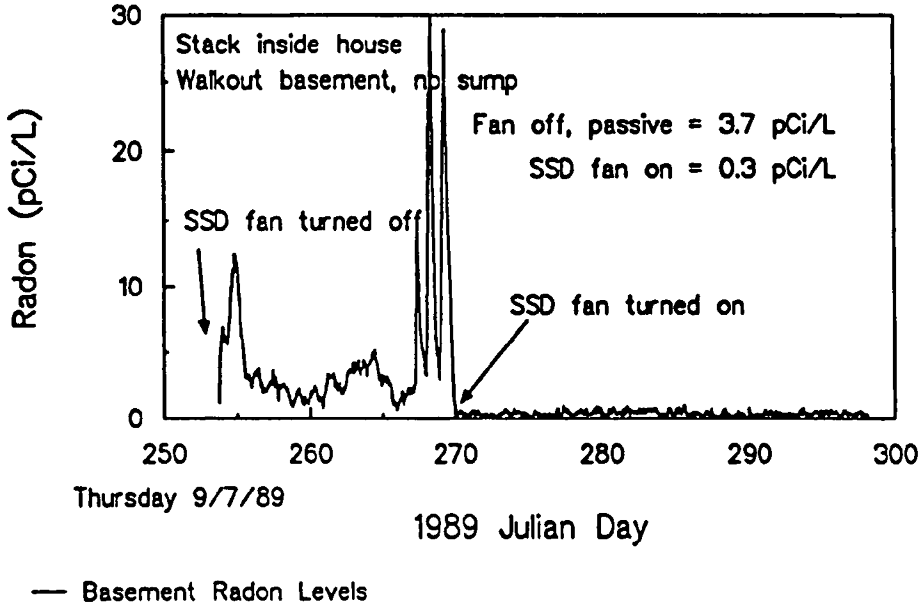


FIGURE 7 Summer Performance of Active and Passive Stack Systems

SUB-SLAB PRESSURE FIELD EXTENSION STUDIES ON FOUR TEST SLABS TYPICAL OF FLORIDA CONSTRUCTION

by: Richard A. Furman
School of Building Construction
University of Florida
Gainesville, FL 32611

David E. Hintenlang, Ph.D.
Department of Nuclear Engineering Sciences
University of Florida
Gainesville, FL 32611

ABSTRACT

The State of Florida is currently in the process of developing, under legislative mandate, a radon resistant building code for new construction. One of the research projects funded by the State is to examine the influences that various construction practices have on the effectiveness of sub-slab depressurization systems. Four test slabs have been constructed and pressure field extension studies have commenced. The influences of several construction practices and techniques including stemwall curtains, types of sub-slab fill, fill depth and sub-slab plumbing influences will be investigated. Climatic and other environmental conditions will be monitored to determine their influence on the sub-slab depressurization systems.

This paper will discuss which typical Florida construction practices have the most significant impact on the effectiveness of different sub-slab depressurization systems.

INTRODUCTION

Indoor radon has been identified as a problem in Florida for more than a decade. Early research in the phosphate mining areas of central Florida reported that substantially elevated levels of radium and radon were present in reclaimed mining lands. Not until the mid to late 1980's did indoor radon become acknowledged as a legitimate health hazard, thereby prompting nationwide political action. In 1988 the Florida Legislature passed legislation mandating the development of a radon resistant building code for new construction. As a result of that legislation the State University System was tasked with developing a draft building code for delivery to the Florida Department of Community Affairs by February 1, 1990. The Florida Board of Regents established the State University System Radon Advisory Board (SUSRAB) to coordinate the research and development activities relating to the production of the draft code.

Early on, the SUSRAB recognized the proven effectiveness of sub-slab depressurization systems and funded several studies to investigate the operational characteristics of these systems. Regional construction techniques and procedures play a critical role in the success or failure of these systems. Differences between the construction features of northern homes with basements and the Sunbelt-type construction have resulted in varying levels of effectiveness of the sub-slab depressurization technique. In order to study the effects of various construction techniques on the sub-slab depressurization system, four test slabs were constructed and tested.

The study, from which this paper was developed, was funded by the Florida Board of Regents to determine what construction processes have the greatest impact on the sub-slab pressure field. From this work guidance was provided to the SUSRAB in the development of the draft radon resistant building code.

FLORIDA TYPICAL CONSTRUCTION

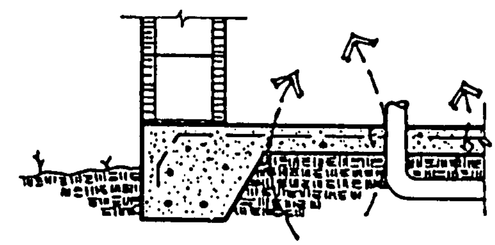
An informal survey of homebuilders conducted by the authors during the 1988 Summer Board Meeting of the Florida Home Builders Association found that over 95% of all residential construction built in Florida is constructed with concrete slabs-on-grade. In the colder climates of the more northern states where there is less rainfall, sub-grade construction of basements is common. In Florida, however, sub-grade construction is a rarity. This result was not unexpected but confirmed that the emphasis of radon control efforts should be focused on slab-on-grade construction. Further analysis of the survey data indicated that a geographical distribution of the type of slab-on-grade system used was evident. Monolithic concrete slabs were found to be the slab system of choice in those areas south of Orlando; slabs constructed on masonry stemwalls or foundation walls were more prevalent in those geographical areas north of Orlando. The preference for slab systems with stemwalls north of Orlando is due to increased topographic relief.

Florida's sub-tropical climate and high precipitation levels significantly influence the construction techniques used. The most significant regional construction difference is the type of media used under the slab. Gravels, used primarily in northern U.S. sub-grade construction to facilitate water removal, have substantially higher air permeabilities than the sand fills used in the Sunbelt region. The permeability of these base materials coupled with the effective leakage of the confining construction are of major importance in the effectiveness of the sub-slab depressurization system. However, in slab-on-grade construction sub-grade water control is not normally required resulting in the extremely infrequent use of gravels as a slab base material. Gravel or stone aggregate is a non-standard building component in typical Florida construction.

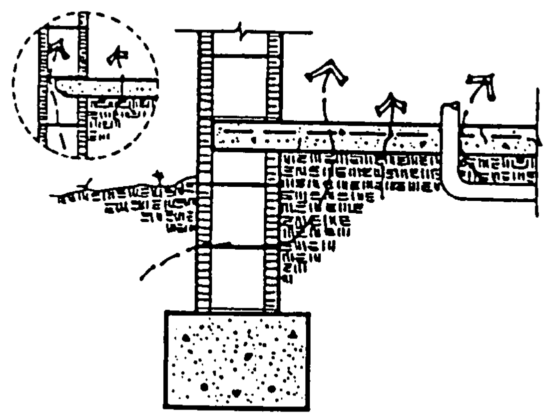
To facilitate the construction of concrete slabs on grade, Florida's abundant supplies of clean construction-grade sands are used as compactable fill material. Fill-sands are frequently relocated from one area of the project site to another or may be hauled in from distant borrow pits. Some of these sands may possess moderate to high radium content thereby raising a concern of transporting radon contamination from one locale to another.

SLAB CONSTRUCTION CATEGORIES

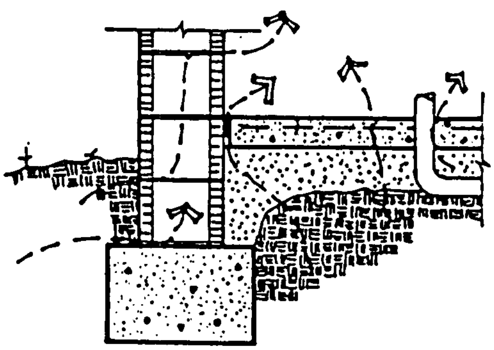
Concrete floor slabs constructed on grade in Florida typically represent one of the following three general slab construction categories: monolithic slabs, floating slabs and slab-in-stemwall slabs (Figure 1).



A. Monolithic



C. Slab-in-stemwall



B. Floating

Figure 1. Typical Florida slab construction techniques and soil gas entry routes.

Monolithic Slabs

Slabs constructed on near-level ground in areas not subject to flooding are constructed most cost effectively as monolithic slabs (Figure 1-A). When site modifications to create a level building platform are more cost effective in areas of irregular terrain. Monolithic slabs are characterized as having the footing and the slab cast as one integral unit. Foundation depth is minimized and radon entry routes through the slab are usually confined to cracks (planned or unplanned) and mechanical system penetrations for plumbing, electrical, etc. In general, fewer foundation entry conditions are present in monolithic construction than in the two other categories.

Floating Slabs

Where terrain features, water considerations and/or other conditions demand the use of foundation walls, which elevate the slab some distance above natural grade, floating slabs are one of two construction techniques commonly employed. Floating slabs are cast against, not into, the foundation wall (Figure 1-B). Expansion joint materials are normally used to separate the slab from the inside face of the foundation wall forming a continuous radon entry route along the perimeter of the slab. In addition to the typical entry conditions associated with slab cracking and penetrations, foundation wall conduction of radon from below the floor slab into the superstructure walls is also common. Most superstructure walls erected on floating slabs are constructed of masonry block. The masonry block wall's thickness is sufficient for the baseboard to conceal the perimeter crack; the crack is virtually inaccessible after construction. The continuous perimeter crack and the foundation/superstructure wall conduction are the most significant radon entry routes associated with this slab system.

Slab-in-Stemwall Slabs

Many contractors prefer frame superstructure walls to masonry and have eliminated the perimeter crack associated with floating slabs by adopting a system of casting the slab into the masonry foundation wall (Figure 1-C). Two types of masonry block may be used to form the edge of the slab. The lintel block can be used so only the outer face shell remains as the slab form. The header block, however, when used retains part of the web partitions as well as the outer face shell. This condition is important because, depending upon the method utilized to prevent concrete from being lost down the block cores, entry routes from the foundation wall into the superstructure may result. If the contractor is careful, the foundation wall superstructure conduction problem can be eliminated. However, contractors have been observed draping the vapor barrier over the header block. After the slab was cast, large holes were found to exist where the concrete had been held away from the outer face shell of the block by the vapor barrier. These holes result in foundation/superstructure conduction.

TEST SLAB PROGRAM

The U.S. Environmental Protection Agency and others have conducted numerous studies in the eastern U.S. over the past several years and have found that sub-slab depressurization systems appear to be more consistently successful than other experimental radon mitigation systems. Most of the early tests of sub-slab depressurization systems were conducted on basement structures using stone aggregate as the slab-bed material. Permeabilities in these stone materials were sufficient to provide adequate pressure field development from usually one suction point. Permeability of the sub-slab media was recognized as the principle characteristic affecting system performance and effectiveness. It is expected that this mitigation technique will maintain a high level of effectiveness in the event that post-construction penetrations occur (2). It was believed that if major entry conditions could be prevented near the suction point, then the negative sub-slab pressure field could successfully protect against radon transport through new pathways caused by aging of the building.

The following testing program was developed to investigate the performance characteristics of sub-slab depressurization systems under conditions typical of Florida. The primary factors that may significantly impact the effectiveness of sub-slab depressurization systems installed in typical Florida homes and that the researchers felt necessary to investigate were: 1) the effects of the type and permeability of fill material; 2) the vertical depth or volume of the fill material; 3) the size and configuration of the "suction pit"; 4) the effects of air infiltration through the stemwall; and 5) the influence of sub-slab plumbing systems (3).

The objective of this testing program was to determine the area of effective depressurization under various conditions created by these factors. Four test slabs were constructed using the slab-in-stemwall technique ensuring that the concrete completely sealed the slab/stemwall junction against any leakage (Figure 2).

Each slab was built with the outside dimensions of 24' x 48' by a local contractor using standard construction practices. Following construction of the footings and masonry stemwalls each slab was provided with a polyethylene "stemwall curtain" placed along the inside face of the stemwall for half of the slab's perimeter (Figures 2-A & 2-B). The curtain extended from the footing to the top of the fill material where it folded over the vapor barrier for a distance of 24 inches. The purpose of this curtain was to effectively seal the masonry stemwall against air infiltration for that portion of the slab.

Two simulated waste plumbing systems were installed to determine the significance of the pipe or its trench of disturbed soil on the pressure field. Where the plumbing penetrated the slab and stemwall, great care was taken to seal against air infiltration.

The clean sand fill used in each test slab was provided from the same borrow pit by one supplier. Uniformity of the fill material was maintained as much as could be reasonably achieved.

All four slabs were constructed such that the foundations were at the same elevation, and they penetrated into the native soil to the same distance. This procedure provided uniform conditions so the movement of atmospheric air under the foundation could be examined.

Specific construction details for each test slab follow.

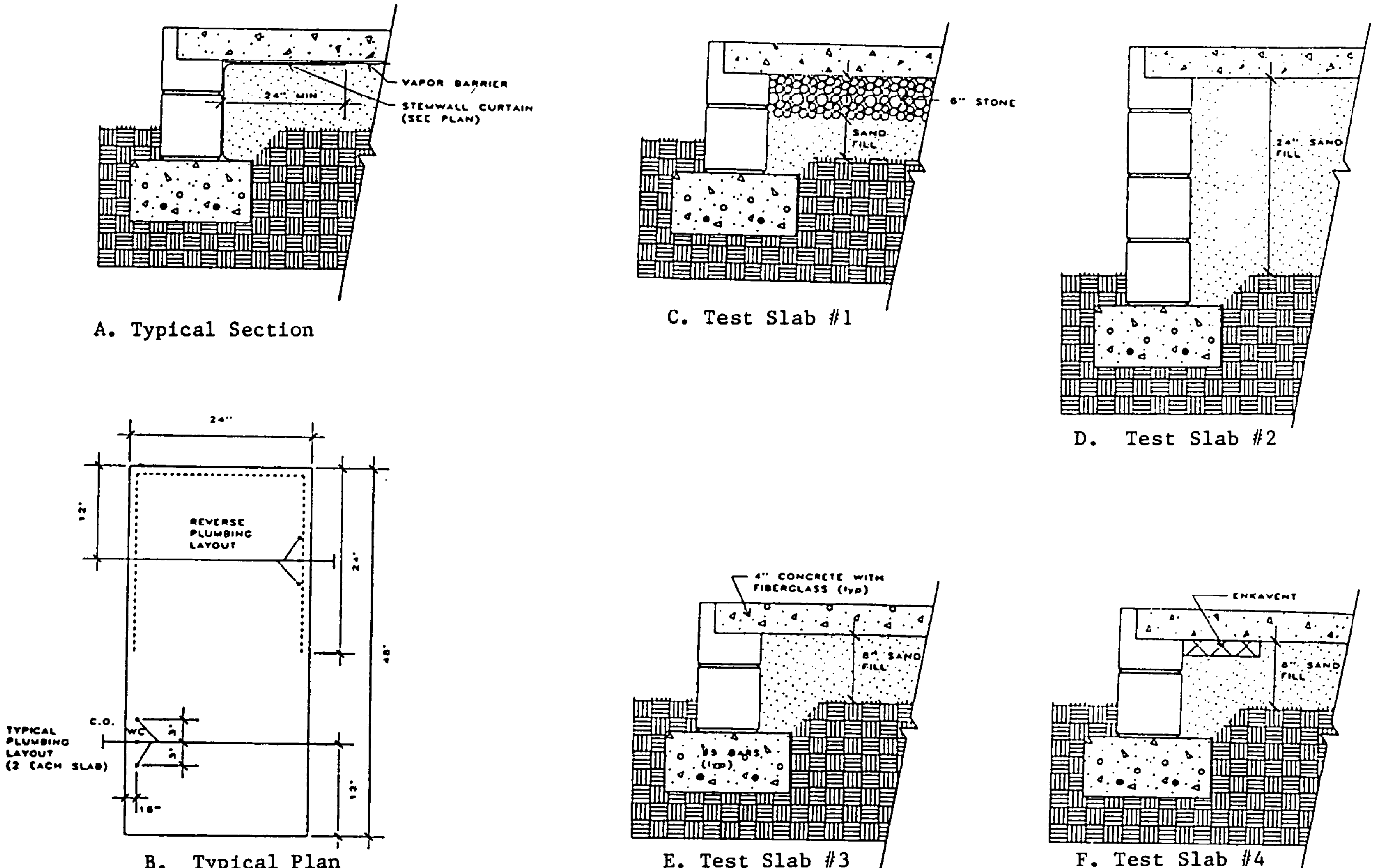


Figure 2. Test slab construction details

Test Slab #1

Test Slab #1 was constructed to simulate the sub-slab conditions found in basement structures previously studied and to provide a means of evaluating the permeability of various sub-slab materials (Figure 2-C). A six-inch layer of 3/4" to 1 1/2" crushed drain-field stone similar to that used in basement construction was placed as the slab bed over several inches of clean sand fill. It was assumed that during placement and grading one to two inches of stone would be compressed into the underlying sand fill resulting in a nominal four inch permeable stone layer.

Test Slab #2 & #3

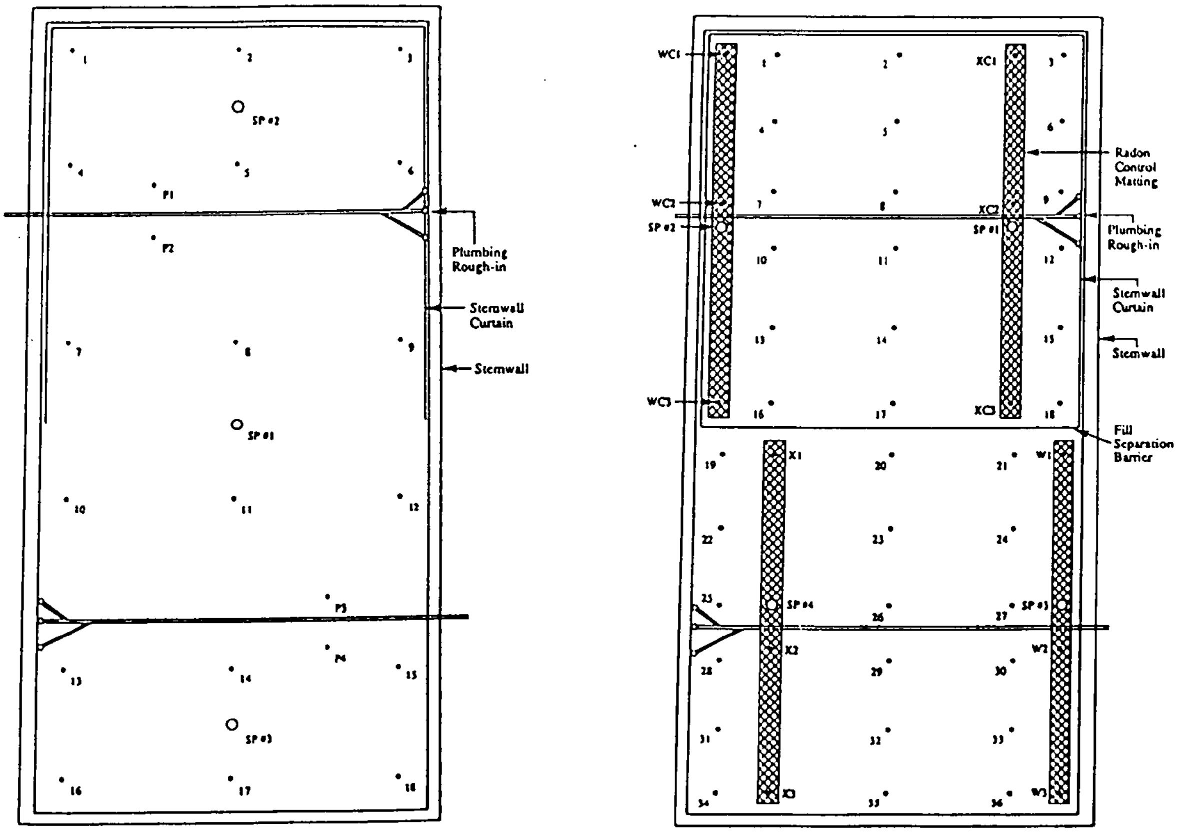
These slabs were constructed in order to study the effects of fill depth and stemwall leakage. Both Test Slab #2 and #3 were constructed with sand fill to different depths (Figures 2-D & 2-E). Test Slab #2 had a 24" deep layer of clean sand fill while Test Slab #3 had only an 8" deep layer of fill over the native soil. Test Slab #2, after final grading, had 288 square feet of stemwall with half of it protected by the stemwall curtain. Test Slab #3 had 96 square feet of exposed stemwall with half of it protected by the stemwall curtain.

Test Slab #4

While the other three test slabs were designed to study various media and leakage conditions, Test Slab #4 was constructed to evaluate an extended suction pressure distribution system. This slab was constructed with four separate strips of plastic drainage matting installed over 8 inches of fill with each strip having a separate suction point (Figure 2-F). This test platform provided the opportunity to study the effectiveness of a continuous, linear suction pit versus the point source suction pit used on the other three test slabs. The stemwall curtain on this slab was not only installed around half the perimeter of the slab but extended across the midsection of the slab to effectively divide the fill into two separate regions. This was done to minimize the communication of pressure fields developed in different suction strips.

Test Procedure

Following construction of the test slabs, multiple suction points and monitoring points were installed. The suction points were installed at the time the testing was to commence at that location. A 5" hole was cored through the slab and the pit excavated by hand to the desired configuration. Following the pit excavation a 4" PVC clean-out adapter with plug was installed and sealed. The suction device was then attached to this adapter when testing commenced. The monitor points were installed by drilling a hole through the slab and sealing a 3/4" PVC pipe 6" long into place. The pipes were then plugged with rubber stoppers. Figure 3 illustrates the arrangement of the suction and monitor points.



Test Slabs #1, 2, 3

Test Slab #4

Figure 3. Test slab suction & monitor point locations.

Pressure testing was conducted using an industrial vacuum cleaner as the suction source regulated through a bleed-valve assembly. Pressure measurements were made at the suction point and the monitoring points using a Neotronics Model MP20SR micromanometer. Air flow measurements were taken with a Kurz model 440 air velocity meter at the suction point and periodically at a remote monitoring point.

Testing routinely started with a measure of air flow at the suction point at suction pressures ranging from 500 Pa to as high as 6000 Pa. After this procedure was finished the suction pressure was reduced to approximately 500 Pa and a pressure measurement at each monitor point was taken. A commercial software package (Surfer, Golden Software) was used to interpolate between data points, using a Kriging algorithm, and to develop contour lines of constant pressure.

RESULTS AND DISCUSSION

Figure 4 illustrates the difference in air flow rates for a high permeability condition (Test Slab #1) and a low permeability condition (Test Slab #2). A comparison of the four curves from the sand fill (low permeability) with the stone fill (high permeability) demonstrates the dramatic increase in air flow that is generated at any given pressure for high permeability fills. The line representing Test Slab #1 (stone media) indicates that high permeability materials require fans capable of handling high flow rates in order to achieve the desired pressure conditions under the entire slab. The large amount of air infiltration into the system on Test Slab #1 must be entering both through the unsealed stemwall and/or under the foundation from the atmosphere. The pressure field for this test slab is nearly uniform in all directions. The half of the slab protected by the stemwall curtain has slightly high pressure produced by limiting infiltration through the stem wall.

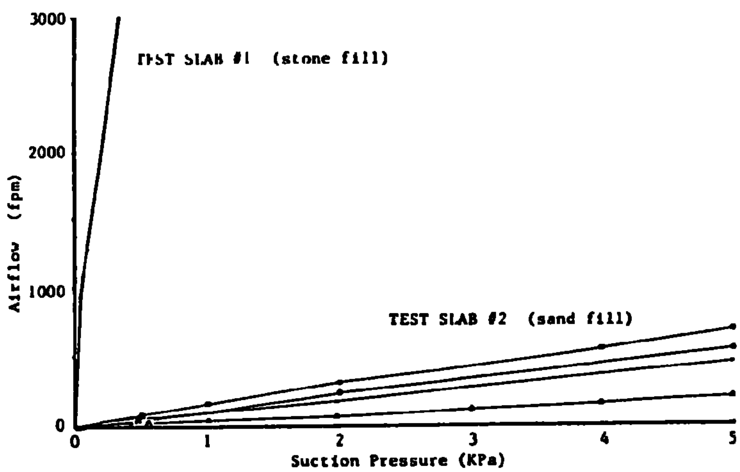


Figure 4. Comparison of airflow rates of high and low permeability fills.

Figure 5 and Figure 6 illustrate the effects of different suction pit configurations. Four different suction pit configurations were constructed at the same suction location on Test Slab #2. Each configuration was tested for air flow and pressure field development. Figure 5 illustrates the relationship of pit contact area to air flow. The greater area of sub-slab media exposed to the highest suction pressure allows a larger pressure field to develop and the induces a larger air flow.

Figure 6 shows the pressure field contours for each suction pit configuration. Note must be made of the contour values to properly compare the effectiveness of the suction systems. All plots on Figure 6 indicate a better field development toward that half of the slab with the stemwall curtain.

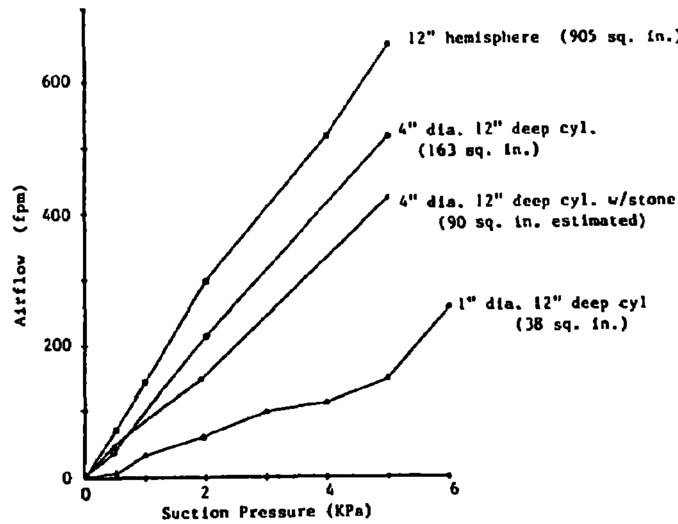


Figure 5. Comparison of flowrates for different suction pit configurations.

The effectiveness of controlling stemwall infiltration is illustrated in Figure 7. Figures 7-A and 7-B are pressure field plots for Test Slab #2 (24" fill -72 sf unsealed stemwall) where a 500 Pa suction was placed at each end of the slab. The results clearly show that, where stemwall air infiltration is controlled, the sub-slab pressures are higher over a larger area. Figure 7-B represents the situation where the suction point is located at the end of the slab where no stemwall seal is provided. The smaller and less well developed pressure field is interpreted to be the result of higher infiltration through the stemwall.

The results of the tests inducing a 500 Pa suction at each end of Test Slab #3 is illustrated in Figure 7-C & 7-D. Test Slab #3 is constructed over 8" of fill which results in a smaller area of stemwall succeptable to infiltration. Where Test Slab #2 had a total of 72 square feet of unsealed stemwall, Test Slab #3 had only 24 square feet. Not only did Test Slab #3 differ in having less stemwall area but it also had a shallower depth of the permeable fill material. Higher levels of compaction in the thinner fill layer are expected to negatively influence the development of the pressure field. However, it can still be observed that a larger pressure field is developed on the stemwall-curtained half of the slab. The magnitude of differences in pressure field between Figure 7-A and 7-C is a result of the reduced transport distance from the atmosphere to the sub-slab environment. This reduction and transport distance results from the shorter stemwall construction of Test Slab #3.

Test Slab #4 provided an opportunity to observe the effectiveness of a suction strip versus the pit. Each 18" wide by 20' long strip was tested individually and monitored for air flow and pressure. Figure 8 shows the relationship of each suction condition and the induced air flow. The suction strips adjacent to the stemwall were expected to generate the greatest air flow with Suction Point #3 (no curtain) generating the highest infiltration. Figure 8 clearly shows that having high suction pressures in very close proximity to

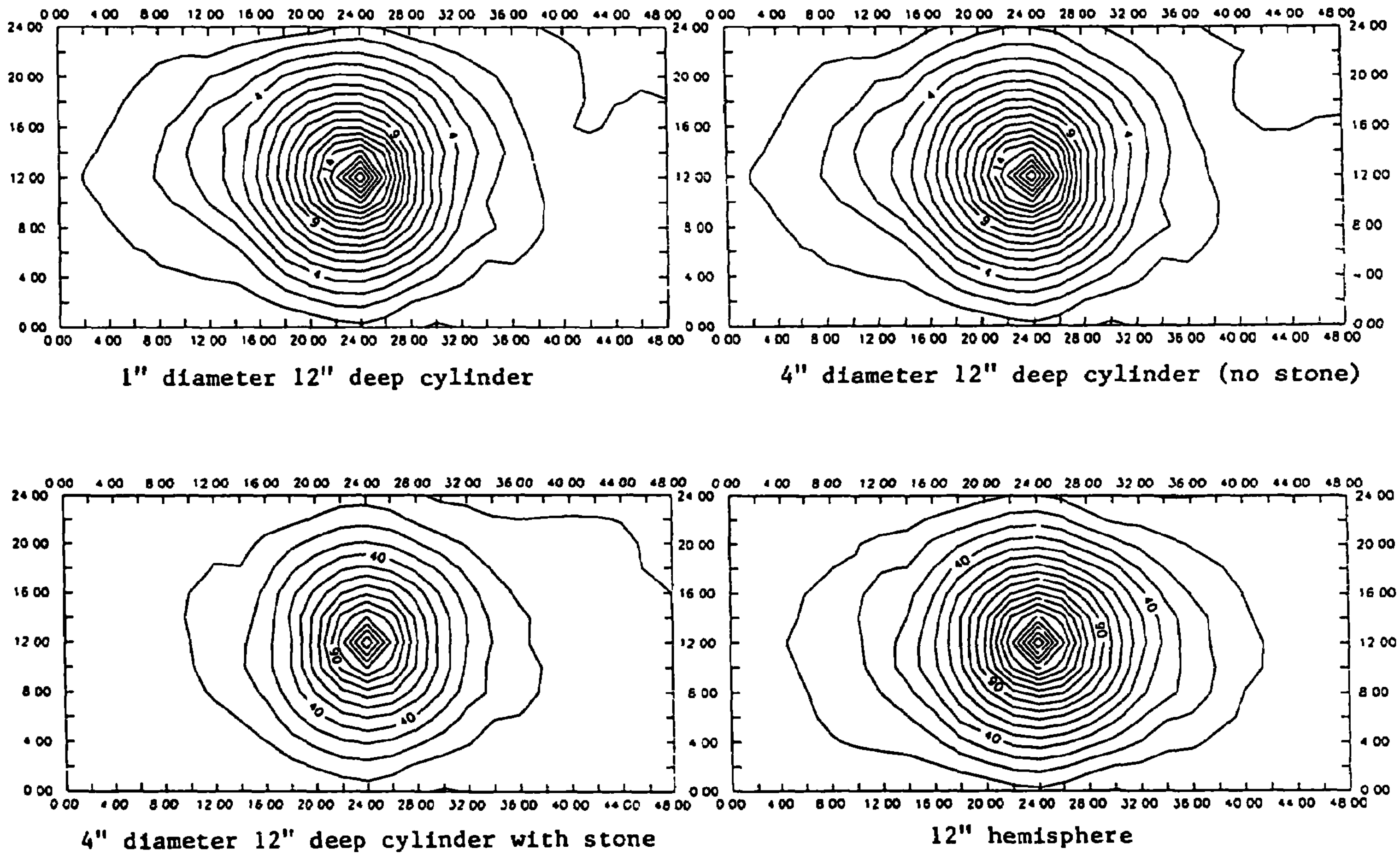
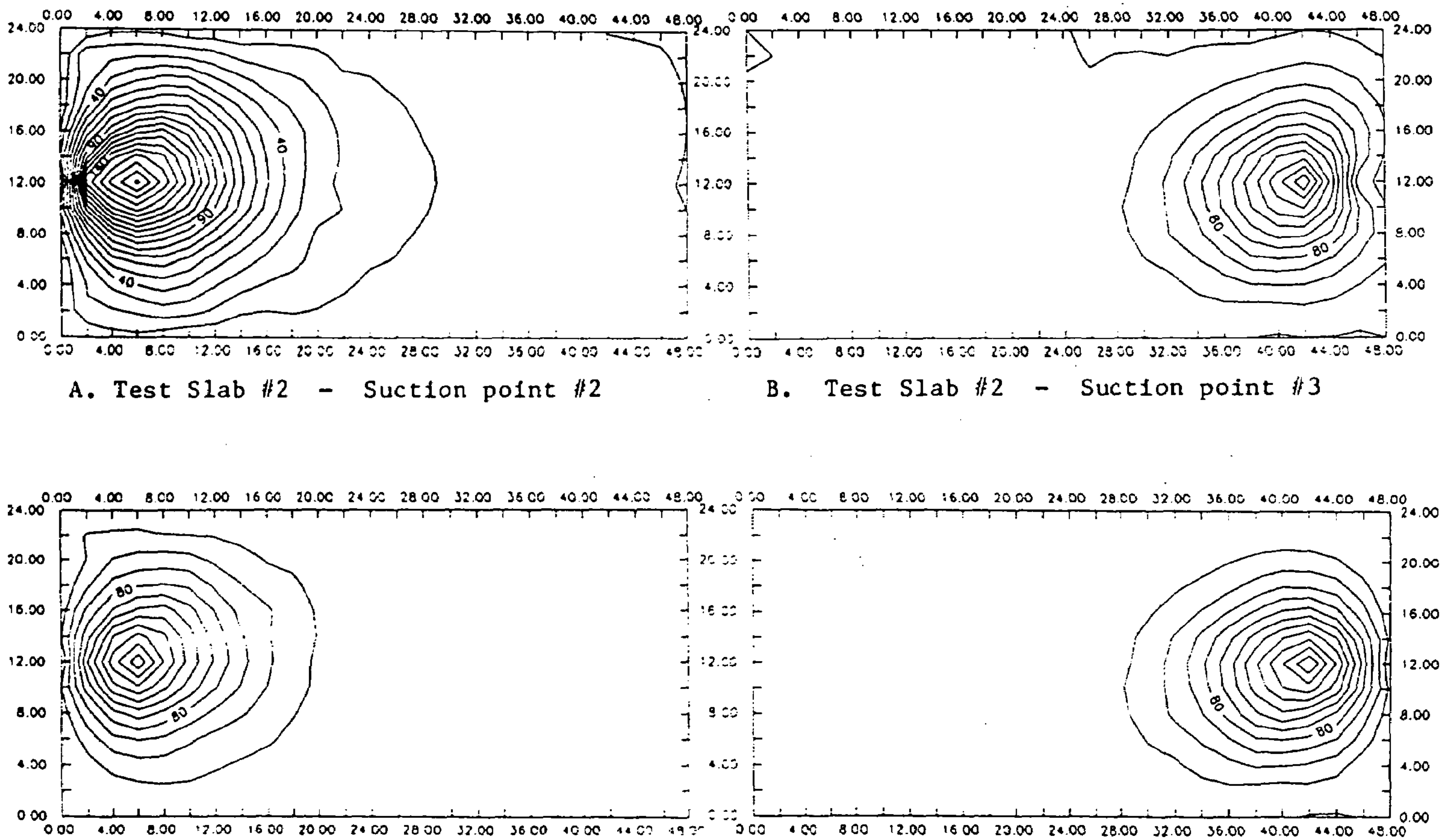


Figure 6. Pressure contours produced on Test Slab #2 by various suction pit configurations.



A. Test Slab #2 - Suction point #2

B. Test Slab #2 - Suction point #3

C. Test Slab #3 - Suction point #2

D. Test Slab #3 - Suction point #3

Figure 7. Test Slabs #2 and #3 pressure contours illustrating effects of stemwall curtain.

the stemwall induces significant infiltration through both the stemwall and soil under the footing. Since Suction Point #2 is located immediately adjacent to a curtained stemwall, the air flow at this suction point must come primarily from under the footing. The curve for Suction Point #3 results from both stemwall infiltration and atmospheric transport under the footing since the stemwall curtain is absent. The difference between the plots for Suction Point #1 and #4 is very small and results from the fact that the pressure differential at the stemwall and ground surface is greatly reduced by having located the suction strip several feet in from the edge of the slab. The pressure field plots contained in Figure 9 illustrate the degree of pressure field development for each suction strip. Figures 9-A & 9-D show that, where the strip is several feet inside the stemwall, the field development is virtually identical for both suction strips. Marginal stemwall leakage is expected. However, Figure 9-B and 9-C show marked differences in pressure field development. These results demonstrate how eliminating stemwall leakage allows higher suction pressures to be developed and that stemwall infiltration limits pressure field extension. These tests demonstrate a very promising approach to cost effective pressure field development. Locating the suction strip 8 ft. to 15 ft. inside the stemwall would likely have resulted, on this slab, in only one strip being necessary to develop adequate pressure field coverage.

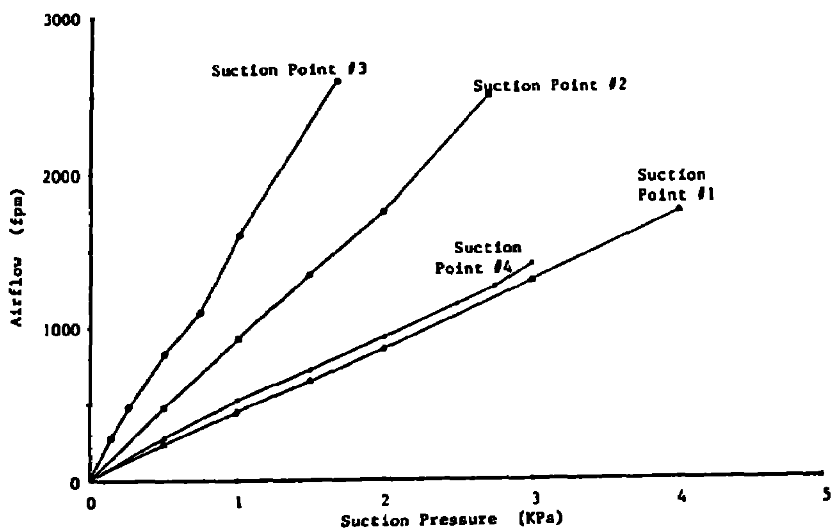


Figure 8. Airflow rate comparison for different suction points on Test Slab #4.

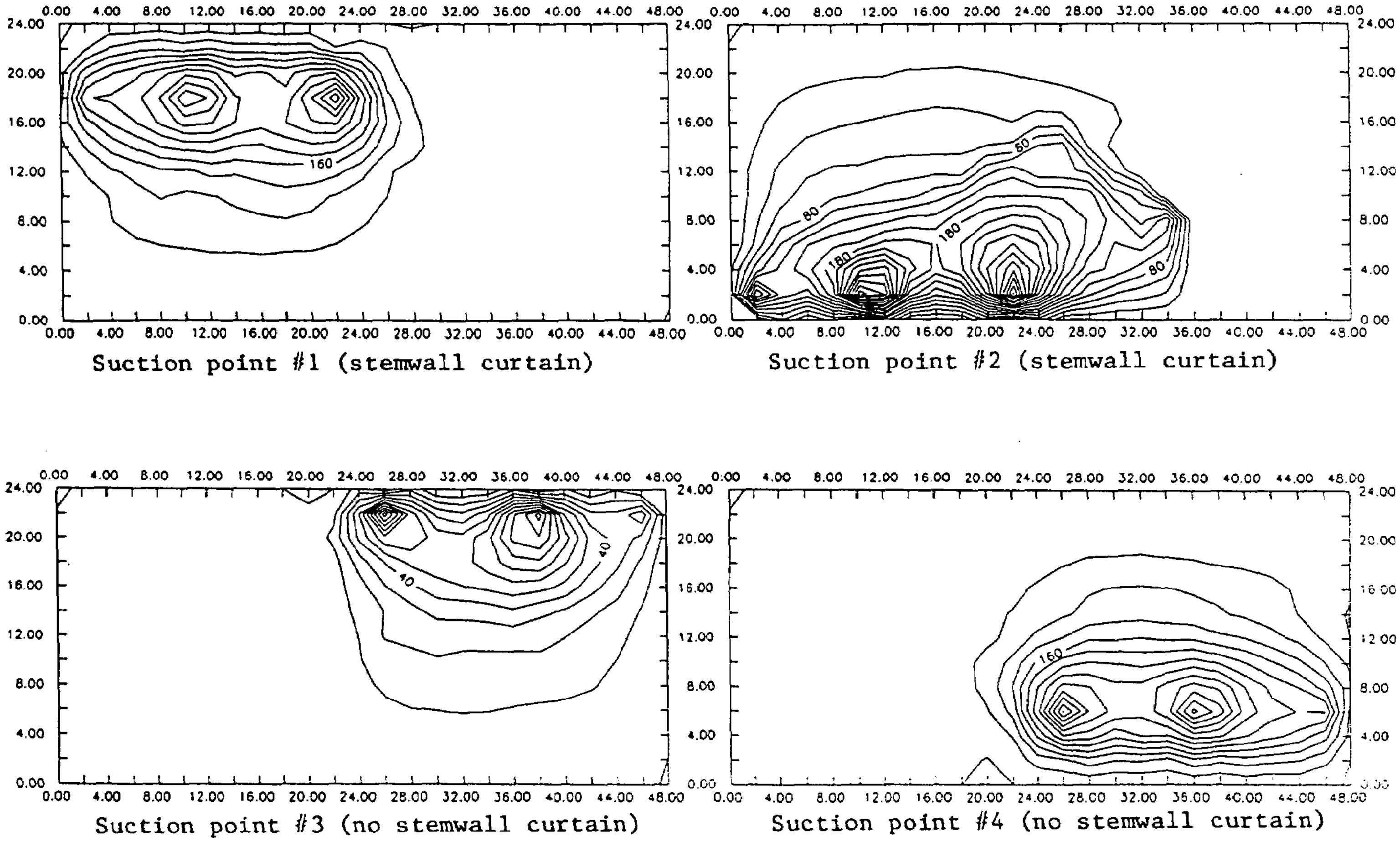


Figure 9. Pressure contours produced at each suction point on Test Slab #4.

CONCLUSIONS

The studies conducted thus far in this research effort seem to provide the following guidelines.

The amount of suction contact area is vital to pressure field development. Larger pits shaped to maximize surface area function much better than pits of smaller surface area. The drainage matting material used as suction strips appear to be very promising in its effectiveness if placed 8-15 ft. inside of a perimeter stemwall. This suction system took several minutes to install versus several hours for the excavated pits.

Stemwall curtains in slabs with deep layers of fill and corresponding large stemwall areas will perform better with the protection of the stemwall curtain. Slabs with short stemwalls probably will not realize a positive cost benefit of the stemwall curtain.

Finally, highly permeable fill, such as the stone used in Test Slab #1, provides for excellent pressure field development if it is placed over low permeability soil and could be used effectively as an active sub-slab ventilation system. On the other hand, in Florida, where stone is not a locally produced material it appears to be the most expensive option.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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EVALUATING RADON RESISTANCE OF FILMS AND SEALANTS USING PERFLUOROCARBON TRACER GASES

Mark Nowak and Ban-Huat Song
NAHB National Research Center
Upper Marlboro, Maryland

Abstract

Movement of radon into a home is controlled by two mechanisms: diffusion and convective flow. Although many different materials have been suggested as mechanical barriers to reduce radon flow, there is very little data to substantiate a material's effectiveness. This paper discusses a relatively low-cost laboratory method to evaluate materials using perfluorocarbon tracer (PFT) gases to simulate diffusion of radon.

The test method uses a modified version of the Air Infiltration Measurement Service (AIMS), originally developed for measuring infiltration rates into homes. The procedure is conducted in an enclosed glass desiccator that is divided into two zones by the test material. The PFT source is placed in the lower chamber and samplers are located in the upper chamber. Two results are reported: the reduction in diffusion achieved by the material as compared to diffusion in an open chamber, and the rate of diffusion through the barrier.

INTRODUCTION

Movement of radon from soils into a home is controlled by two mechanisms: Diffusion, which is a random scattering of a gas across a concentration gradient; and convection, which results from driving forces that transport radon with other gases.

The driving force behind convective flow can occur in homes as a result of a reduced pressure that develops in the lower level of a home relative to surrounding soil. The thermal stack effect, wind, and operation of HVAC equipment are principal factors contributing to this pressure differential. Diffusion is generally thought to be less significant than convective flow, and consequently most attention has been focused on developing barriers to reduce convective flow of radon into homes. However, in some areas diffusion could result in elevated indoor radon levels. Barriers that effectively retard both mechanisms of transport will increase the radon-resistance of a building.

Barriers are recommended as the first line of defense in new construction by most radon mitigation experts. Barriers are frequently used under floor slabs and on below-grade walls to reduce radon entry through cracks, pores, and other openings. Another important use of barriers -- as interior sealants applied over building materials -- will become increasingly important if the national goal to reduce radon levels to outdoor levels is to be taken seriously.

Testing the effectiveness of barriers is difficult. One method is to locate a home with high radon levels and measure indoor levels or radon flux through the wall before and after application of the barrier. Another is to test the barrier's resistance to radon movement in a laboratory setting using a controlled radon source. Each of these methods have practical limitations that, in effect, prohibit most manufacturers from testing their products. Costs associated with construction and uncertainties in comparing before and after test results in the first method, and the specialized equipment and use of a radioactive source in the laboratory method are the primary factors that discourage testing.

THE AIMS METHOD

An alternative method discussed here employs a tracer gas to simulate movement of radon. The method incorporates the perfluorocarbon tracer (PFT) gas technology used in the Air Infiltration Measurement Service (AIMS) operated by the NAHB National Research Center.

AIMS was developed in the mid-1980s at Brookhaven National Laboratory as an alternative to higher cost tracer gas systems in use at that time. The system can be used effectively to simultaneously measure infiltration rates in up to four different zones. PFT sources used in the AIMS program emit the gas at a constant rate. Sampler tubes, which passively adsorb the tracer gas, are placed in the measurement area. At the end of the test period, samplers are returned to the AIMS Laboratory and analyzed using a gas chromatograph equipped with an electron capture detector to determine the concentration of the tracer gas in the sampled air space.

Dietz et. al.,(1985) discussed the analytical procedure and assumptions for determining infiltration rates using PFT tracers, termed the steady-state tracer gas method. As the term implies, the critical assumption is that steady-state infiltration conditions occur within a well mixed chamber. Calculations (by Dietz et. al.) shown below are based on conservation of mass (mass-balance) within a single zone. The mass-balance equation for a single-zone room or chamber yields:

$$dC/dt = (S/V) - nC \qquad \text{(equation 1)}$$

where,
C = tracer concentration in chamber (pL/L),
S = tracer source strength (nL/hour),
V = volume of area to be sampled (m^3),
n = air changes per hour (ACH).

Under steady-state conditions, $dC/dt = 0$, and the equation becomes:

$$n = S/VC \qquad \text{(equation 2)}$$

MEASURING RADON RESISTANCE

Perfluorocarbons are gases whose physical behavior is similar to radon. PFTs are also very similar to radon in size: radon has a molecular weight of 222, the PFTs used in the procedure have a molecular weight of 350. This similarity permits application of AIMS technology to evaluate the radon resistance of a barrier using a low-cost laboratory procedure.

TESTING PROCEDURE AND EQUIPMENT

The modified AIMS test of a radon barrier employs a small scale dual-zone chamber. The two chambers of the glass testing device are separated by an aluminum disk with a six-inch diameter opening. The test sample is sealed to the opening to form a barrier between the upper and lower chambers. A PFT source with an emission rate of 24.1 nL/min at 25°C was placed in the lower chamber and multiple sampler tubes were deployed in the upper chamber. The samplers were removed and analyzed with a gas chromatograph after a 30 minute sampling period.

Two tests of the procedure were conducted on four different samples. Sample No. 1 consisted of 4-mil polyethylene film typically used as a vapor barrier in construction and generally believed to be a good radon-resistant material. No. 2 consisted of a single coat of a common water-based acrylic paint applied over a porous paper backing. The third sample consisted of a second coat of paint applied over sample No. 2. Sample No. 4 consisted of the paper used as a backing for the paint samples.

RESULTS AND CONCLUSIONS

Results of the testing are shown in Table 1. Reduction percentages shown in Column 3 are based on a comparison with a value calculated for diffusion in an unobstructed chamber. The diffusion rates in Column 4 are of primary importance in evaluating the relative effectiveness of barriers. This value was calculated from the measured concentration per unit time and the internal sampling area.

Under the conditions of this test, the one-coat paint sample was partially effective at slowing the diffusion rate of the PFT. The polyethylene and the two-coat paint sample were much more effective at slowing diffusion. Diffusion through the polyethylene occurred at a rate approximately 2.8 times that of the two-coat paint sample. Due to different properties of the backing material, it is expected that the painted sample would not perform as well if applied to a more porous surface like concrete.

In summary, this procedure offers a relatively inexpensive method to measure and compare the effectiveness of materials in resisting movement of gases. It is expected that future modifications will be made to more closely reflect conditions of use. For example, the test can be run with a pressure differential between the chambers induced with a small vacuum pump. The pressure differential could range from three to five pascals, which is similar to pressure differentials in some homes during winter. Modification to the procedure could also be made to more closely simulate the block or concrete substrates to which paints and other sealants are applied in construction.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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Table 1 - Test Results

Test Sample	Average Concentration* (pL/L)	% Reduction**	Diffusion Rate (mole/L-hr.-sq.in.)
Polyethylene	19.524	99.977	7.063×10^{-12}
Paint-1 coat	619.048	99.268	2.281×10^{-10}
Paint-2 coats	7.024	99.992	2.542×10^{-12}
Paper	51,310.242	39.322	1.856×10^{-8}

* 1 picoliter (pL) of PFT gas is equivalent to 1.79×10^{-9} grams.

** Based on a comparison of the average concentration to a value of 84,561.40 pL/L in the open chamber (calculated from an emission rate of 24.10 nL/min and a volume of 8.55 L).

The Use of Coatings and Block Specification to Reduce Radon Inflow Through Block Basement Walls

John S. Ruppersberger
U. S. EPA, Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

ABSTRACT - Samples of six different coatings were evaluated in specially designed chambers built around 1.5 m^2 concrete block wall sections. Data were collected over a pressure range of 1 to 12 Pa with flows ranging from less than 0.01 standard liters per minute (SLPM) to 50 SLPM. A major preliminary finding is that all these coatings proved to be highly effective (98+%) when enough material was carefully applied. Baseline (uncoated) flows varied by a factor of 2 (12.1 to 23.5 SLPM/m^2 at 3 Pa) between the two batches of lightweight block used for coatings testing that came from a North Carolina manufacturer; these differed by an order of magnitude from normal weight blocks received later from a Minnesota manufacturer (1.8 SLPM/m^2 at 3 Pa). This large difference found in a small sampling of blocks is significant not only in the potential impact on coating performance, but more significantly that specification of blocks with low air permeability for new construction of substructures could greatly reduce soil gas entry, even if left uncoated.

INTRODUCTION - Pressure driven transport of soil gas carrying radon is believed to be the major entry mechanism for indoor radon. For houses with basements that have been mitigated as part of the EPA's research program, the perimeter crack where the floor slab meets the basement walls has often been considered the primary entry route. Generally, sound poured concrete has not been found to offer a significant entry route, even with typical hairline cracks. Therefore, coating poured concrete as part of a radon mitigation effort is not considered worthwhile when working toward a guideline of 4 pCi/L. Basement walls built of hollow concrete masonry units (CMUs) have always been suspect, and mitigation has included some work with this type of wall. The surfaces of these walls have been known to be an entry route, but given less treatment since other mitigation techniques such as active (fan driven) suction on the soil side of the substructure/soil interface have been shown to often be effective in achieving a 4 pCi/L

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guideline. Active systems are often powerful enough to extend their suction into the core of the CMU wall, effectively reversing the premitigation condition of the basement air, typically being the suction side of a slight pressure on the order of -3 to -5 Pa. Efforts to quantify the CMU wall source term is not commonly included in radon mitigation work to date. When quantified, it was found to contribute up to approximately 20% (1). Reports of the effectiveness of painting the surface of CMU walls have been mixed with success credited to the treatment by some mitigators and no benefit even after thorough treatment with expensive paints by others. The recent development of the long term goal of ambient radon concentration supports more effort toward the more common houses, those with a premitigation level of less than 4 pCi/L. The relative significance of radon entry routes may be different for this large group of houses. Another major concern of active soil ventilation systems is the large volume of conditioned indoor air they draw through a typical uncoated CMU basement wall, producing inefficiency in the system and resulting in an energy penalty of conditioning the outside replacement air that is brought to the temperature of the house. Trace gas experiments indicated that 50% of the air exhausted from one active sub-slab mitigation system was from the basement. (1) Extension of the suction to all essential areas of the soil/substructure interface is made more difficult if CMU walls allow large flows of indoor air into the system.

In a Canadian study, external coatings were evaluated for their ability to form an airtight membrane that would remain intact even if cracks occurred in the substrate subsequent to their application. Coatings were applied to two adjacent concrete blocks, which were then moved apart to simulate opening of a crack. (2)

Recent work performed at Princeton University found that block wall air permeability was reduced by 99.5+% with two coats of a special rubberized paint, a polysulfide copolymer. One coat was 91% effective. Two coats of either ordinary latex or oil base paints reduced wall permeabilities by 95%. Air permeabilities were determined from flow versus pressure data. (3)

A "standard test method for rate of air leakage through exterior windows, curtain walls, and doors" has been established by ASTM. (4) This test method covers the determination of resistance of curtain walls to pressure driven air infiltration. The EPA test method complies with the ASTM test method in every major aspect, and differs only in data collections at lower pressure differentials, in the range of 1 to 12 Pa. Its instrumentation exceeds accuracy requirements to permit precise measurements at these very low pressures and flows.

MATERIALS AND PROCEDURES - Concrete masonry units of the type used in this test are covered by an ASTM "standard specification for hollow load-bearing masonry units". (5) This specification covers hollow load-bearing concrete masonry units made from portland cement, water, and mineral aggregates with or without the inclusion of other materials. The three weight classifications are normal, medium, and lightweight.

Coatings selected for evaluation include a two part catalyzed water based epoxy paint, an elastomeric paint, a cementaceous block filler, a fiber reinforced surface bonding cement, a polysulfide vinyl acrylic paint, and a latex paint. Selection criteria included an attempt to sample various types of coatings that might be used on CMU basement walls under various conditions. Some coatings are not well suited, or even recommended by the producers for negative side (inside) basement walls, but were evaluated because they may already exist on some walls of basements needing mitigation, or might be better suited for application to walls under certain conditions than other coatings. Coatings were applied separately to bare wall specimens even though the desired result of a continuous gas flow resistant film might better be achieved by a combination, such as a block filler and a coat of paint. This was done to collect data on each coating separately - - performance of various combinations may be estimated from the data, but to be more precise, and perhaps more realistic in some instances, reasonable recommended combinations should be subjected to further evaluations. The effectiveness of a single coat of the two part water based epoxy argues against a strong need for further tests. Freshness of samples and adherence to application directions were emphasized. No two coatings were produced by the same manufacturer.

The test stand was designed for a 16 ft^2 (1.5 m^2) CMU wall. The wall assembly is made by pouring a concrete footing (48 x 16 x 6 in., or 122 x 41 x 15 cm) on which a block wall of 15 standard blocks and 6 half blocks is carefully built. Mortar construction techniques vary; these walls were built with two fairly generous strips of mortar on which the base course of blocks are laid. Mortar is applied to all horizontal surfaces of the previous course and to the end of the next block that will butt up against the last block on a course in progress. After the wall has set up for over a week it is caulked generously and, while wet, the side and top panels are assembled then fitted with covers to encapsulate the wall with a plenum on either side. Closed cell rubber gasket material is sandwiched between all mating metal surfaces, and between the metal and acrylic plastic covers.

The completed assembly is leak tested by pressurizing to between 2 and 3 in. H_20 (500 to 750 Pa) using helium gas, and tested for leaks using a halogen gas leak detector. Leak testing is also conducted on the pressure side of the air delivery equipment. The control panel is composed primarily of computer controlled mass flow controllers, a pressure transducer, a pump, and a bypass valve that provide precise control of flows from less than 0.01 to 50 SLPM over a pressure range of 1 to 12 Pa. The acrylic plastic cover over the side of the wall to be painted is then removed. After baseline data are collected, the coating is carefully applied. Care is taken to quantify material used. Additional coats were applied a day after the previous coat except when data collection needs dictated longer periods or when it might be reasonable to stop application of that paint with that coat. It is important to note that the coatings were applied by brush, carefully working material into the block surface and leaving as much material on the wall as possible without runs. Primary consideration was sealing the porous block surface, not the amount of material used. Exceptions are the elastomeric paint which was applied at the maximum recommended rate and the surface bonding cement which was applied using a steel trowel.

The initial wall was constructed as part of prototype development and was used for the polysulfide vinyl acrylic paint evaluation. Its baseline flow was as shown in Figure 1, Line a, 35 SLPM at 3 Pa, or about 2 SLPM per full block. The remaining five coatings were evaluated from walls built later, from a different batch of blocks. Although from the same local North Carolina manufacturer, meeting the same ASTM specifications for CMUs, and with no noticeable difference in appearance, the baseline flows were approximately half of that of the prototype wall, as shown in Figure 1, Line b, 18 SLPM at 3 Pa, or about 1 SLPM per full block. Then an opportunity developed to evaluate blocks received from a Minnesota manufacturer. The baseline flow for these blocks is on average approximately an order of magnitude lower than the local blocks, as shown in Figure 1, Line c, 2.7 SLPM at 3 Pa or about 0.15 SLPM per full block. Blocks from both manufacturers are typical of those used in their geographical regions for residential construction. The more air permeable North Carolina block is lighter, 12.1 kg, and has become common in the southeast. It contains expanded lightweight aggregate, filled with numerous discrete voids that do not appear to be interconnecting. The less air permeable Minnesota block weighed 16.9 kg, uses natural aggregate, and has a smoother, less porous surface appearance.

WATER BASED EPOXY PAINT - This is a water based catalyzed (two part) epoxy resin paint. Its analysis by weight, as supplied by the manufacturer, is 16.5% titanium dioxide pigment and 83.5% vehicle (7.7% epoxy resin, 6.6% ethylene glycol and alcohol, 20.7% acrylic resin, 46.5% water, and 2.0% additives). The data for this paint are summarized with other coatings in Table 1. Even with a slightly higher baseline flow of 19.8 SLPM, a single coat of this epoxy paint resulted in the lowest airflow for one coat of any paint evaluated, 0.75 SLPM (96.2% reduction) at 1 day drying time, and was also lowest for any two coats of paint evaluated, at 0.01 SLPM (99.9% reduction). The paint film is very smooth, and dried specimens exhibited unexpected elongation and strength upon being pulled apart, although these observations were not quantified by any standard testing techniques. Application was considered easier than average to provide a continuous film for both the first and second coats.

ELASTOMERIC PAINT - The analysis of this elastomeric acrylic emulsion paint was not given. Application rate for concrete block was specified as 50 to 125 ft^2/gal. (1.23 to 3.07 m^2/L). The first coat was applied at 50 ft^2/gal. Based on the performance of the first coat, a second coat was also evaluated. About a third of the quantity of paint used for the first coat was used for the second coat. The data for this paint are summarized with other coatings in Table 1. The measured effectiveness of the elastomeric paint was second only to the epoxy: 1.36 SLPM (92.1% reduction) for one coat, and 0.025 SLPM (99.9% reduction) for two coats. Application by brush was considered the easiest of any paint evaluated.

CEMENTACEOUS BLOCK FILLER - This is a portland cement plaster that can be troweled, sprayed, or brushed. There was no information concerning composition on the container (a bag holding 50 lb, or 23 kg) or sales literature, other than references to portland cement. In keeping with the general trend of brush application, this product was applied with a "masonry brush" purchased from the dealer. It required a different technique than typical paints, but application progressed satisfactorily after a brief time. Application was considered more difficult than average to provide a continuous coating with reasonable surface appearance. Experience would probably improve both application rate and appearance. The other cementaceous product evaluated was troweled on, but that product specified a 1/8-in. thick coating; this cementaceous block filler (also called a "finish coat" by the manufacturer) was applied at a thinner consistency and thinner than 1/8-in. by brush. The data for this coating are summarized with other coatings in Table 1. The single thick coating resulted in an air flow of only 0.06 SLPM (99.7% reduction); only about half of the flow through the fiber reinforced surface bonding cement, and over an order of magnitude less than one coat of the most effective paint.

SURFACE BONDING CEMENT - This is a mixture of portland cement, fiberglass reinforcement fibers, and unspecified (proprietary) ingredients. Application is specified as a minimum of 1/8-in. thick with coverage per 50 lb bag of approximately 50 ft^2. Trowel or spray application options are in the product literature supplied by the producer. Application was with a steel trowel by an experienced mason to a thickness of slightly over 1/8-in (0.32-cm). The data for this coating are summarized with other coatings in Table 1. The single application resulted in an air flow of only 0.10 SLPM.

This is more than the other portland cement coating evaluated in this study, but still is highly effective at 99.5% flow reduction in one application. This single application allowed less than 14% of the flow of one coat of the most effective paint.

POLYSULFIDE VINYL ACRYLIC PAINT - The supplier described it as polysulfide/vinyl acrylic dispersion without giving any further specifics on composition. It was offered at the time the program was started and was used for the original prototype test stand and equipment testing. Since it was accepted for those first developmental tests, it was decided to evaluate it as the first coating using the equipment after it was fully calibrated to QA/QC specifications. It is currently available commercially to radon mitigators. Application was considered average to provide a continuous film for both the first and second coats, although pinholes were observed soon after application and their apparent number and size increased with drying time. The data for this paint are summarized with other coatings in Table 1. Specifically, the baseline flow was much higher than for the walls built later from another batch of blocks. The measured effectiveness of one coat of this paint was 78.6%; many pinholes were apparent in one coat. The second coat reduced air flow at 3 Pa substantially, with an effectiveness of 99.4%: 0.20 SLPM of the baseline flow of 35 SLPM. The observed time dependence on measured effectiveness resulted in reconsideration of a standard condition of 2 weeks drying time since data collected at different drying times exhibited different slopes and a consistent trend of increasing flows with increasing drying time. Performance deteriorated further between 2 weeks and 2 months with visual pinholes becoming more numerous and larger.

LATEX PAINT - This is a latex semi-gloss paint. It is commonly sale priced at retail and might be considered the type of latex paint homeowners would often buy; there are both less and more expensive latex paints available. Its analysis did not list ingredients by weight, merely as pigment (titanium dioxide, and hydrous aluminum silicate) and vehicle (polystyrene resin, acrylic latex, vinyl acrylic resin, 1, 2 propanediol, additives, and water). Application information on the label stated 400 ft^2/gal.(9.82 m^2/L) or less, and that textured surfaces may require more paint. Actual application rate on the test wall was approximately 100 ft^2/gal (2.46 m^2/L). That first coat took as much paint as the next two coats combined, resulting in a coverage after the three coats of approximately 50 ft^2/gal (1.23 m^2/L). Application of the paint by brush was considered slightly more difficult and time consuming than the average of the paints evaluated. The data for this paint are summarized with other coatings in Table 1. The measured effectiveness of this latex paint was less than any of the other three paints evaluated for either one or two coats. One coat was not very effective, about an order of magnitude less effective than the epoxy or elastomeric paints, allowing 11 of the baseline 19 SLPM (42.1% reduction) to pass at 3 Pa after 1 day drying time. It was the only paint applied with three coats, but that third coat greatly increased the effectiveness, from 84.2% with two coats up to 98.1% (0.37 SLPM) at three coats.

DISCUSSION - Reduction of air entry is the primary concern that motivated this work and all aspects of the test program. Several observations are especially noteworthy. The first is that, of these coatings, everything works well in reducing air flow across these test walls (initially at least, under these ideal conditions) if sufficient material and care are used in their application. A major finding, and a surprising one after discussions with several paint chemists working to formulate especially effective radon flow resistant paints, and seeing fairly expensive specialty paints being advertised specifically as radon resistant, is that all these coatings, when carefully applied with sufficient quantity, demonstrated that they can be highly effective in reducing gas flow across the face of concrete masonry units. Another is the interesting observation that the data for any particular set of flow vs pressure plots are a straight line on arithmetic paper. Apparently, flow through these small openings at low pressure differentials is laminar.

A comparison of percent effectiveness in reducing the baseline flow and estimated cost associated with do-it-yourself (approximated by the material cost) and professional application total cost is summarized in Table 1. Among the paints, the polysulfide vinyl acrylic offered as specifically formulated for radon control performed much less effectively (78.6%) than either the epoxy (96.2%) or elastomeric (92.1%) with only one coat. Cost of the polysulfide vinyl acrylic paint sold by the manufacturer to radon mitigators is nearly equal to that of the water based expoxy. Of commercially available paints, the latex is the least expensive material for three coats. However, a do-it-yourselfer would have to be strongly motivated to save a few pennies per square foot and get about 2% more effectiveness, to go to the trouble of applying three coats of a slightly more difficult to apply paint, than one coat of the epoxy that provided almost equivalent effectiveness. The better appearance and other desirable properties of this epoxy over the latex paint might also influence a final decision. Considering just the paints, one coat of an equivalent water based epoxy might be a reasonable choice since the trouble and expense of a second coat produce only a little over 3% increase in effectiveness.

From these data, the clear performance value leader is the cementaceous block filler. This product contains portland cement, but no fiberglass. The product evaluated was white; if a natural grey color similar to the original block wall is acceptable, it would be approximately'a penny less per square foot material cost. This type of coating, highly effective at the lowest cost, and with the effect of significantly changing the block wall appearance to a much smoother plastered look, is an apparent first choice unless conditions in the basement do not favor its application. Such adverse conditions would also produce problems with paints in general. The surface bonding cement is only slightly more expensive. It has added advantages of its fibers providing added tensile strength that may be helpful for walls experiencing problems with minor cracking, and also has a higher portland cement content that imparts improved waterproofing performance -- although this and most others are recommended for exterior application.

In summary, considering both cost and effectiveness, for coating an existing wall, a cementaceous product such as the cementaceous block filler is apparently the first choice. If a paint is desired, the choice is more complicated based on these results, but one coat of a similar performing water based epoxy would be good if about 96% effectiveness is acceptable. If top effectiveness is the only criterion, two coats of the water based epoxy is found to be the most effective of the coatings evaluated. Of course, building the wall with low air permeable blocks in the first place could decrease the need for any coating at all. Dry stacking with fiber reinforced surface bonding cement would also provide soil gas entry resistance.

PRELIMINARY CONCLUSIONS AND RECOMMENDATIONS:

1) All of the six coatings selected for evaluation can provide highly effective reductions in air flow under the conditions of the tests when sufficient quantity is carefully applied.

2) Considering both cost and effectiveness, a cementaceous product such as the cementaceous block filler offers highly effective flow reductions in a single application at low cost. Among paints, two coats of the water based catalyzed epoxy was found to be most effective in these tests, although one coat may be adequate for some situations.

3) The variation in air flow characteristics between similar looking blocks is large; in this limited sampling of only two batches of lightweight blocks from a North Carolina manufacturer, it was found to vary by about a factor of 2 (12.1 to 23.5 SLPM/m^2 at 3 Pa). The difference between the North Carolina blocks (lightweight, 17.8 SLPM/m^2 average flow at 3 Pa) and Minnesota blocks (normal weight, 1.8 SLPM/m^2 at 3 Pa) is an order of magnitude. This large difference found in a small sampling of blocks is significant not only in the potential impact on coating performance, but more significantly that specification of blocks with low air permeability for new construction of substructures could greatly reduce soil gas entry, even if left uncoated.

4) Flow vs pressure data collected for these carefully constructed test walls and at this very low pressure range were found to be linear.

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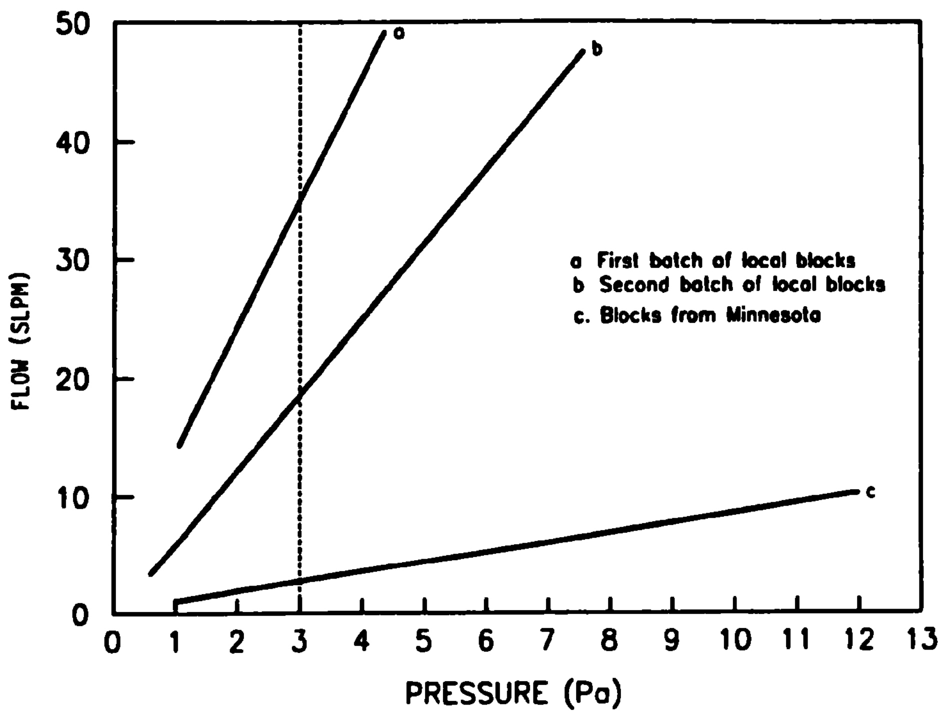

FIGURE 1. Air flow through block walls.

TABLE 1. EFFECTIVENESS OF COATINGS IN REDUCING AIR FLOW THROUGH CONCRETE BLOCKS AT 3 PASCALS

Effectiveness (%)		Estimated Cost (dollars) 1989				
		Per Square Foot			Typical Basement[1]	
Greater Than 99% Effective		Material	Labor	Total	D.I.Y.	Professional
Epoxy, 2 coats water based	99.9	0.37	0.34	0.71	440	850
Elastomeric, 2 coats	99.9	0.50	0.30	0.80	600	960
Cementaceous Block Filler (brushed thick)	99.7	0.14	0.20	0.34	170	410
Surface Bonding Cement (1/8 - in. troweled)	99.5	0.20	0.22	0.42	240	500
Polysulfide Vinyl Acrylic, 2 coats	99.4	0.36	0.30	0.66	430	790
Greater Than 98% Effective						
Latex, 3 coats	98.1	0.22	0.42	0.64	260	770
Greater Than 90% Effective						
Epoxy, 1 coat, water based	96.2	0.25	0.20	0.45	300	540
Elastomeric, 1 coat	92.1	0.37	0.18	0.55	440	660
Greater Than 75% Effective						
Latex, 2 coats	84.2	0.17	0.30	0.47	200	560
Polysulfide Vinyl Acrylic, 1 coat	78.6	0.23	0.18	0.41	280	490
Less Than 75% Effective						
Latex, 1 coat	42.1	0.11	0.18	0.29	130	350

[1] "Typical" is assumed to be approximately 1200 ft^2 of wall surface, in good condition, ready to be painted. Costs for brushes, dropcloths, preparing the basement area and walls, etc. are not included. D.I.Y. Means Do It Yourself.

Session C-VIII:

Radon Prevention in New Construction—POSTERS

RADON REDUCTION IN WOOD FOUNDATION SYSTEM

by: Roscoe J. Clark
Permanent Wood Foundation, Inc.
Flint, Michigan 48501

ABSTRACT

Radon, ...an issue of growing concern to the building industry. Silently, invisibly, it invades existing structure ...as it will future foundation structures.

This paper will address the nature and causes of radon, and cost-effective prevention and retrofit techniques used for wood foundation systems.

Radon also can enter homes with foundations that use the under-floor as an air distribution system. These building practices will be shown; even materials used in construction may release radon, for example, this may be a problem in a house that has a solar heating system in which its heat is stored in large beds of stone. Stone is most often used in wood foundation construction.

The common radon entry points will be looked at, and the latest prevention techniques will be illustrated, such as natural and forced ventilation, sealing major radon sources and entry routes, and sub-slab and sump crock ventilations.

P.W.F. STUDY

The U.S., Canada and overseas are studying the effectiveness of various ways to reduce high concentrations of radon in houses.
Each year the study gives us a better understanding about radon and its effects. This paper describes methods that have been designed for successful reduction in permanent wood foundations. The information presented here is concerned primarily with radon which enters a house from the underlying soil.

FACTS

The first fact about radon reduction is "no two houses are alike." Houses that are built exactly the same have small differences in them that affect radon entry. These differences can effect the design and effectiveness of radon reduction techniques. P.W.F. homes can have major differences in radon sealing techniques compared to conventional foundations.

This paper is intended primarily for permanent wood foundations and those who have decided that they need to incorporate radon-reduction methods. The two basic goals are to minimize radon entry and the removal of radon gas. In fact, it is potentially more cost-effective to build a P.W.F. Home that resists radon entry than to remedy a radon problem after construction. This paper should only be used as an attempt to remedy a radon problem, and to give an understanding so not to cause other performance problems to be discussed below.

THE RISKS

The known health effect associated with exposure to elevated levels of radon is an increased risk of developing lung cancer. There is no doubt that sufficient doses of radon and its progeny can produce lung cancer in humans. Radon is believed to be the greatest risk of getting lung cancer for non-smokers.

As with other pollutants, when studying the exposure to radon, there is some uncertainty about the amount of health risk. The risk estimates are based on scientific studies of miners exposed to varying levels of radon in underground work. A more certain estimate of risk (than on studies) rely solely with animals. Despite that same uncertainty in the risk estimates for radon, the greater your exposure to radon, the greater your risk of developing lung cancer.

RADON ENTRY

Radon is a gas which can move through small spaces in the soil and gravel on which a house is built. Radon can seep into a home through the sump crock, joints, floor drains, cracks in concrete floors, etc. Radon has been found in well water and can release radon into the home when the water is used.

Some building materials have released radon; for example, stone fireplaces or solar systems which used stone beds for heat storage. However, building materials are not a major source of indoor radon.

The physical relationship between the major sources of radon and the indoor structure of a house is illustrated in figure 1. Common entry routes for radon gas into the house are shown. The major entry points for radon into the house include:

A. Cracks in concrete floors
B. Joints in building materials
C. Sumps - exposed soil and tile
D. Stone materials (i.e., granite)
E. Water (i.e., shower)

The soil is believed to be the greatest contributor of indoor radon in typical homes.

NEW CONSTRUCTION

1. Homes should be designed and built to maintain a neutral pressure differential between indoors and outdoors.

2. Homes should be designed and constructed to minimize pathways for soil gas to enter.

3. Features can be incorporated during construction that will facilitate radon removal after completion of the home if prevention techniques prove to be inadequate.

4. The first step in building new radon-resistant permanent wood foundations is to determine the potential for radon problems at the building site. Check with neighbors or state and local health agencies for soil test results.

CONSTRUCTION TECHNIQUES

Some of the radon prevention techniques are common building practices in permanent wood foundations. Others are less costly if accomplished during construction. The cost to retrofit an existing home with the same features would be significantly higher. These construction techniques do not require any fundamental changes in building design. Supervision over quality control is needed for certain construction details. Radon entry techniques can be grouped into two basic categories:

1. Methods to reduce pathways for radon entry.
2. Methods to reduce the vacuum effect of a home on surrounding and underlying soil.

These techniques are used in conjunction with each other (see figure 2).

UNDERSTANDING THE PERMANENT WOOD FOUNDATION BASIC REQUIREMENTS

The Permanent Wood Foundation is a load-bearing wood frame wall system designed for below-grade use as a foundation for light-frame construction.

The stress-graded lumber framing and plywood sheeting in the system are carefully engineered to support lateral soil pressure as well as live, dead and climatic loadings. Vertical loads are distributed to the supporting soil by a composite footing consisting of a wood footing plate and a structural gravel layer.

All lumber and plywood in contact with or close to the gravel is protected against decay and insects by pressure treating with time proven wood preservatives.

Moisture control measures based on the latest development in foundation engineering, construction practice and building materials technology are employed to achieve dry and comfortable living space below grade.

The most important of these measures is a porous gravel envelope surrounding the lower part of the basement. This porous layer directs ground water to a positive drain or sump, thus preventing hydrostatic pressure on the basement walls or floor. Similarly, moisture reaching the upper part of the basement foundation wall is deflected downward to the gravel drainage system by polyethylene sheeting or by the treated plywood itself. The result is a dry basement space that is readily insulated for maximum comfort and conservation of energy.

WORD OF CAUTION

What works for conventional foundations may have significant negative effects when applied to Permanent Wood Foundations. It is important to understand the basic requirements of the Permanent Wood Foundation system before applying mitigation measures which could cause problems to the system's performance. This Radon Check List may be helpful when applying mitigation measures.

RADON CHECK LIST

SEALING WALL POLY FOR RADON CONTROL

Six-mill thick polyethylene sheet should be applied over the below grade portion of exterior basement wall prior to backfilling. Joints in the polyethylene sheet shall be lapped 6 inches and bonded.

The top edges of the polyethylene sheeting should be bonded to the plywood sheeting. A treated lumber strip should be attached to the wall to cover the top edges of the polyethylene sheeting. The wood strip shall extend 8 inches above and 4 inches below finish grade level as required to protect the polyethylene from exposure to light and from mechanical damage at or near grade. The joint between the strip and the wall shall be caulked full length prior to fastening strip to the wall. The polyethylene sheet shall extend down to the bottom of the wood footing plate but shall not overlap or extend into the grave footing. Do not seal the bottom of the polyethylene sheet to the plywood wall for radon resistance. Moisture is deflected downward to the gravel drainage system by this polyethylene sheeting and by the treated plywood wall itself. Sealing this joint would result in preventing positive drainage to the gravel. Simply put, the basement may leak.

SEALING FLOOR POLY FOR RADON CONTROL

A six mill thick polyethylene moisture barrier shall be applied over the porous layer of gravel. Overlap the seams in the barrier 12 inches and seal. Penetrations of the barrier by plumbing should be sealed and care should be taken to avoid puncturing the barrier when pouring the floor. The floor polyethylene should not lap under the footer plate or seal to the wall poly for radon control. This will prevent positive drainage of the wall poly or moisture from inside the basement wall plates draining through the footer plate to the gravel footer. Moisture would be drained on top of the floor poly causing hydrostatic pressure and dampness. The poly can be brought up on the inside wall surface and sealed to the screed board.

INSTALLING POLY FOR WOOD FLOOR SYSTEM

Where wood basement floors are used, the polyethylene sheeting six mill shall be placed over the wood sleeper supporting the floor joist and, provisions are made for drainage to the porous layer below at the end of each bay. The sheeting should not extend beneath the wood footer plate. The poly is overlapped 12 inches and is not sealed for radon control.

Water that accumulates on top of the moisture barrier during construction can be dried out by venting the wood floor. Radon gas can also be vented out through these vents by convection. The studies show that three vents work better than two and should be placed 4 feet or farther away from any corners for best performance. (see figure 3)

USING LARGE GRAVEL TO VENT RADON

Gravel should be washed and well graded. The maximum size stone should not exceed 3/4 inch. Gravel shall be free from organic, clay or salty soils.

Sand shall be coarse, not smaller than 1/16 inch grains and shall be free from organic, clay or salty soils.

Crushed stone shall have a maximum size of 1/2 inch. Crushed stone must also be compacted before installing footer plate.

The Permanent Wood Foundation system incorporates a composite footing consisting of a wood footing plate and a layer of gravel, coarse sand or crushed stone. The wood footing plate distributes the axial design loads from the framed wall to the gravel layer which in turn distributes it to the supporting soil:

*the use of larger than 3/4 inch stone for radon mitigation can cause inadequate bearing transfer. This means less wood to stone surfaces that can cause the stone to crush into the wood footer plate causing settling of the foundation.

*the use of larger than 1/2 inch crushed rock will have jagged edges that will break off under load causing settling.

*larger stone makes it harder to level foundation walls.

CAULKING THE P.W.F.

The sealant used for caulking joint in plywood wall sheeting should be capable of producing an effective moisture seal under the conditions of temperature and moisture content at which it will be applied and used. Buytl caulking is commonly used for this purpose. To correctly apply caulking into joint, apply caulking on edges of plywood joint, push next sheet into place. Be careful not to slide off caulking. This has several purposes; one is to be an expansion joint for the plywood, and another is to give resistance to moisture flowing down the wall and can have sealing effects in radon control. Caulk end and center seam of wall plywood. Do not caulk the bottom edge of plywood where it buts up next to bottom plate. This will stop the pathway for any water that accumulates from condensation on the inside plywood surface during winter construction. This damming of water can be picked up by the wall insulation and lead to mildew and drywall staining.

TOOLING BASEMENT FLOOR/WALL FLOOR JOINT

The more common radon entry pathway are inside perimeter floor/wall joints. To reduce radon entry through these joints, install a wide plywood screed board along the perimeter of the foundation. This wider screed board can be sealed to the drywall finish installed later on the foundation wall above. Mud and tape this joint when finishing the drywall above.

The concrete floor is poured against the screed board and the concrete edge is tooled round for a caulk sealer to be applied later.

Oversize tooling of this joint may cause lateral wall deflection at the floor/wall assembly. Proper floor height against studs will allow adequate bearing area. This bearing area is figured from the bottom of the tool joint.

Remove all grade stakes and fill the holes as the slab is being finished. This will prevent future radon pathways through the slab which might otherwise be created, as embedded untreated wood eventually deteriorates.

Carefully seal around all pipes and wires penetrating the slab. Pay careful attention to the bathtub, shower, and toilet openings around traps.

Floor drains, if installed, should drain to a sealed sump crock, and used traps in all floor drains.

Sump should be sealed at the top with a plywood and gasket lid. Use only submersive-type sump pumps in the crock to prevent high humidity corrosion. For sump crock sub-slab ventilation, drill holes near the top of the sump wall to let soil gases enter crock. (see figure 4)

METHODS TO REDUCE PATHWAY FOR RADON ENTRY

The most effective way to seal a P.W.F. basement wall is by drywalling the wall. First, the bottom seal must be applied. This is done by applying a gasket to the bottom edge of a added plywood screed board. This is pushed down into place and the wood strip is nailed into place (use 1/2 inch plywood for 1/2 inch drywall). Next, install a gasket at the top top-plate. Now install new drywall, compressing the gasket between the plate and the drywall. (see figure 5)

SUB-SLAB VENTILATION USING WOOD FLOOR SYSTEM

To seal a wood basement floor system, first install a wider plywood screed board. A gasket is installed to the plywood screed where it will be sandwiched between the wood floor ban joist. A gasket is installed on the top edge of the ban joist so that gasket will be sandwiched between the plywood and ban. The gasket makes a more permanent seal over caulk or glue.

Caulk plywood edges as the floor is installed with buytl caulking. If mechanical ventilation is needed, put suction pipe under poly film for better performance. Keep above the water line. A tee fitting will add to the performance. (see figure 6)

SUB-SLAB VENTILATION USING SUMP SUCTION APPROACH

Where better performance is needed, the P.W.F. sump can be vented by sealing the top with a plywood lid and gasket. The water enters the sump from the bottomless crock. This system will cause a water trap effect. Therefore, drilling holes at the top of the crock will help let in the soil gases so it can be vented. (see figure 7)

SUB-SLAB VENTILATION OF WOOD FLOOR SYSTEM

To vent a wood basement floor, cut out a section of the ban joist. Install 2x2 and sheeting to make a pathway to the outside up the foundation wall. Install a screen vent cover on the outside. (see figure 3)

SUB-SOIL VENTILATION USING HORIZONTAL RUN UNDER VAPOR RETARDER

When using the crawlspace as a heat plenum, always have the crawlspace in a positive air flow. Running the blower constantly will minimize the negative pressure differences. A polyethylene film is installed over a 4 inch layer of gravel and the polyethylene is covered with 2 inches of sand. Overlap the polyethylene 12 inches at all seams and seal. Seal polyethylene to film on the wall. For better performance, a tee or cross network of 4 inch p.v.c. can be connected to a fan-driven system.
(see figures 8 and 9)

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the agency and no official endorsement should be inferred.

MAJOR RADON ENTRY ROUTES

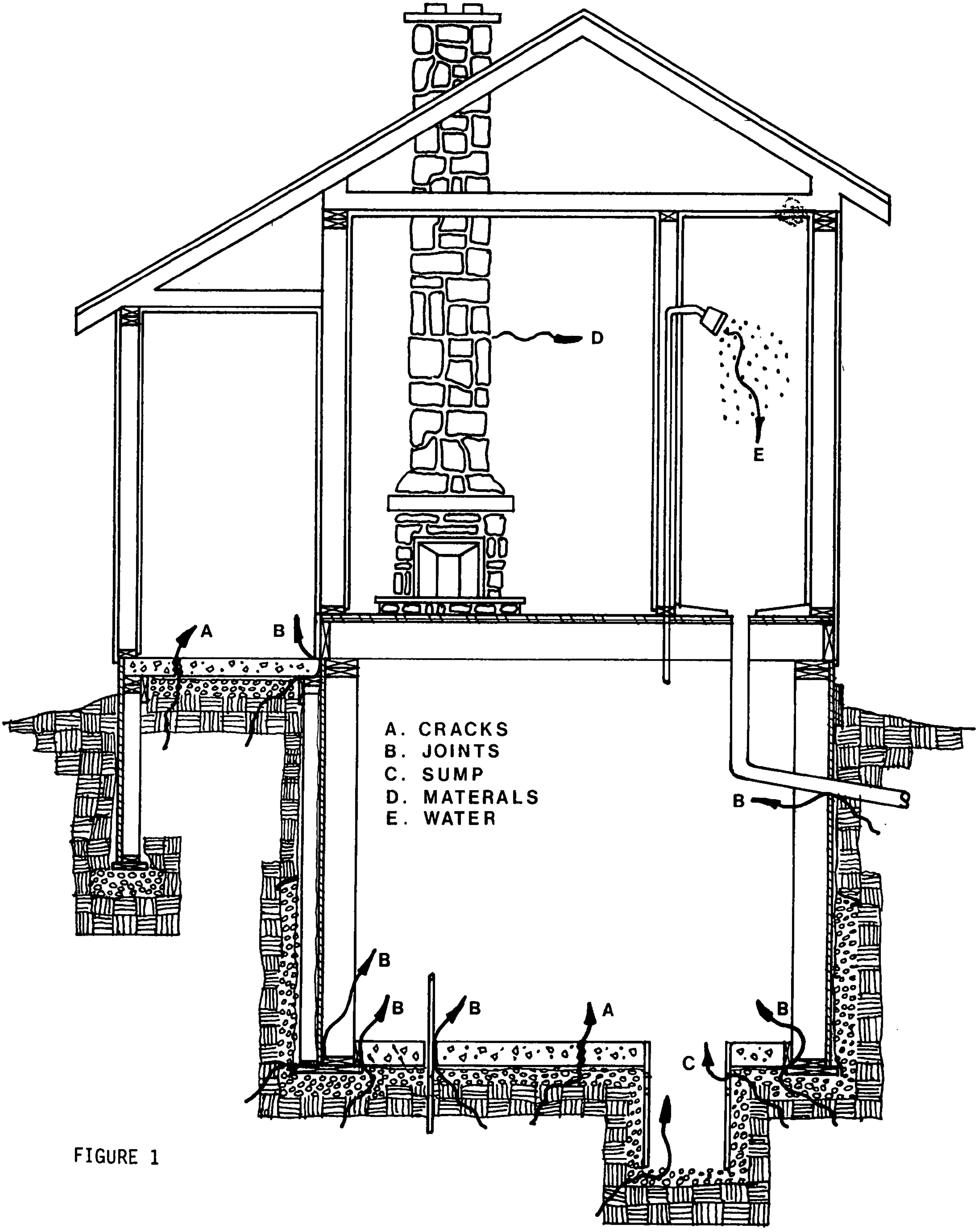

FIGURE 1

METHODS TO REDUCE THE VACUUM EFFECT

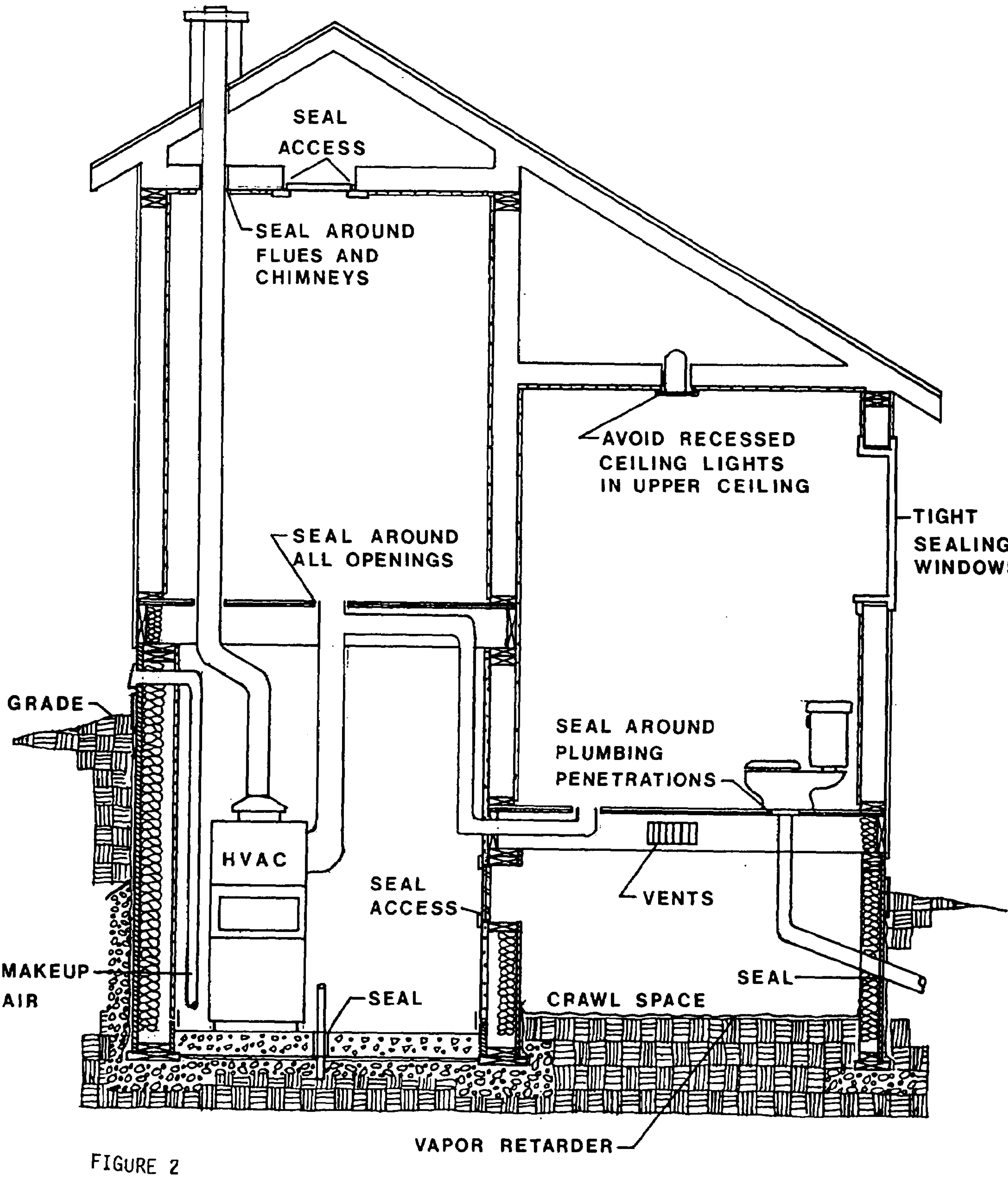

FIGURE 2

SUB-SLAB VENTILATION OF WOOD FLOOR SYSTEM

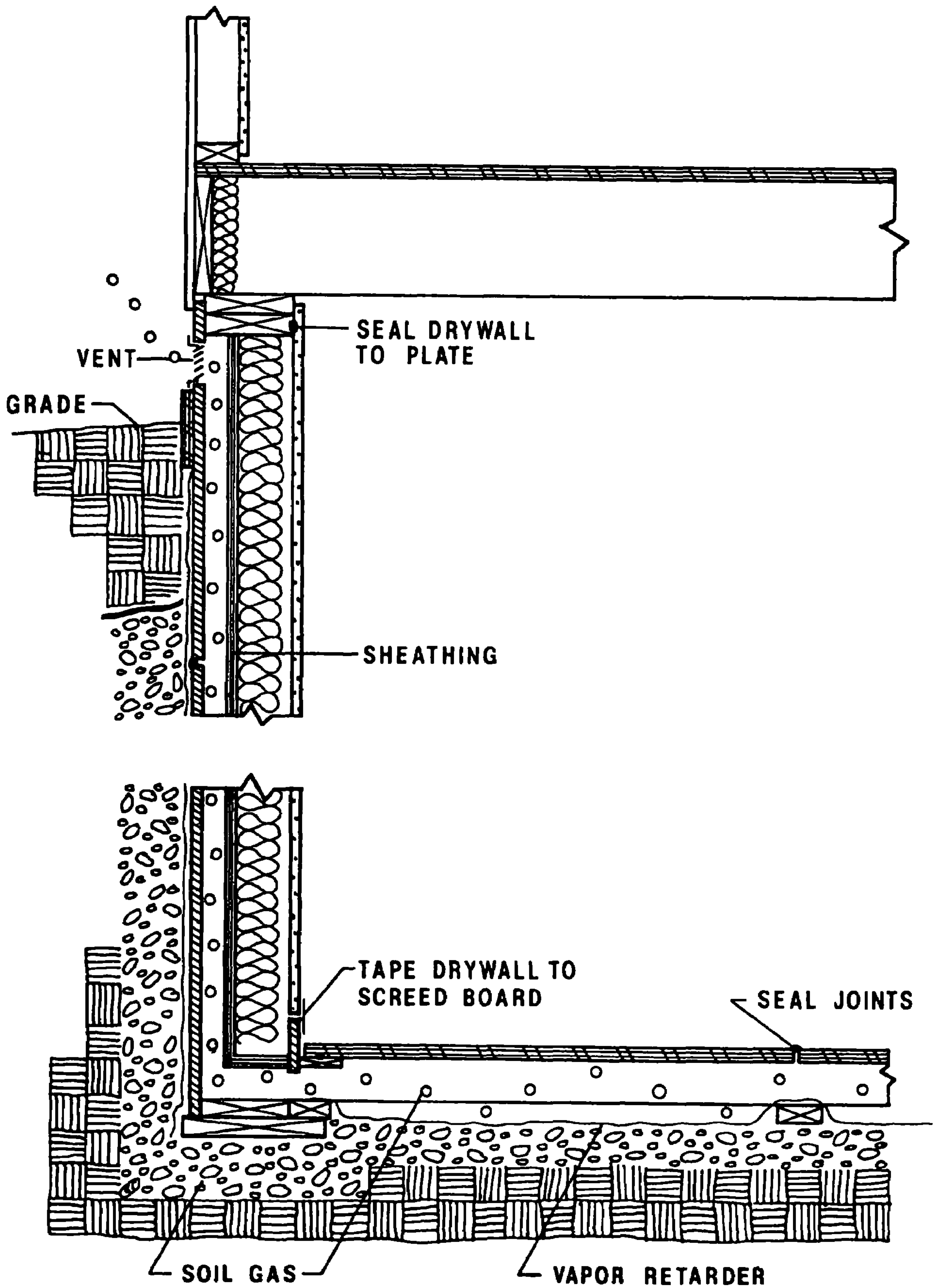

FIGURE 3

Sub-slab ventilation using individual suction point approach.

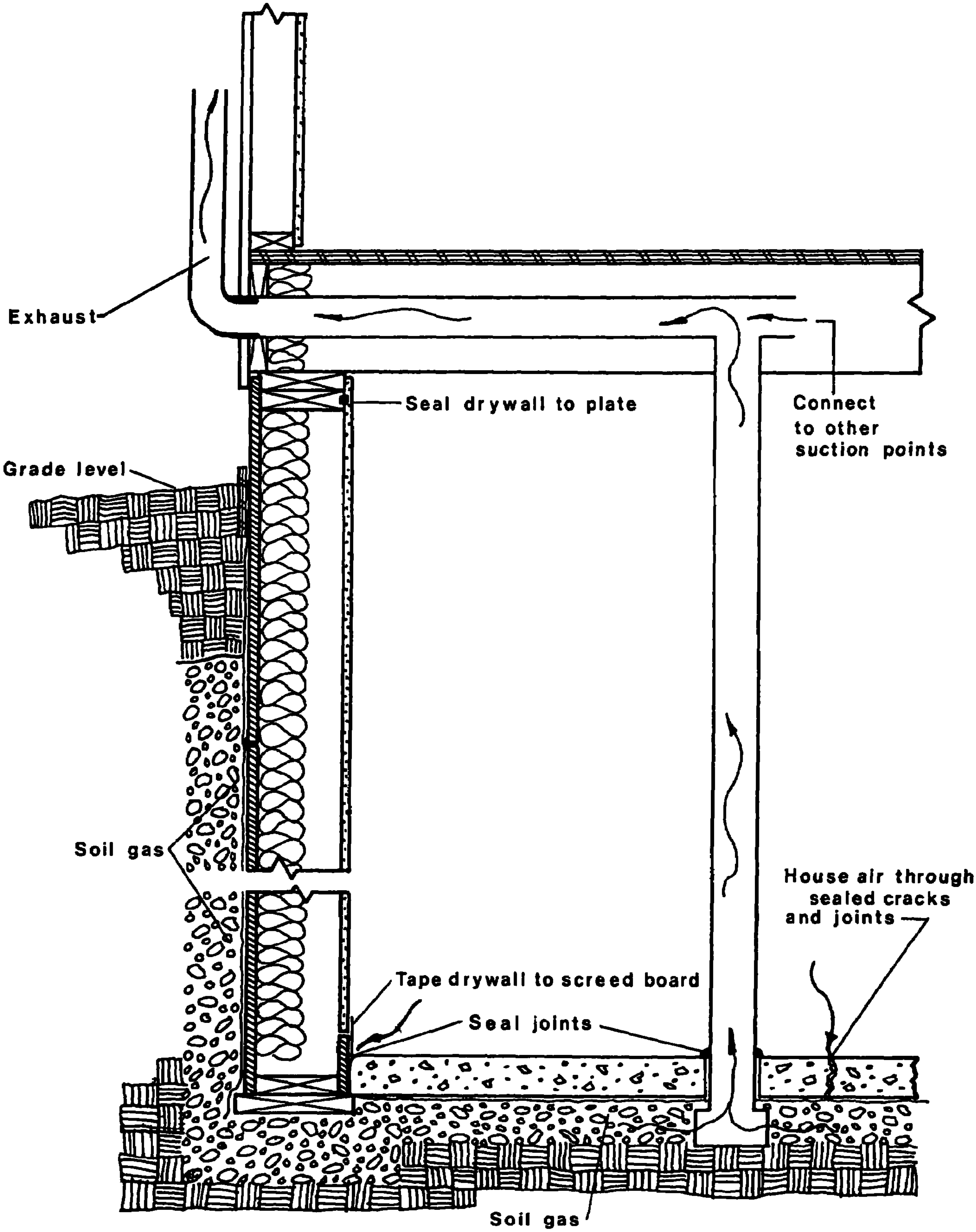

FIGURE 4

METHODS TO REDUCE PATHWAYS FOR RADON ENTRY

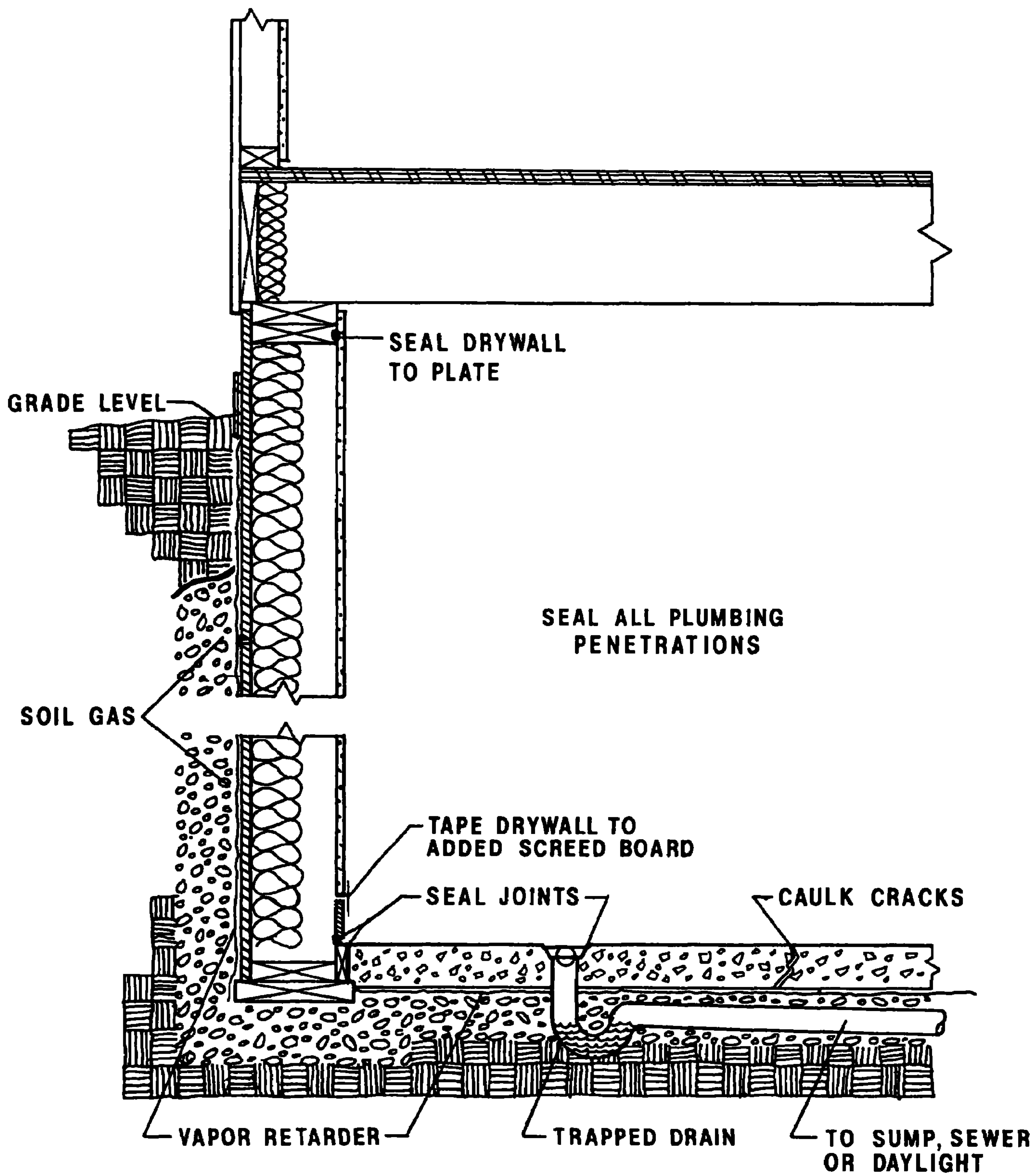

FIGURE 5

Sub-slab ventilation using wood floor system

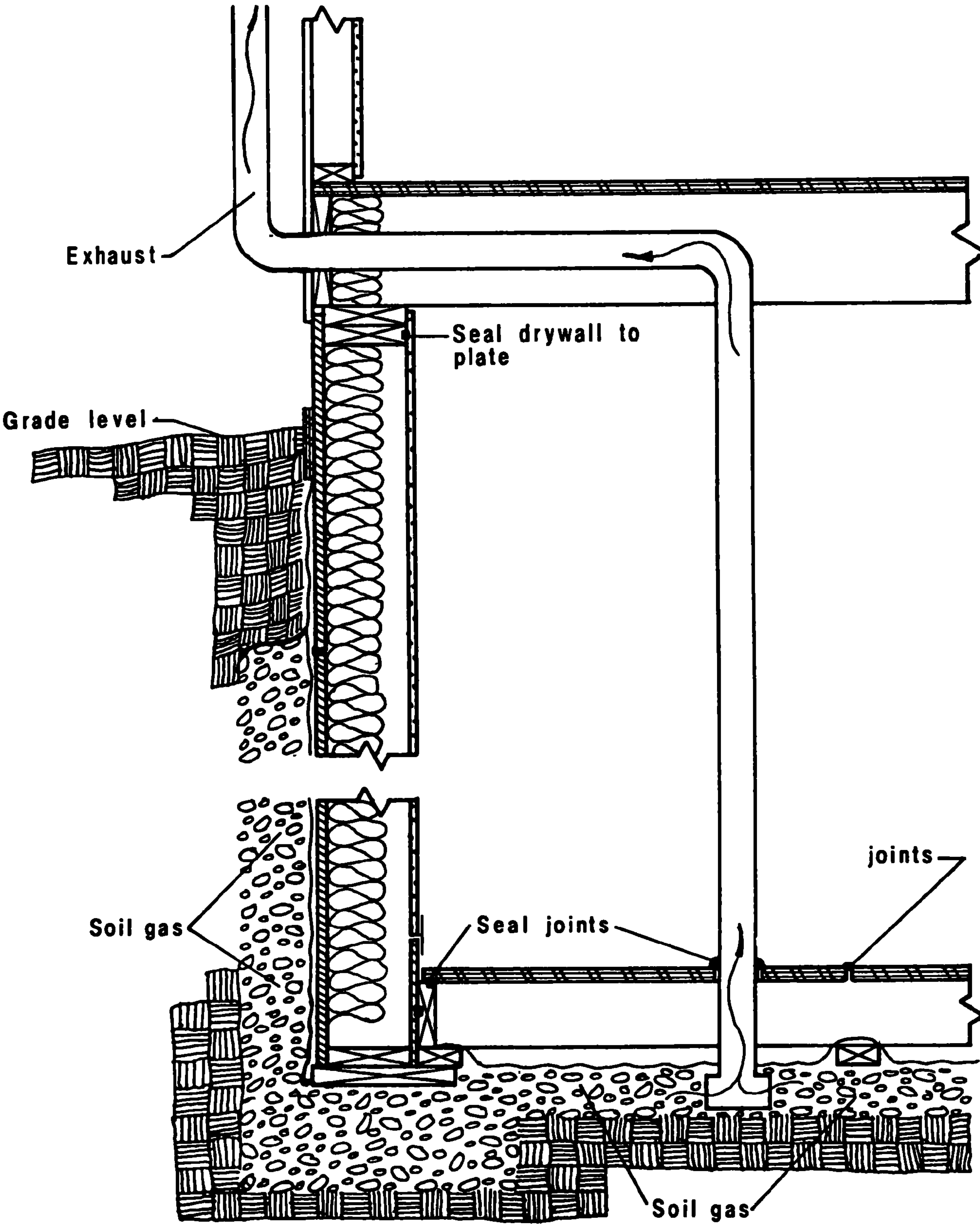

FIGURE 6

Sub-slab ventilation using sump suction approach.

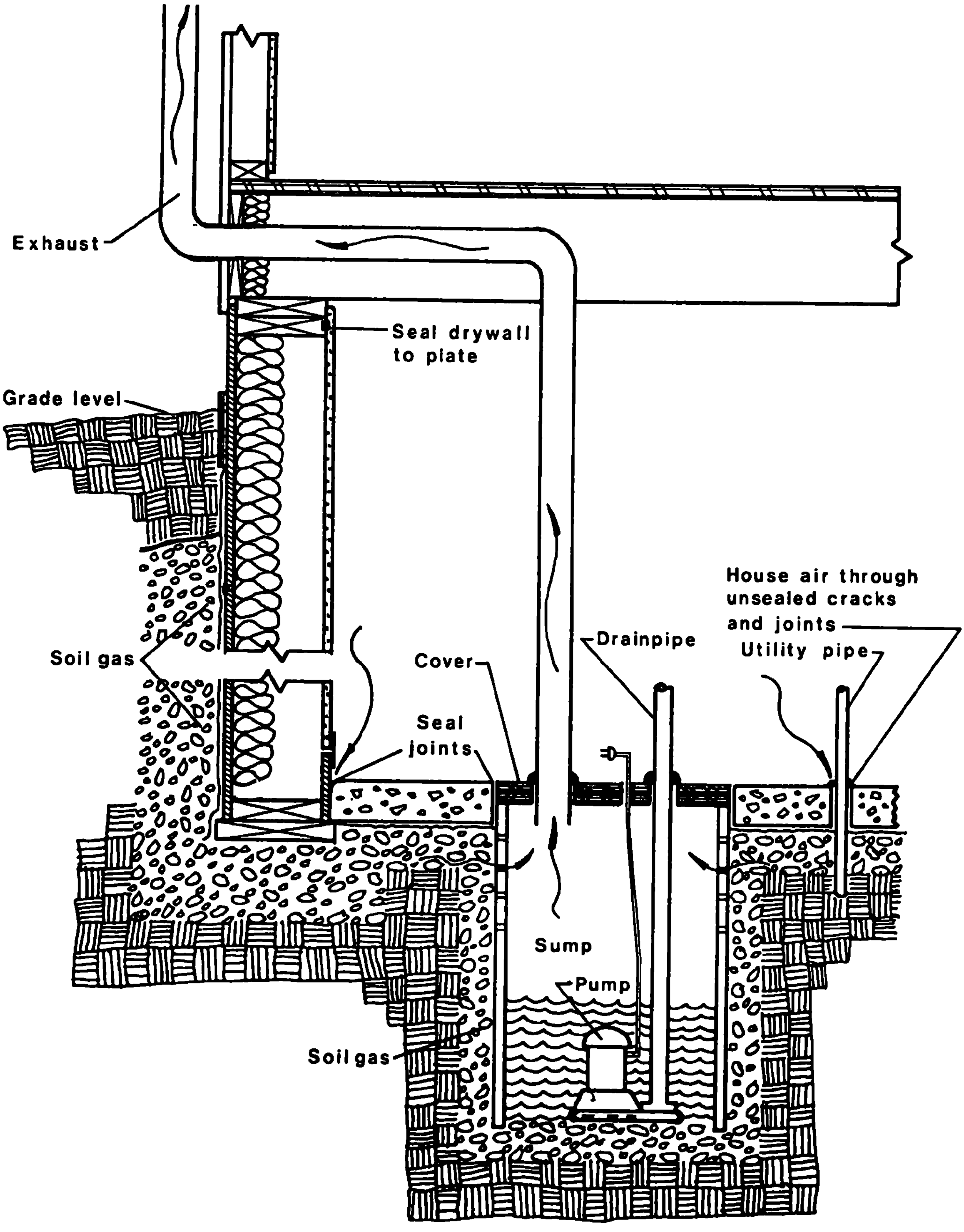

FIGURE 7

Perimeter drain tile ventilation where tile drains to sewer or daylight.

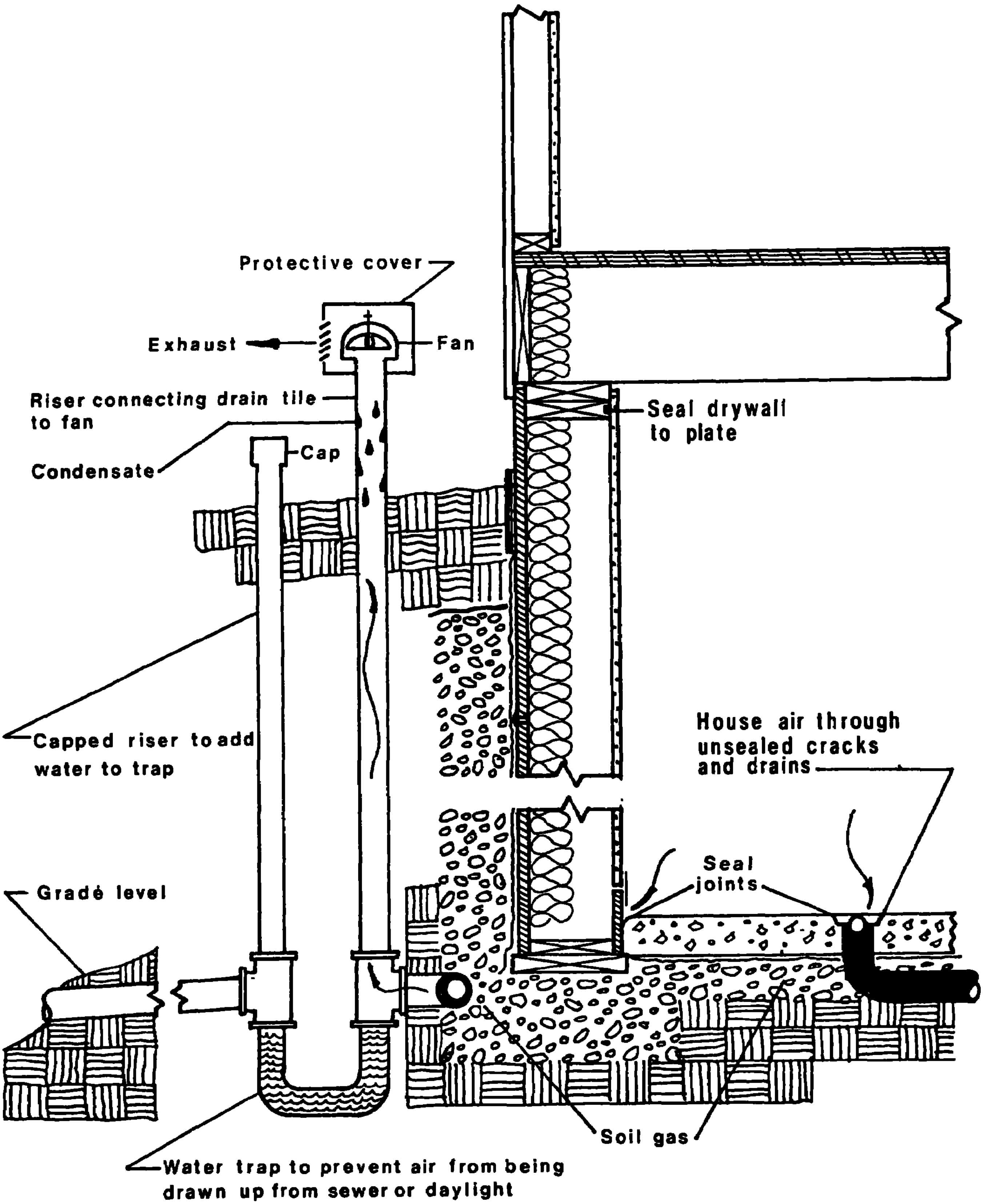

FIGURE 8

Sub- soil ventilation using horizontal run under vapor retarder.

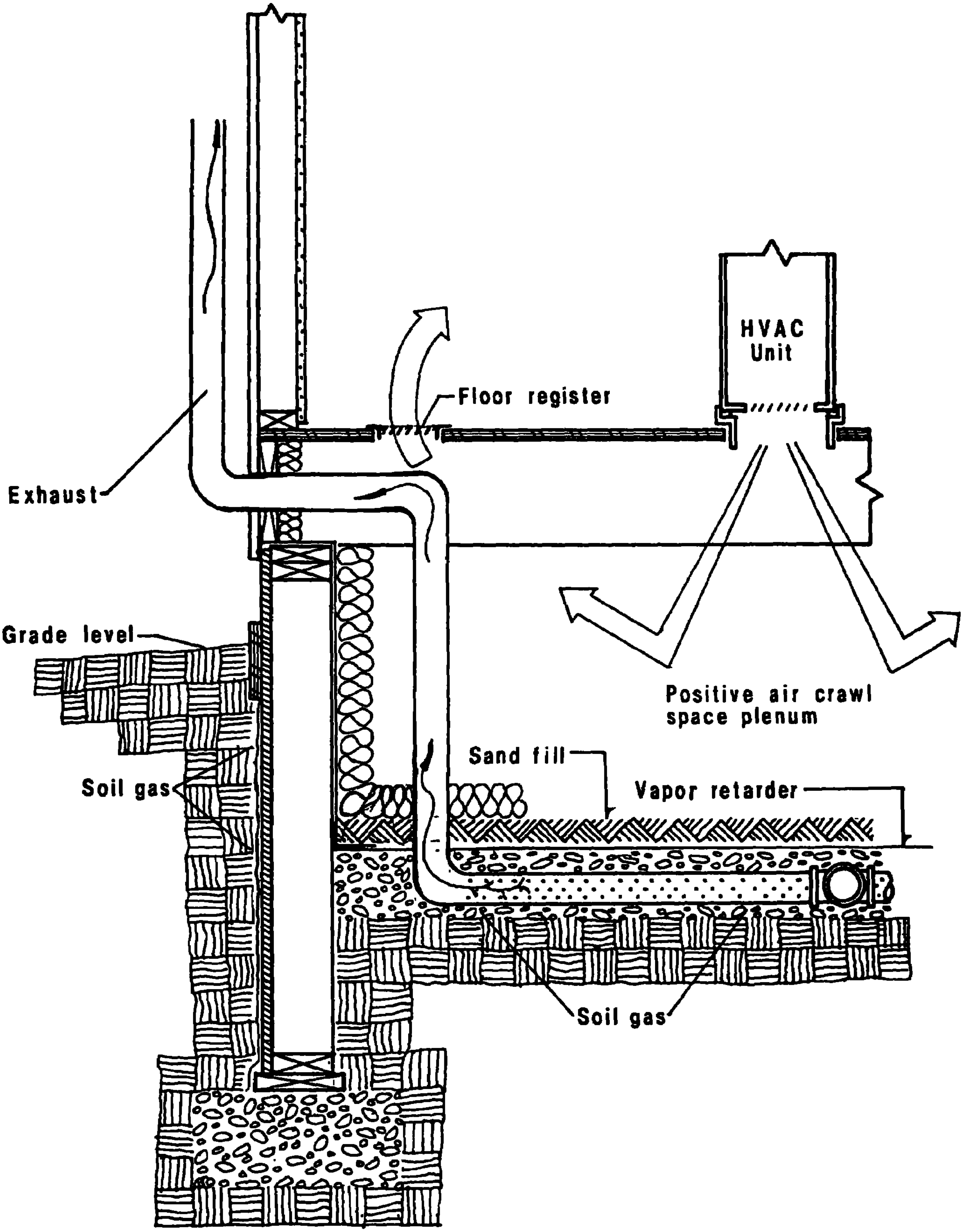

FIGURE 9

Session IX:

Radon in Schools and Large Buildings

Radon Measurements in 130 Schools Across the US

R. Thomas Peake
Anita Schmidt
US Environmental Protection Agency

ABSTRACT

During the winter of 1989, screening Rn measurements were made in 130 schools geographically dispersed across the U.S. The purpose of the study (Phase I) was to identify a subset of schools suitable for year long follow-up study (Phase II), the results of which will be used to udpdate EPA's guidance for Rn testing in schools. The 130 schools were selected nonrandomly using school characteristics and accessibility in areas where there were known or suspected radon problems in homes. Because of this selection, it is postulated that levels found in this study may represent an upper boundary for screening radon measurements in US schools.

The findings from this study confirm previous findings (1) that Rn concentrations can vary significantly from room to room within a school. The average Rn level for the 130 schools is 3.7 pCi/L (geometric mean of 1.4 pCi/L); over half of the schools tested had at least one screening Rn measurement above 4 pCi/L. The study also indicates that schools in the same area can have similar or significantly different radon concentrations.

This paper has been reviewed in accordance with the U. S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

(1) R. Thomas Peake et al., Radon Measurements in Five Fairfax County, Virginia Schools, 1989, EPA International Conference on Radon and Radon Reduction Techniques Symposium Proceedings.

RADON DIAGNOSTICS AND MITIGATION IN TWO PUBLIC SCHOOLS IN NASHVILLE, TENNESSEE

by: Alfred B. Craig, Kelly W. Leovic, and D. Bruce Harris
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

Bobby E. Pyle
Southern Research Institute
Birmingham, Alabama 35255-5305

ABSTRACT

Diagnostic measurements and mitigation studies were carried out in two schools in Nashville, Tennessee, as part of the Environmental Protection Agency's (EPA's) School Radon Mitigation Development/Demonstration Program. Diagnostic studies included architectural plans and building examination, sub-slab radon concentrations, sub-slab communications measurements, and detailed classroom radon measurements using 2-day charcoal canisters, electret ion chambers, and continuous monitors. Although sub-slab communications varied significantly between the two schools, both were amenable to mitigation using sub-slab suction. Average premitigation levels of 39.5 and 29.7 picocuries per liter (pCi/L)* were reduced to 0.78 and 1.7 pCi/L in the two schools.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

*See conversion factors listed at end of paper.

INTRODUCTION

In February 1989, the Environmental Protection Agency (EPA), in cooperation with state and local officials, measured radon levels in over 3,000 classrooms in 130 schools located in 16 states spread across the United States using 2-day charcoal canisters. The purpose of these tests was to select 20 schools for detailed testing over a 1-year period to improve interim radon measurement protocols for schools. Two of the schools in Nashville, Tennessee, with very high levels of radon in most of the classrooms were selected for inclusion in EPA's School Radon Mitigation Development/Demonstration Program. These were the Two Rivers Middle School and Glenview Elementary School, both located in a high radon-risk area of Nashville where numerous outcroppings of Mississippian-Devonian black shale, commonly referred to as Chattanooga shale, occur. This shale deposit runs through the middle of the state of Tennessee and is the source of high radon levels in houses in the central Tennessee area, including parts of Nashville. EPA has also been studying the mitigation of radon in existing houses in Nashville over the past 3 years.

Results of diagnostic and mitigation techniques used in the two schools are discussed separately and compared.

TWO RIVERS MIDDLE SCHOOL

Figure 1 is a floor plan of the first floor of Two Rivers Middle School with dates of construction of each area and classroom numbers. This school was

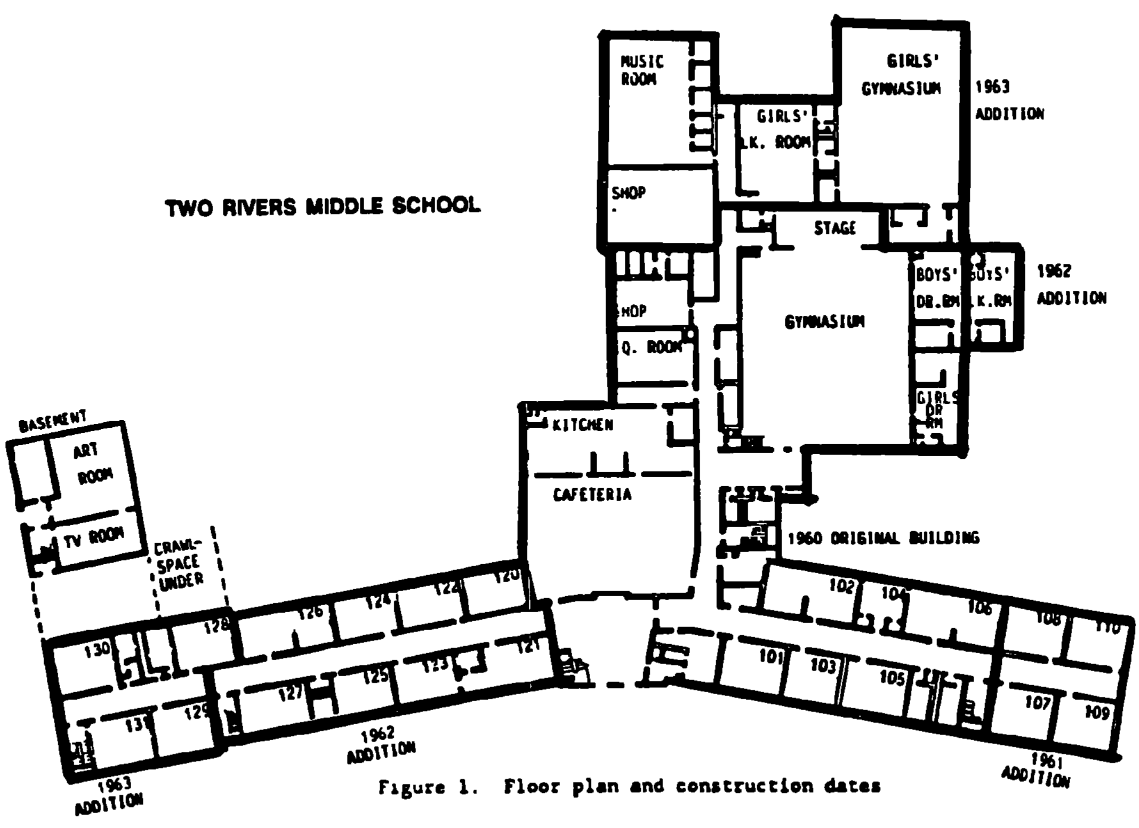

Figure 1. Floor plan and construction dates

built as a high school between 1960 and 1963 in four phases. The school contains 19 slab-on-grade classrooms and 2 classrooms located over a crawlspace on the first floor, and 2 basement classrooms. In addition to these classrooms, there are two gymnasiums with boys' and girls' locker rooms, cafeteria, kitchen, and three rooms for music and shop. Part of the locker rooms and gymnasium are over crawlspace and the rest is slab-on-grade. The two classroom wings contain a second story with 23 classrooms and a library. Mitigation studies at this school were limited to the two, two-story classroom wings and the two basement rooms under the end of one classroom wing.

Thirty classrooms were initially tested over the weekend of February 4, 1989. The average of these tests was 39.5 picocuries per liter (pCi/L) and ranged from 1.5 to 136.2 pCi/L. Only three rooms were below 4 pCi/L. These measurements are shown on the floor plan in Figure 2. The three highest rooms were tested 2 weeks later to verify these high readings. One room, initially measured at 136.2 pCi/L, increased to 148.8 pCi/L, and radon levels in the other two rooms decreased to about 50 pCi/L. The average decrease of the three rooms was 18.5 percent. Retest data are given in parentheses in Figure 2. Testing was carried out in accordance with Report EPA-520/1-89-010, "Radon Measurement in Schools, An Interim Report."(1)

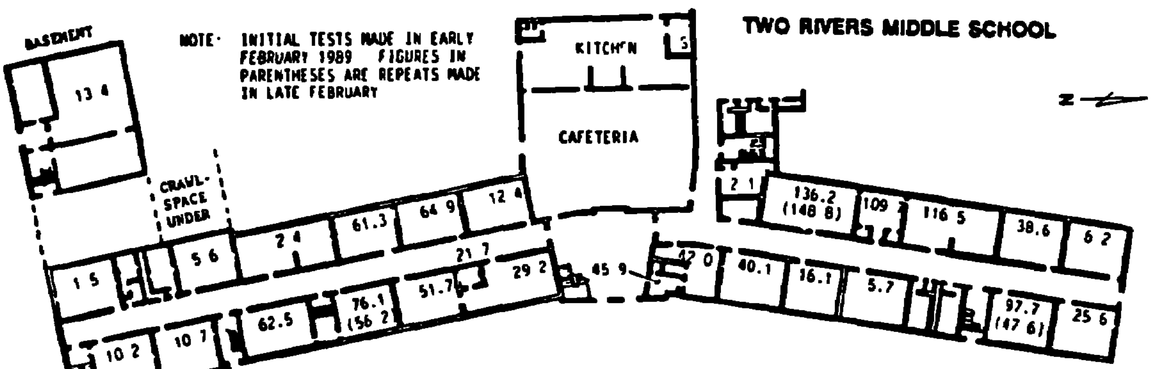

Figure 2. Radon measurements, February 1989, pCi/L

Because of the very high readings, school maintenance personnel sealed floor cracks and openings in the 10 classrooms with the highest readings, all but one of which were above 50 pCi/L. These 10 rooms were reduced from an average of 81.7 pCi/L in the initial test to 29.0 pCi/L, a 64.5 percent reduction. However, the readings in all 10 rooms were still above 20 pCi/L after sealing, the highest level being 41.7 pCi/L.

Prior to initiating diagnostic studies in early June, the building was re-tested over a weekend under the same test conditions as the first set. The 26 rooms had an average level of 10.1 pCi/L and ranged from 1.9 to 32.4 pCi/L, with 8 of the 26 rooms being below 4 pCi/L. This decrease could be partially attributed to the sealing carried out by the school maintenance personnel, but it was also probably the result of the difference in summer and winter readings. However, the levels were sufficiently high to cause a health concern; consequently, diagnostic measurements were made and mitigation carried out.

DETAILED DIAGNOSTIC STUDIES

Inspection of Architectural Drawings and Building

Examination of the foundation and wall section plans disclosed that the two hall walls in the slab-on-grade areas are load bearing, resting on a thickened slab footing, with aggregate shown extending under the footing. The walls between classrooms are not load-bearing and do not extend through the slab. The addition of the four classrooms at the north end of the building resulted in what appeared to be a solid wall under the slab between the last four rooms and the initial part of the building.

Eight classrooms in the south wing are slab-on-grade and the southernmost part is a four classroom addition built partly over crawlspace and partly over basement. This is shown in Figure 1. The drawings show that aggregate had been used under the slab throughout the building, including the basement.

The building has hot water radiant heat along the outside walls in all areas except the basement. (These two basement rooms had two separate HVAC systems.) The portion of the building heated with hot water has no active ventilation except infiltration. The original windows have been replaced with a combination of solid panels and weather stripped windows, reducing the potential for ventilation through infiltration. A blower test run on a segment of four rooms indicated a very tight building. The entire building is air-conditioned by window units installed in one of the solid panels in each of the classrooms. All of the fresh air supplies for the air-conditioning units were closed for energy conservation.

Measurement of Sub-slab Radon Levels

Sub-slab radon levels were measured by "sniffing" through a 1/4 in. hole in the center of each room using a Pylon AB-5 continuous monitor. Levels under the original building ranged from 2400 to 5700 pCi/L. The four-room addition on the north end of the building ranged from 1300 to 1700 pCi/L. The portion of the south wing of the building which was slab-on-grade ranged from 200 to 2200 pCi/L. The levels under the cafeteria were 4100 pCi/L. Levels under the two basement rooms at the south end of the building were 500 and 800 pCi/L. Sub-slab radon levels for individual rooms are shown in Figure 3.

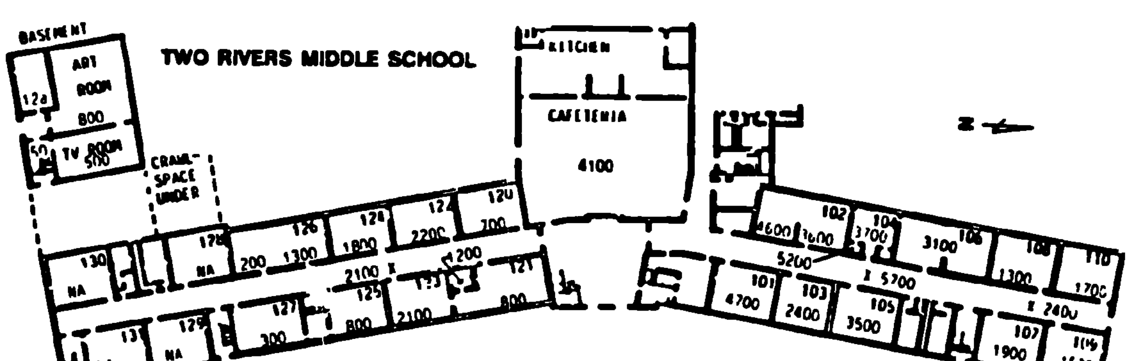

Figure 3. Sub-slab radon measurements, pCi/L

Sub-slab Communication Testing

Sub-slab communication was measured using an industrial vacuum cleaner. The hose of the vacuum was inserted through a 1-1/2 in. hole drilled through the slab in the closet in Classroom 104 (north wing). The speed of the industrial vacuum cleaner was varied to draw vacuum in the hose of 2, 4, and 6 in. W.C. Pressure difference between the sub-slab and the room was then measured at the center of each room (as a minimum) using a micromanometer sensitive to less than 0.001 in. W.C. The measurement was made in the hole (in the middle of the room) which had been drilled for radon sub-slab profile measurements. The suction hose of the vacuum cleaner and the hose from the micromanometer were carefully sealed at the floor surface using rope caulking. Negative sub-slab pressures shown in Figure 4 were measured at 4 in. W.C. on the vacuum cleaner line.

Excellent sub-slab depressurization was measured from Classrooms 101 to 106. Depressurization under the rooms on the east side of the hall appeared to be as good as those on the west side of the hall, showing that pulling under the thickened slab sections under the two hall walls did not cause any significant loss of pressure confirming that there was aggregate under the thickened slab as indicated on the plans. The negative pressure found in the slab under Rooms 107 through 110 was surprising: it was not anticipated that these rooms would communicate with the rest of the rooms in the wing because they were added at a later date, leaving the north wall of the building in place. (These brick walls were left exposed in Rooms 107 and 108.) However, when the wall at the end of the initial hall was broken out to extend the hall, the foundation was apparently broken below the aggregate level; the aggregate continues down the hall. Consequently, it was possible for the suction to reach these other four rooms. The center of Room 109 was approximately 120 ft from the suction point.

Sub-slab communication was measured in the south wing by placing a suction point in the office in the south west corner of Classroom 121. Negative pressures under the slab in these rooms are also shown on Figure 4. Note that the suction field extension is not nearly as great in this wing as in the north

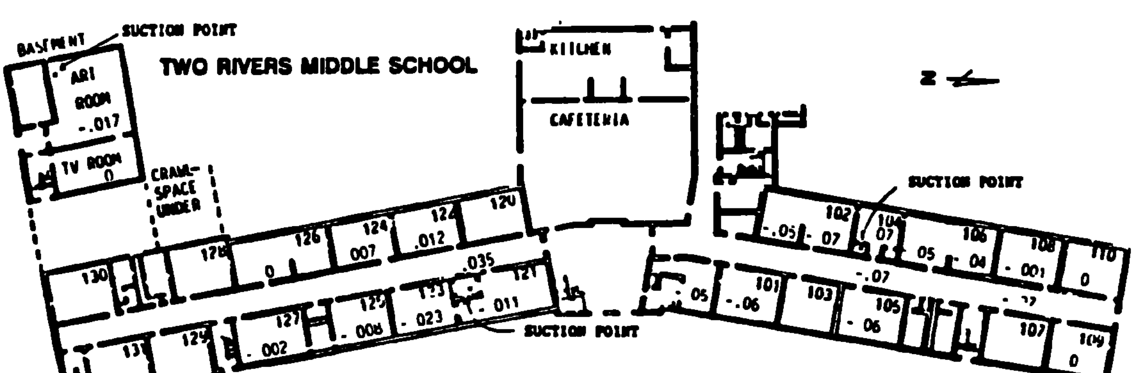

Figure 4. Negative sub-slab pressures, in. W.C.

wing; apparently sub-slab communication is not as good. Although Room 126 (farthest from the suction hole) did not show a negative pressure under the slab with the vacuum cleaner test, it was anticipated that the installation of a suction point where the suction hole was would reach Room 126. The larger suction hole and fan of the permanent system normally give a greater suction field extension than is typically seen with the vacuum cleaner test.

Sub-slab communication was measured in the basement rooms (containing the art and TV rooms) at the south end of the building. A suction point was made in one corner of the art room, and it was possible to measure negative pressures in the middle of the room. However, there was no indication of any negative pressure under the slab of the TV room.

MITIGATION DESIGN AND INSTALLATION

The degree of sub-slab communication in the north wing was much greater than had been found in any other school tested in EPA's School Radon Mitigation Development/Demonstration Program. Sub-slab depressurization in the original building was measured at 0.05 in. W.C. as far as 60 ft from the suction point. Even in the four rooms of the addition at the north end of the wing, depressurization was readily achieved from the one suction point in the original building. The center of the farthest classroom (109) in the north addition was 110 ft from the suction point and still showed a negative pressure of 0.003 in. W.C. at a vacuum suction of 6 in. W.C., in spite of the intervening sub-slab wall. Consequently, it was anticipated that one suction point in the storage room of Classroom 104 would be satisfactory for the entire north wing (about 15,000 sq ft).

Although the communication in the south wing was not as good as in the north wing, it was adequate to expect mitigation in all the rooms (except the basement rooms and possibly the rooms over the crawlspace) with a single suction point located in the office of Classroom 121.

Two temporary mitigation systems were installed using 6-in. diameter flexible PVC drain pipes exiting through the classroom windows and attached to individual fans. The turbo fan had a rating of 410 cfm at 1 in. W.C. With the temporary system operating in the north wing, all rooms measured below 4 pCi/L during weekend charcoal canister measurements except for the classroom closest to the exhaust line through the exterior of the building. This classroom measured 5.3 pCi/L; it was suspected that the higher level was the result of reentrainment. All the rooms in the south wing were below 4 pCi/L except those over the crawlspace and basement and the basement rooms. (These tests were made before the basement sub-slab system was installed in the TV and art rooms.) Sub-slab communication was again measured in all the rooms with the temporary systems in place and later with the permanent systems in operation. As expected, the negative sub-slab pressure, achieved with the temporary and permanent systems, was greater than had been achieved with the vacuum cleaner as shown by comparing the negative sub-slab pressures in Figures 5 (permanent systems in operation) and 4 (vacuum cleaner tests). The center of the classroom at the far end of the north wing was 112 ft from the suction point and had a negative sub-slab pressure of 0.007 in. W.C. with the permanent system in operation.

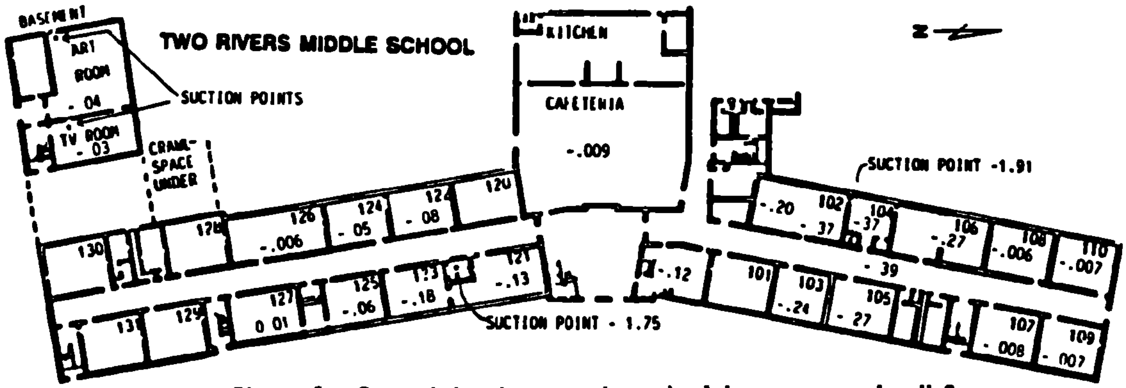

Figure 5. Post-mitigation negative sub-slab pressures, in W C.

In view of these findings, a decision was made to convert the temporary systems into permanent systems. In both cases the pipes were run overhead to the rear of the building and up the outside of the building with the fan located under the overhang and the exhaust extended over the top of the roof. There are no air intakes within 50 ft of these exhaust points. (Note that Tennessee State codes require any exhaust to be a minimum of 10 ft from any fresh-air intake.)

The two basement rooms had much poorer communication than the first floor slab-on-grade wings. It appeared that there was a subslab barrier between the TV room and the art room; consequently, a 4-in. suction point was installed in each of the two rooms manifolded to a common exhaust line run out the back of the building and to the roof using the same configuration as in the other systems. With this third system in operation, pressure field extension measurements under the slab of the two basement rooms showed that adequate sub-slab depressurization had been achieved as shown in Figure 5.

MITIGATION RESULTS

Installation of the sub-slab system in the two basement rooms was completed during the last week of July. All rooms in the two classroom wings, including the basement, were tested over the first weekend of August with charcoal canisters under closed building conditions. Results of these tests are shown in Figure 6. The average level of all measurements in August, with the three mitigation systems operating, was 0.78 pCi/L, ranging from 0.5 to 1.3 pCi/L.

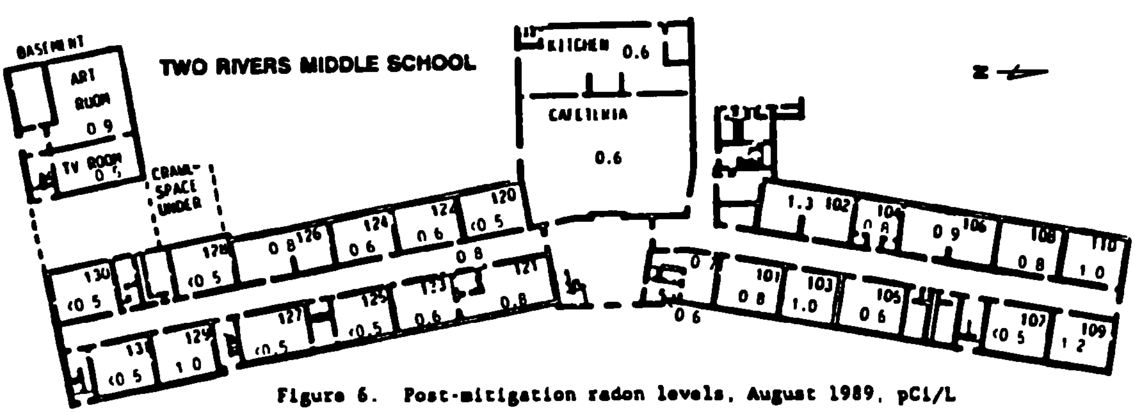

Figure 6. Post-mitigation radon levels, August 1989, pCi/L

Pressure-actuated switches served the three permanent systems: a green light indicated when negative sub-slab pressures were being maintained, and a red light showed when the system was inoperable. These warning lights are checked daily by the custodial staff.

All the rooms were retested during cold weather in December. Results of mid-winter tests will be reported at the Symposium.

GLENVIEW ELEMENTARY SCHOOL

Glenview is a 21-classroom elementary school. The original part of the building was constructed in 1954 and included 13 classrooms, an auditorium/cafeteria, a kitchen, and administrative offices. The first addition was built in 1957 and consisted of four classrooms at the south end of the original building. Both the original structure and the 1957 addition are slab-on-grade; the addition is about 4 ft lower than the original building because of the topography of the site. The second addition, built in 1964, consisted of a four-classroom separate structure on the northwest side of the building. This addition is a raised slab over a crawlspace. Mitigation studies during the summer of 1989 were limited to the slab-on-grade portion of the building. The crawlspace wing will be mitigated during the 1989-90 school session. Figure 7 is a floor plan showing dates of construction and classroom numbers.

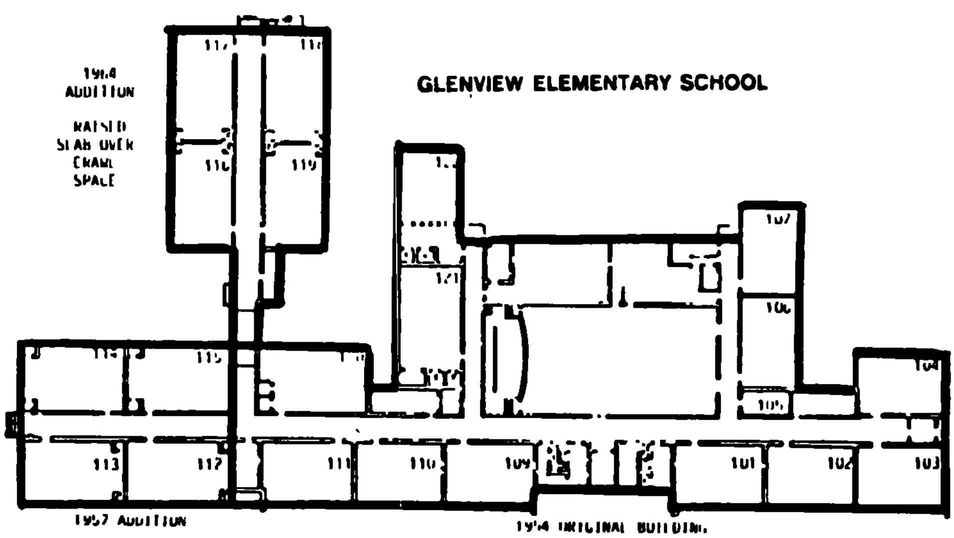

Figure 7 Floor plan and construction dates

All classrooms and the two administrative offices were initially tested over the weekend of February 4, 1989. The average level of the 22 locations tested was 29.7 pCi/L, ranging from 8.9 to 52.5 pCi/L. Individual classroom levels are shown in Figure 8. The four rooms with highest radon levels (average of 44.5 pCi/L, ranging from 40.1 to 52.5 pCi/L) were retested the weekend of February 18. Retests of these four rooms gave an average level of 37.5 pCi/L, ranging from 30.0 to 42.6 pCi/L. This was less of a decrease than found in the Two Rivers School during the same period, indicating that seasonal variation is school-specific. All the rooms were retested in late June and again in July.

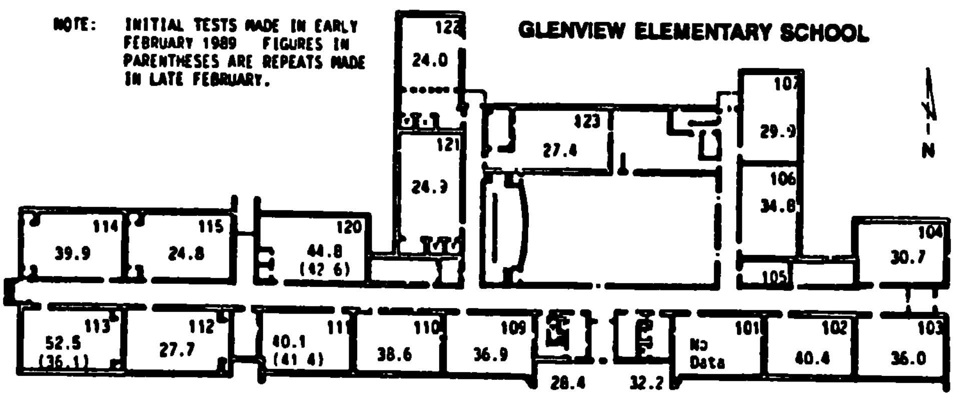

Figure 8. Radon measurement, February 1989, pCi/L

Levels in both tests were approximately 25 percent lower than they were in February. The room that measured highest in February decreased from 52.5 to 13.4 pCi/L in June and to 4.4 pCi/L in July. The next highest room, which was 44.8 pCi/L in February, increased to 93.4 pCi/L in June and to 108.9 pCi/L in July.

DETAILED DIAGNOSTIC TESTING

Inspection of Architectural Drawings and Building

Examination of the foundation and wall section plans disclosed that block walls on all four sides of all rooms and closets extended to footings under the slab with no indication of breaks in these sub-slab walls, reducing the potential for sub-slab communication between rooms. The wall section drawings showed the presence of 4 in. of aggregate of unspecified size under the slab.

Each room is heated by a fan coil unit mounted above the dropped ceiling. The heated air from the fan coil is ducted to the ceiling registers near the outside wall. Cold air return is through an unducted opening very close to the air intake of the fan coil. Consequently, it is unlikely that the fan coil causes much of a negative pressure in the plenum above the ceiling. The rooms are cooled in the warmer months by individual window-mounted air-conditioners in each room. The fresh air intakes for these have all been closed off. Five wind-driven turbine roof ventilators exhaust air from the building. These are located in the hallways in the plenum above the suspended ceiling. Most of the classrooms in the original structure also have small ventilator fans mounted in the hall wall and exhausting into the hall. It is not certain how these fans are operated, if at all. There are two large kitchen exhaust fans, an exhaust hood over the cooking unit, and an exhaust fan for the dishwasher.

The foundation drawings of the 1957 addition, containing four slab-on-grade rooms, indicated that not all the walls go through to footings; there was a possibility of good sub-slab communication between these four rooms. This was confirmed by communication testing reported later in this paper.

Measurement of Sub-slab Radon Levels

Sub-slab radon levels were measured through a 1/4-in. hole in the center of each room using a Pylon AB-5 continuous monitor. Sub-slab radon levels were between 300 and 1900 pCi/L as shown in Figure 9, much lower than those found at the Two Rivers School. There appears to be no correlation between the levels in the room and the sub-slab levels.

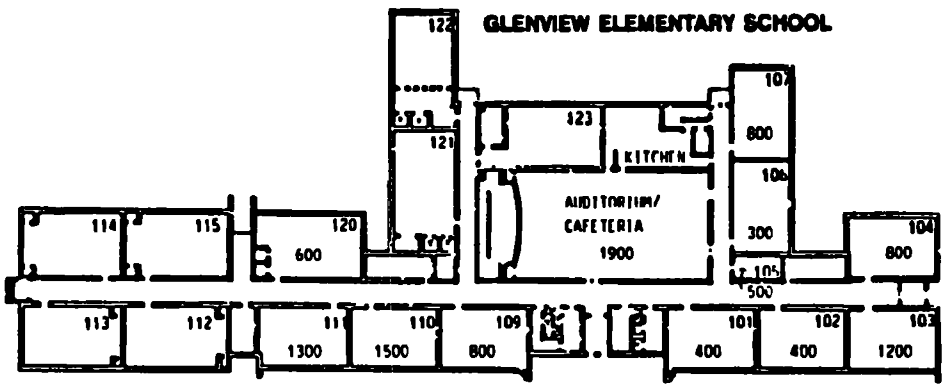

Figure 9. Sub-slab radon levels, pCi/L

Sub-slab Communication Testing

Sub-slab communication test measurements were carried out using the test method described previously for the Two Rivers School. The initial suction hole was placed just inside Room 110, near the door. It was possible to pull a negative pressure in Classrooms 109 and 111, and in the hall just outside of Classroom 110. However, no communication could be detected with Classroom 120, the room across the hall. Similar results were obtained at the other end of the building. From these tests, it was concluded that sub-slab communication could be extended about 30 ft in the original building and could pull through one sub-slab wall, but not two. Even within the same room, pressure-field extension was much poorer than found at Two Rivers. Consequently, it was felt that the aggregate was not as open as it was at Two Rivers. This was confirmed when aggregate from the two slabs was removed during the installation of mitigation systems. At Two Rivers, the stone was very large, from 3/4 to 1 in. in diameter. At Glenview, it was much finer, averaging about 1/4 in. in diameter and contained some fines and dirt. Both were screened river gravel.

A suction point in Classroom 114 of the four-room addition indicated good sub-slab depressurization in Classrooms 112 to 115 as expected from the examination of the foundation drawing.

MITIGATION DESIGN AND INSTALLATION

In view of the relatively poor sub-slab communication, it was decided that a minimum of one suction point in every other room would be necessary on both sides of the hall. Three systems were laid out as shown in Figure 10. Two multi-point systems had 6 in. trunk lines in the hall plenums with 4 in.

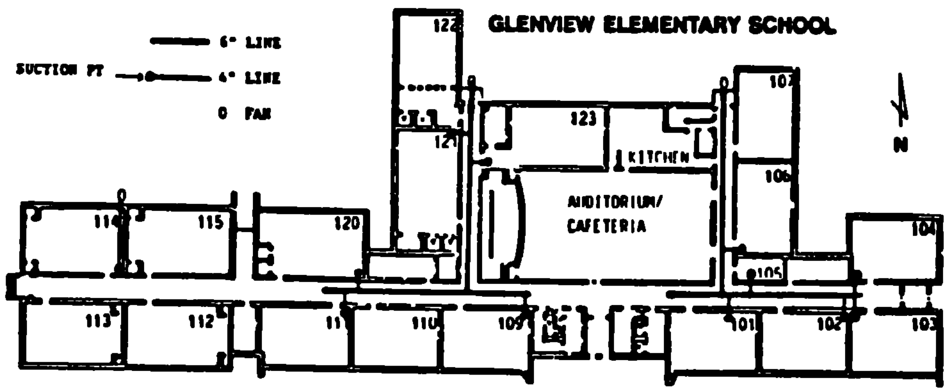

Figure 10. Mitigation system layout

drops to suction points in the rooms. Trunk lines were run over the dropped ceiling of the hall and 4-in. drops were placed as indicated in Figure 10. In the trunk lines, T's were installed and capped off to facilitate the addition of suction points to all of the remaining rooms if necessary. One mitigation system had five suction points and the other had six, as shown in Figure 10. Each used a turbo fan rated at 410 cfm at 1 in. W.C.

Communication testing in the 1957 four-room slab-on-grade addition at the south end of the building indicated that one suction point would likely mitigate all four rooms. A 4-in. suction point was put in the corner of Room 114 behind the door and the pipe was run overhead through the outside wall at the rear of the building. Suction was achieved using a turbo fan rated at 210 cfm at 1 in. W.C.

Pressure activated visual alarms, as described for Two Rivers, were installed for each mitigation system. These were put on the mitigation trunk lines and are checked daily by the custodial force.

MITIGATION RESULTS

Mitigation installation was completed the first week of August, and all systems were put in continuous operation. The following weekend all rooms were tested with charcoal canisters under closed conditions with all air handlers off. Average radon levels in all rooms were 1.7 pCi/L, ranging from 1.2 to 2.9 pCi/L. Post-mitigation radon levels in each room are shown in Figure 11.

Glenview Elementary School was also retested in December, and the average levels during cold weather will be reported at the Symposium.

As stated above, the 1964 four-classroom addition is built over a crawl-space and will be mitigated in early 1990. Suction under polyethylene sheeting in the crawlspace will be compared to pressurization and depressurization of the crawlspace. This will be EPA's first detailed study of mitigating a school building over a crawlspace. This addition is ideal for these studies since it is small with adequate headroom and contains no asbestos.

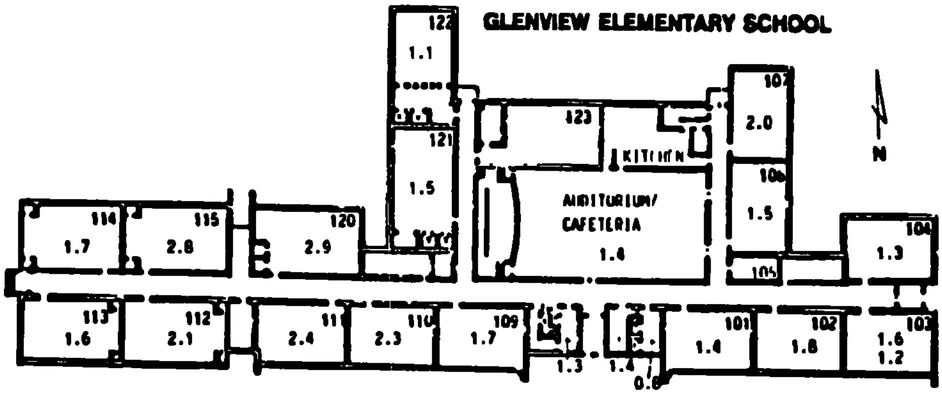

Figure 11. Post-mitigation radon levels, August 1989, pCi/L

CONCLUSIONS

The following conclusions are drawn from these studies.

1. The two schools studied had widely different sub-slab communication resulting from different sub-slab construction details and from differences in aggregate. The poorer sub-slab communication in Glenview was overcome by increasing the number of suction points. The number used was based on the communication determined using vacuum cleaner communication testing.

2. Two Rivers Middle School was built using a thickened slab under interior load-bearing walls but contained no interior sub-slab block walls on separate footings. This resulted in a continuous aggregate layer under each classroom wing. As a result, one suction point was capable of depressurizing the sub-slab area of an entire classroom wing (15 rooms) of over 15,000 sq ft. Negative sub-slab pressure of 0.004 in. W.C. was measured as far as 120 ft from the suction point. Average radon levels in the mitigated portion of the building were reduced from 39.5 to 0.78 pCi/L.

3. All interior walls in Glenview Elementary School extended through the slab to footings. This resulted in a compartmentalized sub-slab area equivalent to the room configuration of the school. In addition, the aggregate had a smaller average particle size and contained more fines and dirt. As a result of these two factors, sub-slab communication was found to be much poorer than at Two Rivers. Pressure field extension was limited to a maximum of 30 ft. Mitigation was accomplished with three suction systems containing 12 sub-slab suction points or an average of about 1 suction point for every 2 rooms. Average radon levels were reduced from 29.7 to 1.7 pCi/L.

REFERENCES

1. United States Environmental Protection Agency, Office of Radon Programs, "Radon Measurements in Schools - An Interim Report." Washington, D.C. 20460, EPA-520/1-89-010, NTIS PB89-189-419AS, March 1989.

CONVERSION FACTORS

1 picocurie/liter (pCi/L) = 37 becquerels/cubic meter

1 inch (in.) = 2.4 centimeters

1 inch (in.) water column (W.C.) = 249 pascals

1 foot (ft) = 300 centimeters

1 square foot (sq ft) = 929 square centimeters

1 cubic foot/minute (cfm) = 472 cubic centimeters/second

THE EFFECTS OF HVAC SYSTEM DESIGN AND OPERATION ON RADON ENTRY INTO SCHOOL BUILDINGS

by: William A. Turner
Harriman Associates
Auburn, ME 04210

Kelly W. Leovic and Alfred B. Craig
U.S. EPA, AEERL
Research Triangle Park, NC 27711

ABSTRACT

Heating, ventilating, and air conditioning (HVAC) systems in schools vary considerably and tend to have a greater impact on pressure differentials -- and consequently radon levels -- than do heating and air-conditioning systems in houses. If the HVAC system induces a negative pressure relative to the subslab area, radon can be pulled into the building. If the HVAC system pressurizes the building, it can prevent radon entry as long as the fan is running. However, school HVAC systems are normally set back or turned off on evenings and weekends and, even if the HVAC system pressurizes the school during operation, indoor radon levels may build up during setback periods.

Many of the historical methods utilized to deliver ventilation air (outdoor air) over the past 40 years are summarized. In addition, for each type of system presented, the possible impact the ventilation system might be expected to have (positive or negative) on the pressure of the building envelope (and subsequent radon levels in the building) is discussed.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

THE EFFECTS OF VENTILATION ON BUILDING PRESSURE DIFFERENTIALS

The primary mode of radon entry into a school is normally from soil gas that is drawn in by pressure differentials between the soil surrounding the substructure and the building interior. If the building interior is at a lower pressure than the soil surrounding the substructure, radon can be pulled in through cracks and openings that are in contact with the soil. The amount of radon in a given classroom will depend on the level of radon in the underlying material, the ease with which the radon moves as a component of the soil gas through the soil, the magnitude and direction of the pressure differentials, the number and size of the radon entry routes, and dilution and mixing of the room air.

Pressure differentials that contribute to radon entry can result from operation of a heating, ventilating, and air conditioning (HVAC) system under conditions that cause negative pressures (in the building relative to the subslab area), indoor/outdoor temperature differences (including the "stack effect"), use of appliances or other mechanical devices that depressurize the building, and wind.

HVAC systems in schools and other large buildings vary considerably and tend to have a greater impact on radon levels than do heating and air-conditioning systems in houses.[1] The design, installation, and operation of the ventilation equipment will cause the building envelope to be at a positive, negative, or neutral pressure with respect to the outdoors, depending on the system design, how it was initially installed and balanced, and how it has been historically maintained and operated. Sometimes schools and similar buildings were not designed with adequate ventilation, and in other instances, ventilation systems are not operated properly due to factors such as increased energy costs or uncomfortable conditions caused by a design or maintenance problem. Such circumstances may enhance radon entry into the building.

If the HVAC system induces a negative pressure in the building relative to the subslab area, radon can be pulled into the building through floor and wall cracks or other openings in contact with the soil. (Even if the HVAC system does not contribute to pressure differentials in the building, the natural stack effect in a leaky building can cause the building to be under a negative pressure so that radon-containing soil gas is pulled into the school.)

If the HVAC system pressurizes the building -- which is a common design in many systems -- it can prevent radon entry as long as the fan is running. However, school HVAC systems are normally set back or turned off during evenings and weekends, and even if the HVAC system pressurizes the school during operation, indoor radon levels may build up during setback periods. Once the HVAC system is turned back on, it may take several hours for radon levels to be reduced. Consequently, how the ventilation air (outdoor air) is supplied to the building (i.e., whether the ventilation system is pressurizing or depressurizing the building) can be expected to drastically affect the radon levels in a building when the ventilation system is operating. Even when a building is operated overall slightly positive with respect to the outdoors, localized negative pressures may exist. If openings to the earth are present where these localized negative pressures exist, soil gases will be drawn in.

BUILDING VENTILATION HISTORY

Buildings designed for human occupancy (in particular, public buildings such as schools) have historically been required to be designed to provide ventilation air (outdoor air) to the occupants. This outdoor air has been provided historically by non-powered design features such as operable windows and gravity ventilators (which allow air movement created by wind and temperature differences), more recently by powered ventilating equipment, or some combination of both. In many areas of the country where air conditioning has not been utilized, it has been popular to provide a base level of ventilation by mechanical systems and to allow supplemental ventilation to occur through the use of large operable windows as weather conditions allow.

Historically, the introduction of fresh outdoor air into buildings has been relied upon to dilute the contaminants which are generated by the occupants within the building and to provide free (economizer) cooling when weather conditions permit. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standards documents have provided, and continue to provide, engineering professionals with guidelines to the suggested minimum quantities of outdoor air which should be provided to the occupants.[2] Building Codes (laws) also govern the amounts of outdoor air to be provided; often these codes refer to the ASHRAE guidelines. The most up-to-date ASHRAE ventilation standard, ASHRAE 62-1989, prescribes that 15 cfm (1 cfm = 0.47 L/s) of outdoor air be supplied to a classroom for acceptable indoor air quality.[2]

MULTIPLE ZONING OF VENTILATION AIR

In large buildings with multiple exhaust fans, supply air systems, and system balancing dampers, some section of the building will frequently be designed to be operated negative and other sections positive with respect to adjoining areas in order to minimize the spread of an internally generated irritant or odor. Thus, with regard to radon entry from the soil, the expected and measured overall pressure balance of the total building envelope and the expected and measured pressure relationship in individual areas of the building must be considered.

Typical areas which might be expected to be designed and operated negative with respect to adjoining areas include any area where identifiable sources of pollutants may be generated; e.g., toilets, locker rooms, shops, print rooms, art areas, laboratories, kitchens, gymnasiums, hallways, lounges, and janitor's closets. Areas which might be expected to be designed and operated positive with respect to adjoining areas include classrooms, computer rooms, and libraries Thus, it is important to know the expected and measured pressure relationship of individual zones within the envelope as well as the overall building envelope.

In addition to affecting the pressure relationships, the ventilation air (outdoor air) will also be available to dilute radon gas once it has entered the building. The dilution effect of outdoor air (ventilation air) is primarily a control strategy for other pollutants (bioeffluents) generated primarily by the occupants; however, dilution alone is seldom adequate to reduce elevated levels of radon without the proper pressure relationship.

The following section presents an overview of the various types of ventilation systems which might be found in school buildings and the potential (positive or negative) impact each type of system would be expected to have with regard to radon entry (i.e., the expected overall impact on the pressure relationship between the building envelope and the soil).

TYPES OF HVAC SYSTEMS

Many of the HVAC systems discussed below have the option of being designed to supply a fixed or variable amount of outdoor air. In addition, the total supply air moved by an air handling system (i.e., the combination of outdoor and recirculated air) may be fixed (constant volume) or modulated (variable volume). A variable air volume (VAV) system is typically designed to deliver more total supply air as additional cooling is called for. With a VAV system, the amount of outdoor air delivered may also be designed to be fixed or modulated.

EXHAUST-ONLY SYSTEMS

One of the basic systems is an exhaust-only system; i.e., the system consists of exhaust fans (often installed in hallways, bathrooms, and locker areas). Building leakage or the opening of windows is typically the source of outdoor makeup air. Even more basic systems include gravity ventilators (non-powered exhaust shafts dependent upon the building stack effect, and operable windows). Such systems that do not supply tempered makeup air typically lead to stuffy conditions in the winter time, when occupants are hesitant to open windows due to cold drafts.

Exhaust-only systems would be expected to cause the overall pressure within the building to be negative with respect to the outdoors, thus increasing the flow of soil gas into the building envelope. Depending on the degree of building depressurization, and the location and size of the envelope leakage, the radon levels in a building should increase during operation of an exhaust-only system.

RADIANT HEAT SYSTEMS

Radiant heat systems in schools tend to be of three types: hot water or steam radiators, baseboard heaters, or warm water radiant heat within the slab. Schools heated with radiant systems should have a ventilation system to achieve the fresh air requirements recommended by ASHRAE; however, many of these schools provide no ventilation other than natural infiltration. In other schools, there are exhaust ventilators on the roof. These can be passive, allowing some ventilation through the stack effect, or they can be powered. Powered roof ventilators (PRVs) can cause significant building depressurization, particularly if a fresh air supply is not provided. This can cause considerable radon entry into the building while such exhaust systems are operating.

UNIT VENTILATORS

The use of unit ventilators in schools has been and continues to be very popular. They are available in a number of different arrangements: horizontal, vertical, draw-through, and blow-through; and are made by a wide variety of manufacturers.

In a typical unit ventilator system, by design, there is a connection to the outdoors, providing makeup air for ventilation and free cooling. In a typical unit ventilator configuration, the outdoor air mixes with return air from the classroom in the plenum portion of the unit ventilator and is supplied to the space typically through the top.

The advantages of this type of system are often economics and architectural flexibility: generally no ductwork is required. Some of the disadvantages of this system are the noise levels generated by the unit ventilators and the numerous wall penetrations that at some points downgrade the architects' elevation aesthetics. Also, a serious concern is the draftiness of these types of units especially in northern climates. Drafts are of concern because, with 20 to 25 students in a typical modern classroom, coupled with well insulated walls and ceilings and 1.5-2 W/ft^2 (335-446 kW/m^2) of lighting, the internal heat gains often outweigh any envelope losses of the classroom. This can require fresh air to be introduced for cooling during major portions of the school year.

Unit ventilator systems would be expected to cause the overall pressure within the building to be positive with respect to the outdoors, thus reducing the flow of soil gas into the building envelope when the unit is operating and outdoor air is being drawn into the unit. Whether or not the space served by the unit ventilator is actually pressurized with respect to the soil will depend on the degree of overall building pressurization or depressurization. If other areas of the building have exhaust-only systems which exhaust more air than is made up by the unit ventilators, then soil gases will still be drawn into the building in areas where the net pressure is negative. The radon levels in a building should decrease when a unit ventilator system is operating properly, if adequate overall makeup air is provided.

TERMINAL AIR BLENDERS

Terminal air blenders have also been used. Initially, this type of system was a good alternative to unit ventilators. There are a number of ways terminal air blenders have been used. They were installed to help combat the energy crunch, while still delivering outdoor air for cooling and ventilation. With these systems in the classroom, even in northern climates, over 90 percent of the time approximately 5 cfm (0.00236 ft^3/s) of outdoor air per student would typically be introduced. Because of the high internal heat gains in the classroom, the intent was to thermostatically control the outdoor air quantity, bringing in the appropriate amount of outdoor air required to satisfy the internally generated heat load. These systems are generally connected to an air duct system to distribute the ventilation air evenly, reducing drafts, and are less noisy than unit ventilators. A consistent outdoor air supply is not provided; however, typically, 90 percent of the time more than 5 cfm per student outdoor air is provided with a thermostatically controlled terminal air blender ventilation system that is functioning properly.

Terminal air blender systems would be expected to cause the overall pressure within the building to be positive with respect to the outdoors, thus reducing the flow of soil gas into the building envelope when the unit is operating and outdoor air is being drawn into the unit and distributed to the occupants. Whether or not the space served by the terminal air blender is actually pressurized with respect to the soil will depend on the degree of overall building pressurization or depressurization. That is, if other areas of the building have exhaust-only systems which exhaust more air than is made up by the terminal air blender, then soil gases will still be drawn into the building in areas where the resultant pressure is negative. The radon levels in a building should decrease when a terminal air blender system is operating properly, if adequate overall makeup air is provided.

UNITARY HEAT PUMPS OR FAN-COIL UNITS

Heat pump units have been utilized to a limited degree in schools. They appear similar to a fan-coil unit and may or may not have outdoor air ducted to the unit. Fan-coil units consist of a fan and heating and/or cooling coils and may or may not have outdoor air ducted to the unit. (They may just recirculate air.)

Unitary heat pumps or fan-coil units would be expected to cause no overall pressure change within the building even when outdoor air has been ducted to the unit unless additional dampers and controls have been added to convert it to function as a unit ventilator. If outdoor air has been provided and the unit converted to a unit ventilator, then the unit would be expected to cause a positive pressure inside the building with respect to the outdoors, thus reducing the flow of soil gas into the building envelope when the unit is operating and outdoor air is being drawn into the unit and distributed to the occupants. Whether or not the space served by the unit is actually pressurized with respect to the soil will depend on the degree of overall building pressurization or depressurization. That is, if other areas of the building have exhaust-only systems which exhaust more air than is made up by the heat pump or fan-coil units, then soil gases will still be drawn into the building in areas where the net pressure is negative. The radon levels in a building should decrease only when a fan-coil or heat pump unit has been equipped with outdoor air, and converted to a unit ventilator (if adequate overall makeup air is provided). If the units are not supplied with outdoor air then the only impact should be from the normal natural stack effect of a leaky building.

HEAT RECOVERY VENTILATORS (HRV)

In general, HRVs are either ducted systems with supply and return ducts servicing different parts of the building or room, or wall-mounted units, similar to wall-mounted air-conditioning units. In both types of units, fresh air is brought in through a heat recovery device, then distributed, or passed through a preheat coil and then out to the system's zones. The exhausts from these zones pass through a separate section of the heat recovery device, and then discharge far enough from the fresh air intake to minimize re-entrainment. One disadvantage of these types of systems is that condensation on the surface of the heat exchanger may frost up and block the heat exchanger when outdoor temperature drops below 20°F [°C=5/9(°F-32)]. To avoid that problem, bypass sections and defrost controls are often available with units as standard features. By temporarily bypassing the outdoor air and, thus, raising the exchange surface temperature to above the dewpoint, frost on the exchanger surface is avoided.

If balanced correctly, HRV systems would be expected to cause the overall pressure within the building to be neutral or very slightly positive with respect to the outdoors, thus reducing the flow of soil gas into the building envelope when the unit is operating and outdoor air is being drawn into the unit and distributed to the occupants. Whether or not the space served by the device is actually pressurized with respect to the soil will depend on the degree of overall building pressurization or depressurization. That is, if other areas of the building have exhaust-only systems which exhaust more air than is made up by the HRVs, then soil gases will be drawn into the building in areas where the resultant pressure is negative. The radon levels in a building should decrease when a HRV system is operating properly, if adequate overall makeup air is provided. One exception is exhaust-only heat recovery devices which would be expected to raise radon levels similar to exhaust-only ventilation systems discussed earlier.

CENTRAL STATION AIR HANDLERS

There are many types of central station systems, many with features similar to those discussed above. The common features of all central units include an air handling unit supply fan and/or return fan and associated tempering coils, dampers and controls, distribution ductwork, exhaust (or relief), mixing box, and outdoor air intake. In the past, constant volume systems, which consisted of central station air handling systems that generally had fixed minimum outdoor air dampers, were used in schools. Typically the outdoor air would be controlled by a two-position damper closed and opened to whatever percentages were predetermined, to be mixed with return air, passed through the supply fan, and introduced to the occupied space.

If designed correctly, central station air handler systems would be expected to cause the overall pressure within the building to be slightly positive with respect to the outdoors, thus reducing the flow of soil gas into the building envelope when the unit is operating and outdoor air is being drawn into the unit and distributed to the occupants. However, in a building with multiple zones, some spaces served by the central system may be adjusted to be positive with respect to the soil, and other areas may be negative. Many areas of the building may have exhaust fans which exhaust more air than is made up by the central system by design. Thus, even if the overall pressure relationship for the building is positive, soil gases will still be drawn into the building in areas where the local resultant pressure is negative. The radon levels in a building should decrease when a central station system is balanced to be slightly positive and operated properly, if adequate overall makeup air is provided. The following sections present a few of these central station air handler systems in detail.

Conventional Constant Volume (CV)

Central stations, predominantly with constant volume air systems with fixed minimum outdoor air entry and reheat coils, have been utilized for many years in a limited number of schools. They are somewhat energy efficient and are easily balanced.

Variable Air Volume (VAV)

With the energy crunch, several manufacturers of air handlers introduced VAV control. The most immediate savings are fan energy and elimination of reheat coils (if individual room VAV diffusers are used); however, outdoor air control is difficult. In many VAV systems, there is no way to control outdoor air to bring the room above bare minimum fresh-air quantities. Central station VAV systems, with static pressure devices in the outdoor air stream and addition of reheat coils, were an answer to outdoor air control. With static pressure control of the outdoor air stream, it is possible to maintain an overall positive pressure within the building under various operating conditions.

VAV with Economizer

As just noted, the VAV helps cut down on fan energy when not dealing with peak cooling loads. If only minimum air movement is needed, the reduced air flow will save energy dollars. Whenever outdoor air is critical (e.g., if all areas must be kept under positive pressure to keep radon out), shutting off the VAV distribution boxes in individual spaces is a concern. One disadvantage of most VAV systems is that they have no sensing in the outdoor air stream that would guarantee the correct amount of outdoor air during part-load operation. One way to avoid this situation is to use an outdoor air flow sensor. With this type of metering system, a drop in velocity in the outdoor air stream will control the air dampers, bringing in more air from the outdoors. (This would be typically called an outdoor air reset.)

VAV with Outdoor Air Control and Heat Recovery

This type of package combines efficient operation with temperature control. Most importantly, the ability to deliver outdoor air capacity is greatly increased, and the facility is not penalized in terms of energy costs, nearly as much as without the heat recovery feature.

Central station heat exchangers are currently being considered in many schools being designed for northern climates. In this type of design, a central air handling system incorporates a heat exchanger. Some reheat may be required in such system.

HVAC SYSTEMS AND RADON MITIGATION

A potential mitigation approach for schools is adjustment of the air-handling system to maintain a positive pressure in the school relative to the subslab area, discouraging the inflow of radon. This technique, referred to as pressurization, has been shown to be an effective temporary means of reducing radon levels in some schools, depending on the design of the HVAC system. If pressurization through the HVAC system is under consideration as a long-term radon mitigation solution in a given school, proper operation and maintenance of the system are critical. Responses to changes in environmental conditions and any additional maintenance costs and energy penalties associated with the changes in operation of the HVAC system must also be carefully considered[3].

Important factors that need to be considered when utilizing the HVAC system for radon control include: (1) How much outdoor air was the system originally designed to supply under what design conditions? (2) How leaky is the shell of the building and can pressurization be utilized? and (3) Is the system currently operating as designed, or has it been modified purposely or through neglect? Once the limitations of the HVAC system and building shell are determined, decisions can be made on the best or most reasonable course of action which can be taken. Some approaches to radon control through the HVAC system that have been used temporarily and permanently are generalized below.

EXHAUST-ONLY VENTILATION AND RADIATION HEAT SYSTEMS

For schools with either exhaust-only ventilation systems or radiant heat, positive pressurization will probably require major modifications if the HVAC system is considered as part of the mitigation strategy.

UNIT VENTILATORS AND EXHAUST-ONLY SYSTEMS

Radon mitigation strategies in schools with unit ventilators might include (1) opening the fresh-air vents (if they have been closed) to improve ventilation and running the unit ventilator fans continuously (or prior to occupancy) to pressurize the room; (2) replacing an exhaust-only ventilation system with a system that operates under a slight positive pressure; or (3) installation of a subslab depressurization (SSD) system that could overpower all negative pressures in the building. If the current HVAC system is providing adequate ventilation to the building or if options (1) and (2) are not feasible, option (3), installation of a SSD system, would be the most practical near-term strategy if there is good subslab communication.

CENTRAL AIR HANDLING SYSTEMS

Although most central HVAC systems are commonly designed to operate at positive or neutral pressures, pressure measurements in schools have indicated that such systems can cause significant negative pressures in the building. HVAC system modifications (such as reducing the amount of fresh-air intake), lack of maintenance (such as dirty filters), unrepaired damage, or other factors can result in substantial negative pressures in some rooms, thus increasing soil gas entry. In addition, operation of localized exhaust fans can cause significant negative pressures in areas of operation.

If positive pressures are not being achieved in a central single-fan system, the system should be checked to ensure that the fresh-air intake meets design specifications and that the intake has not been closed or restricted. Increasing the fresh-air intake if it has been restricted, and operating the fan for a sufficient time prior to occupancy and continuously while the school is occupied will help to reduce radon levels that have built up during setback periods and will maintain low radon levels during occupied hours by preventing radon entry by maintaining a positive pressure and by providing fresh (dilution) air.

In a central dual-fan system, the return-air fan can be set back or restricted so that all of the rooms are under a positive pressure. The fresh-air intake to the supply fan can also be increased up to the design limit of the system, if it has been reduced. If radon control through HVAC system operation is under consideration as a permanent mitigation strategy, proper system operation and maintenance are critical.

Many schools with highly elevated radon levels have installed SSD systems in order to control radon levels even when the HVAC system is not operating.

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RADON MITIGATION EXPERIENCE IN DIFFICULT-TO-MITIGATE SCHOOLS

by:

Kelly W. Leovic and A. B. Craig
Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

and

David W. Saum
Infiltec
Falls Church, VA 22041

ABSTRACT

Initial radon mitigation experience in schools has shown subslab depressurization (SSD) to be generally effective in reducing elevated levels of radon in schools that have a continuous layer of clean, coarse aggregate underneath the slab. However, mitigation experience is limited in schools without subslab aggregate and in schools with characteristics such as return-air ductwork underneath the slab or unducted return-air plenums in the drop ceiling that are open to the subslab area (via open tops of block walls). Mitigation of schools with utility tunnels and of schools constructed over crawl spaces is also limited.

Three Maryland schools exhibiting some of the above characteristics are being researched to help understand the mechanisms that control radon entry and mitigation in schools where standard SSD systems are not effective. This paper discusses specific characteristics of potentially difficult-to-mitigate schools and, where applicable, details examples from the three Maryland schools.

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INTRODUCTION

Subslab depressurization (SSD) has typically been a very effective radon mitigation approach in schools and in houses that are underlain with a continuous layer of clean, coarse aggregate. Recent experience has shown that in schools with 4 in. (1 in. = 2.54 cm) of subslab aggregate -- approximately 0.75 to 1.5 in. in diameter with no fine material -- one SSD point can sometimes mitigate an entire school wing of 10 classrooms or about 15,000 sq (1 ft = 0.09 sq m). Costs of mitigation under these conditions of excellent subslab communication may be as little as $3,500 for materials, in addition to approximately 120 person hours for diagnostics and 160 person hours for installation, depending on the number of suction points needed (1,2).

However, mitigation experience has also identified certain types of schools that are difficult -- and consequently expensive -- to mitigate with current technology. Characteristics of potentially difficult-to-mitigate schools include (but are not limited to): 1) schools with poor subslab communication, 2) schools with return-air ductwork underneath the slab, 3) schools with unducted return-air plenums in the drop ceiling (that are open to the subslab area via open tops of block walls), 4) schools with utility tunnels, and 5) schools constructed over crawl spaces. Mitigation of such schools could be very expensive, especially if the mitigation involves a complete retrofit of the heating, ventilating, and air-conditioning (HVAC) system.

These characteristics that may cause a school to be difficult-to-mitigate are discussed below, and examples from three difficult-to-mitigate schools, currently being researched by the U.S. EPA in Maryland, are discussed. School A is located in Prince Georges County, and Schools B and C are located in Washington County. Note that since School A exhibits more than one of the difficult-to-mitigate characteristics, it is discussed in two sections.

SCHOOLS WITH POOR SUBSLAB COMMUNICATION

Although poor subslab communication is a relative term, for the purposes of this paper it is roughly defined as the inability to measure a negative pressure (in the subslab relative to the building interior) of at least 0.001 in. WC (1 in. WC = 250 Pa) in a 0.25 in. test hole located approximately 10 ft from a 1.5 in. suction point when maximum suction is applied to the suction point with a variable speed industrial vacuum cleaner. As a comparison, in the school with excellent communication mentioned in the Introduction, subslab depressurization was measurable in a test hole 100 ft from the suction point.

Schools with poor subslab communication typically have slabs that are poured directly onto tightly packed soil such as sand or clay, with little or no subslab aggregate. The tightly packed fine material greatly restricts the subslab airflow and limits the practicality of installing a SSD system. Even if a school does show relatively good subslab communication within a given classroom, communication between classrooms may be limited by below-grade walls and footings. As a result, it may be necessary to install a suction point in every or every other classroom in order to control radon entry. An example of such a school is discussed in Reference 1.

If poor communication reduces the subslab area depressurized by a suction point, it may be possible to achieve effective mitigation by installing more suction points. Typically these suction points are installed around the edge of each room in order to depressurize the major cracks between the floor and the walls. A related technique involves the installation of an enclosed channel between the floor and the wall (channel drain) which can be depressurized. Both of these approaches have the disadvantage that they represent a significant investment in time and labor, and they be unsightly or take up excessive space. The area depressurized by each SSD suction point may also be increased by measures that increase the suction, reduce air leakage, and increase communication. Sealing of floor cracks, excavation of subslab cavities under suction points, and increased fan suction are often used to increase pressure field extension. Previous school research has shown that pressure field extension is often doubled by these measures (2). Research on houses in Florida has shown the effectiveness of very high pressure fans (greater than 4 in. WC) in cases of very poor communication due to sandy soils.

SCHOOL A

As shown in Figure 1, initial charcoal canister measurements made in this school in March 1988 averaged 4.2 pCi/L (1 pCi/L = 37 Bq/m^3), with the highest room measuring 12.3 pCi/L. A second set of charcoal measurements made in November 1989 averaged 5.0 pCi/L, with two rooms measuring 10.0 pCi/L.

The school is slab-on-grade construction. Inspection showed that the material under the slab is a mixture of sand and clay. A utility tunnel runs parallel to the corridor in part of the building, as indicated on the floor plan in Figure 1. The original HVAC system consists of a perimeter hot water system, with air movement by convection. There are also overhead exhaust fans in the classrooms; however, school personnel stated that these exhausts are rarely used.

As a result of other indoor air quality problems, overhead air-conditioning units in the classrooms -- that were designed with the capability to provide outdoor air -- have been modified to provide heating so that they can be used year round. Measurements are in progress to determine the ability of these units to pressurize the building to prevent radon entry; however, operation of each unit is controlled in the classroom by the teacher and, consequently, continuous operation cannot currently be ensured.

Room 13, the classroom with the highest initial radon level (12.3 pCi/L in Figure 1) was selected to evaluate the applicability of subslab depressurization in this school with poor subslab communication. (Previous efforts by school personnel to seal the floor/wall cracks did not reduce radon levels sufficiently.) As seen in Figure 2, three 3 in. diameter subslab depressurization points were installed in the corners of Room 13 and manifolded to a 4 in. overhead line, exiting through the window at point A. To improve communication, pits approximately 2 ft in diameter and 1 ft in depth were excavated under the slab at the three suction points. A fan rated at 270 cfm (1 cfm = 0.47 L/s) at 0 in. WC was installed.

In schools with good subslab communication, 4 to 6 in. diameter vertical drops are typically installed because of the high air flow; however, because of the low flow rates anticipated in the mixture of subslab sand and clay, 3 in. diameter vertical drops were used in this school.

Communication measurements made in Room 13 with suction being applied to all three points are summarized in Table 1. With all three suction points operating, a slight depressurization was measurable in the far corner of the room.

TABLE 1. Subslab Communication Measurements, December 1989
(School A - Room 13)

Suction Point	Suction in Pipe, in. WC	Distance from Suction Point, in.	Pressure in Test Hole, in.
A	- 1.48	1	- 0.860
A	- 1.48	60	- 0.171
B	- 1.47	1	- 0.045
B	- 1.47	60	- 0.011
B	- 1.47	120 (toward center)	- 0.086
C	- 1.45	1	- 1.300
C	- 1.45	60	- 0.331
C	- 1.45	180 (near door)	- 0.001

Radon levels measured in this school with the SSD system in operation are shown in Figure 2. It should be noted that a utility tunnel depressurization system -- that will be discussed later -- was also in operation in another part of the building during these measurements. The radon levels in Room 13 and the adjacent room were reduced from premitigation radon levels of 7.1 and 7.4 pCi/L to 1.3 and 1.6 pCi/L, respectively. It is obvious from Figure 2 that radon levels are lower throughout the building -- not only in the areas where mitigation was being applied. However, radon reductions in parts of the building where no mitigation was being applied were about 45 percent (attributed to natural variations resulting from weather, for example), and reductions in these two classrooms were about 80 percent, indicating the positive effects of the SSD system.

FUTURE RESEARCH PLANS

Further work in School A will assess the possibility of installing SSD systems in the other rooms with elevated radon levels (other than the rooms being treated by the tunnel depressurization system). In spite of the poor subslab communication, it is reassuring to learn that the radon levels could be reduced in this classroom by installing enough suction points. However, questions that still remain include: 1) Would this approach work in a similar school with much higher radon levels? 2) What are the mechanisms controlling radon reduction in the adjacent classroom? and 3) If every room in a school with poor subslab communication has elevated levels of radon, would one suction point (or more) in each classroom be a practical mitigation approach or should alternatives be sought?

SCHOOLS WITH RETURN-AIR DUCTWORK UNDERNEATH THE SLAB

Schools with return-air ductwork under the slab are a concern if elevated levels of radon are present in the surrounding soil. Since the ducts are under a negative pressure when the return-air fan is in operation, radon can be pulled into the ducts through unsealed openings in the ductwork. Any radon that enters the ducts from the soil under the slab can then be distributed throughout the school by the HVAC system. In fact, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has recommended that, where soils contain high concentrations of radon, ventilation practices that place crawl spaces, basements, or underground ductwork below atmospheric pressure be avoided since such practices tend to increase indoor radon concentration (3). Unsealed supply-air ductwork located underneath the slab may also be of concern since radon can enter the ductwork if it is subjected to negative pressures when the HVAC system is off and the ductwork is below the neutral pressure plane.

SCHOOL B

In April 1988, initial charcoal canister measurements in this school showed that radon levels in 28 of 39 rooms exceeded 4 pCi/L. Follow-up canister measurements made in 24 of these rooms in December 1988 showed all 24 rooms above 4 pCi/L. All of these measurements were made with the HVAC system off and the building unoccupied.

The original school was constructed in 1954, and four four-room additions were added in 1964. The entire school is slab-on-grade construction, and the foundation plans and specifications call for 4 in. of aggregate under the slab. For the purposes of this paper, only the four additions (which are referred to as pods) are discussed. Each pod has four classrooms and a central media area.

There is a two-fan HVAC system with the return-air ducts located under the slab in each pod. Room air enters the return-air ductwork from registers located on the exterior wall of each classroom and is pulled through the subslab ductwork to a central cold-air return located in the media area. Supply air (including recirculated air from the subslab ducts) is distributed to each classroom through overhead ducts mounted near the interior wall. Radon grab samples collected in the supply air when the system was operating were about 20 pCi/L, indicating that the return-air ducts under the slab were drawing in soil gas and recirculating it throughout the school. Subslab differential pressure measurements (relative to the building interior) made in one of the pods showed a pressure field that ranged from - 0.001 to - 0.1 in. WC with the HVAC system in operation. The greatest negative pressures were near the central cold-air return in the center of the pod. These measurements suggested that it may be possible to install a SSD system to exert a greater negative pressure under the slab than the return air fan.

To evaluate the ability of a SSD system to overcome the negative pressures generated by the return-air system in one of the pods, an exhaust fan rated at 500 cfm (at 0 in. WC) was mounted on the roof, with a 6 in. manifold pipe connected to two 4 in. diameter vertical drops. These two suction points were placed near the return-air exhaust stack in order to maximize the suction in the area where the negative pressures of the return-air ducts were the strongest. The pod with the highest initial screening measurements was selected for installation of the SSD system; however, it should be noted that the most recent measurements in this school show radon levels in this pod to be slightly lower than in the other pods -- even when the mitigation system is not in operation.

Post-mitigation diagnostics indicated that this SSD system could not overcome the negative pressures generated by the return-air ducts and, as a result, radon-containing soil gas was still being pulled into the ductwork with both the HVAC and SSD systems in operation. Pressure measurements made through a test hole drilled in one of the return-air ducts showed a negative pressure of 0.80 in. WC in the duct; whereas, the initial differential pressure measurements made in the subslab aggregate measured only the negative pressure caused by the duct leakage, rather than the actual negative pressure in the duct.

Based on the above results, the school recently installed a new overhead return-air system in all four pods. The new return-air registers are located overhead near the interior walls of the classrooms, and the supply-air ductwork has been extended to supply air closer to the exterior walls. However, the abandoned return-air registers have not yet been sealed off and, consequently, there are still openings from the classrooms to the subslab.

Continuous radon monitors (CRMs) were placed in Classrooms 111 and 115 for a 10-day period as shown in Figure 3. Rooms 111 and 115 are in different pods but are at the same orientation within the pods. The two SSD points are located in Room 111's pod, with one point adjacent to Room 111. As seen in Figure 3, radon levels in Room 115 are consistently higher than those in Room 111, even with the SSD system off. These results are consistent with those from electret ion chamber (EIC) measurements in the other three classrooms in each pod. As shown in Figure 3, the SSD system was on in Room 111's pod from 0 to 120 hours and off from 120 to 240 hours. The averages indicate that the SSD system clearly has an effect on the radon levels, although the effect is much less dramatic than one might expect since the return-air registers have not yet been sealed.

The next plan for this school is to seal the return-air registers in all 16 classrooms. Radon measurements will be made with the registers sealed and the new HVAC system in operation. If necessary, SSD systems will then be installed in the other three pods.

An effort will also be made to tap into the sealed-off return-air system with the SSD system in Room 111's pod to compare its effectiveness in reducing radon levels with that of the current system.

FUTURE RESEARCH PLANS

School B showed that it was not reasonably possible to overcome the negative pressures of leaky return-air ductwork with a typical SSD system, even if the slab is constructed on aggregate. These results will be confirmed with research in additional schools; however, under such circumstances, the current recommendation is to abandon (and seal off) the subslab ductwork and replace the system with an overhead return-air system. Although this may be an expensive retrofit (about $40,000 for the 16 classrooms in School B), the guidance is directly applicable in the design of new buildings or in the remodeling of existing ones.

SCHOOLS WITH UNDUCTED RETURN-AIR PLENUMS IN THE DROP CEILING (THAT ARE OPEN TO THE SUBSLAB AREA VIA OPEN TOPS OF BLOCK WALLS)

Schools with unducted return-air plenums in the drop ceiling may be of concern if elevated levels of radon are present in the surrounding soil and there are openings between the soil and the plenums through the unsealed tops of block walls. The potential problem for radon entry exists if the load-bearing hollow block walls penetrate the slab as shown in Figure 4. The radon-containing soil gas can enter the block walls and be pulled into the unducted plenum which is under negative pressure when the fan is in operation. The soil gas that enters from the block walls could then be mixed with the recirculated room air and redistributed to the building, presenting a potentially difficult mitigation problem.

This specific issue is not currently being addressed in the field but will be included in future studies.

SCHOOLS WITH UTILITY TUNNELS

In some slab-on-grade schools, utility lines are located in a subslab utility tunnel that typically runs parallel to the corridor with sections sometimes branching off to individual rooms. Sizes of utility tunnels may vary from about 5 ft wide and 5 ft deep (to allow maintenance workers to enter them) to 1 ft wide and 0.5 ft deep. Utility tunnels may or may not have poured concrete floors. Even tunnels with poured concrete floors may have many openings to the soil beneath the slab-on-grade, facilitating radon entry. Risers to unit ventilators or fan-coil units frequently pass through unsealed penetrations in the floor so that soil gas in the tunnel has an easy entry route to the classrooms.

Although utility tunnels can be a major radon entry route if the surrounding soil contains elevated levels of radon, depressurization of the utility tunnel has been considered as a potential mitigation approach. If utility tunnel depressurization is attempted, any asbestos in the tunnel should be removed or encapsulated according to the Asbestos Hazard Emergency Response Act (AHERA) before attempting any radon reduction activities (4).

SCHOOL A

A large utility tunnel (about 5 ft wide and 5 ft deep) runs under or near eight of the classrooms in this school as shown in Figures 1 and 2. Radon levels in these eight classrooms averaged 4.4 and 4.3 pCi/L without depressurization being applied to the tunnel. (It should be noted that -- as with the other classroom in school A discussed earlier -- sealing of the floor/wall cracks was attempted in two of these classrooms with negligible results.) Radon levels in the utility tunnel typically range from about 10 to 30 pCi/L.

An exhaust fan rated at 270 cfm (at 0 in. WC) was installed in the tunnel at the end of the corridor. A 4 in. diameter pipe penetrates the tunnel from the outdoors, and the fan is mounted on a vertical riser at roof level. Differential pressure measurements were made with the depressurization fan in operation at the two tunnel access doors; one is located about 3 ft from the suction pipe penetration, and the other is located near the tunnel T by the two farthest classrooms. These measurements showed depressurization of the tunnel of about 0.03 in. WC at both points in the tunnel. A subslab pressure measurement was also made in a classroom test hole about 10 ft from the tunnel, and depressurization from the tunnel was negligible. (Remember from above that this school is constructed on a mixture of sand and clay and, consequently, has poor subslab communication.)

Charcoal canister measurements shown in Figure 2 indicate a reduction in radon levels in the eight classroom area with the tunnel depressurization fan in operation. The classroom levels averaged 1.8 pCi/L with the fan in operation compared to 4.4 and 4.3 pCi/L (Figure 1), a reduction of about 60 percent. (It should again be noted that the unmitigated areas averaged about 45 percent reduction in these measurements.)

Figure 5 shows continuous radon levels for 22 days in one of the classrooms with the tunnel depressurization fan cycled on and off. To include measurements during both occupied and unoccupied periods, the fan was on from Wednesday noon to Saturday noon and off from Saturday noon to Wednesday noon. Radon levels in the classroom averaged 1.2 pCi/L for the 8 days that the fan on and 5.1 pCi/L for the 14 days that the fan was off. The overall average for the 22 days was 3.6 pCi/L.

Recent continuous measurements collected in the tunnel showed that radon levels are similar when the fan is on and when the fan is off. This implies that the radon levels in the classrooms are being reduced because of the reversed pressure differentials between the tunnel and the rooms, rather than by dilution of the radon in the utility tunnel. This will be investigated further by collecting simultaneous radon measurements in the classrooms and tunnel.

FUTURE RESEARCH PLANS

Research on this school will continue at least through the winter months. In addition, utility depressurization will also be studied in other schools to determine its overall applicability.

In slab-on-grade schools with utility tunnels it may also be possible to reduce radon levels with a SSD system if subslab communication is good. However, two potential problems could be 1) too much SSD system air may be lost to the tunnel, and 2) the depressurization may not be able to reach the radon entry routes in the tunnel. This will be addressed in future research.

SCHOOLS CONSTRUCTED OVER CRAWL SPACES

Mitigation techniques applied in crawl space houses include: submembrane depressurization (SMD) in the crawl space, depressurization or pressurization of the crawl space, and natural ventilation of the crawl space. To date, research of crawl space houses has shown SMD to be the most successful technique of the four in reducing radon levels in the living area. However, since schools constructed over crawl spaces are typically much larger than houses constructed over crawl spaces, the practicality of installing a SMD system in a school crawl space may be very limited. In addition to the larger size of the crawl space, school crawl spaces often have structural support walls and piers throughout, which could quickly increase the cost of installing a SMD system. If the crawl space contains asbestos, any techniques that may increase air movement or require entering the crawl space should be avoided.

SCHOOL C

Crawl space depressurization is currently being tested in a school in Washington County, Maryland. Half of this single-story school is constructed over a crawl space with two slab-on-grade additions. The crawl space part of the building was built in 1936 and is wooden floor joist construction with a dirt floor. The HVAC system is a single-fan system with overhead ductwork. The crawl space is approximately 14,000 sq ft and has numerous support piers that would make installation of a SMD system very difficult.

A 500 cfm (at 0 in. WC) fan was installed to depressurize the crawl space. Figure 6 shows continuous radon levels in the school office and in the crawl space for a 16-day period cycling the crawl space depressurization fan on and off for 4-day periods. Operation of the depressurization fan tends to smooth out the peaks in the indoor radon levels, although spikes above 4 pCi/L do occur. Spikes exceeding 10 pCi/L occur during periods when the fan is not operating.

School vacation began on day 357 and continued until day 369. Radon levels in the office drop considerably on day 369 when school was back in session even though the crawl space depressurization fan was off and radon levels in the crawl space were still quite high. The lower radon levels on days 369 to 371 seem to indicate that normal HVAC operation creates a positive pressure, but that during setback periods (nights, weekends, and holidays), the building is under negative pressure.

FUTURE RESEARCH PLANS

Research of mitigation approaches in a relatively small crawl space (4,800 sq ft) will be initiated in early 1990. The school is located in Nashville, Tennessee, and is a four-classroom addition to one of the slab-on-grade schools discussed in Reference 1. SMD, crawl space depressurization, crawl space pressurization, and natural ventilation of the crawl space will be tested and compared for effectiveness. Available data will be presented at the Symposium.

CONCLUSIONS

Based on the authors' experience in these schools, the following conclusions can be made:

1. In schools with poor subslab communication, it may be possible to adequately depressurize the subslab area by adding enough suction points (three in one classroom in this case), excavating a pit under

the suction point, and using a high suction fan. However, the applicability and practicality of this approach in schools with highly elevated radon levels throughout the entire building, must still be addressed.

2. Since subslab return-air ductwork is under a negative pressure when the HVAC system is in operation, radon can be pulled into the ductwork through unsealed openings, and then distributed in the building with the recirculated supply air. In some cases, it may be necessary to relocate the subslab ductwork overhead since a SSD system may not be able to overcome the negative pressures generated in the subslab ductwork. If this is done, the return-air registers should be sealed since they are a radon entry route. Future research will determine the possibility of depressurizing the sealed subslab duct system for radon reduction.

3. Schools with unducted return-air plenums in the drop ceiling that are open to the subslab via uncapped block walls should be researched to determine their impact on radon entry.

4. In slab-on-grade schools with utility tunnels, it is sometimes possible to reduce radon levels in the classrooms by depressurizing the utility tunnels. This approach needs to be studied in additional schools.

5. Thus far, crawl space depressurization has shown some potential for reducing radon levels in schools constructed over crawl spaces. Future research will look at the applicability of SMD, crawl space depressurization, crawl space pressurization, and natural ventilation of the crawl space in more detail to determine their performances in large crawl spaces typical of schools.

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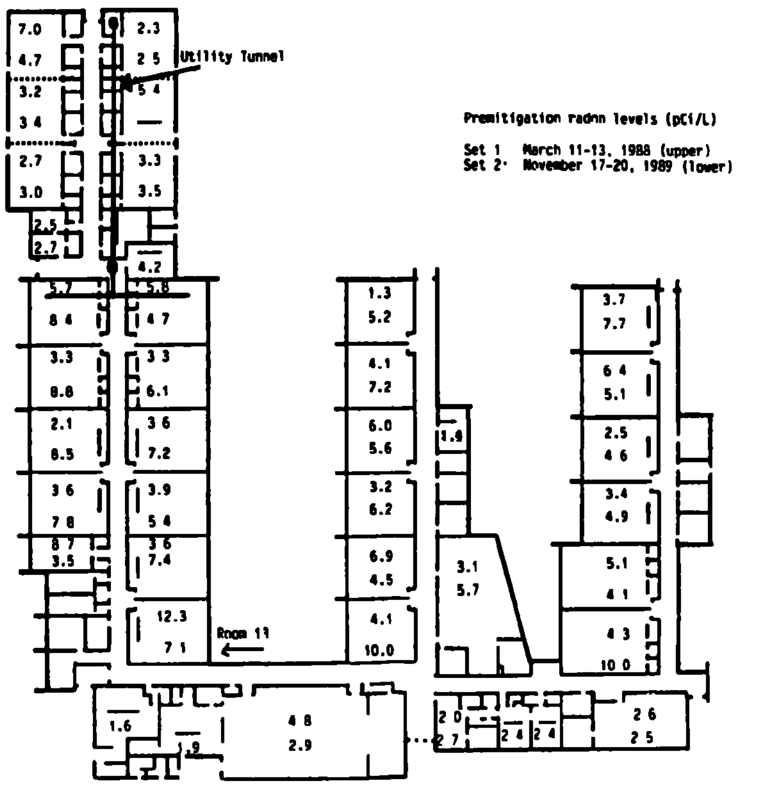


Figure 1. Premitigation radon levels in School A.

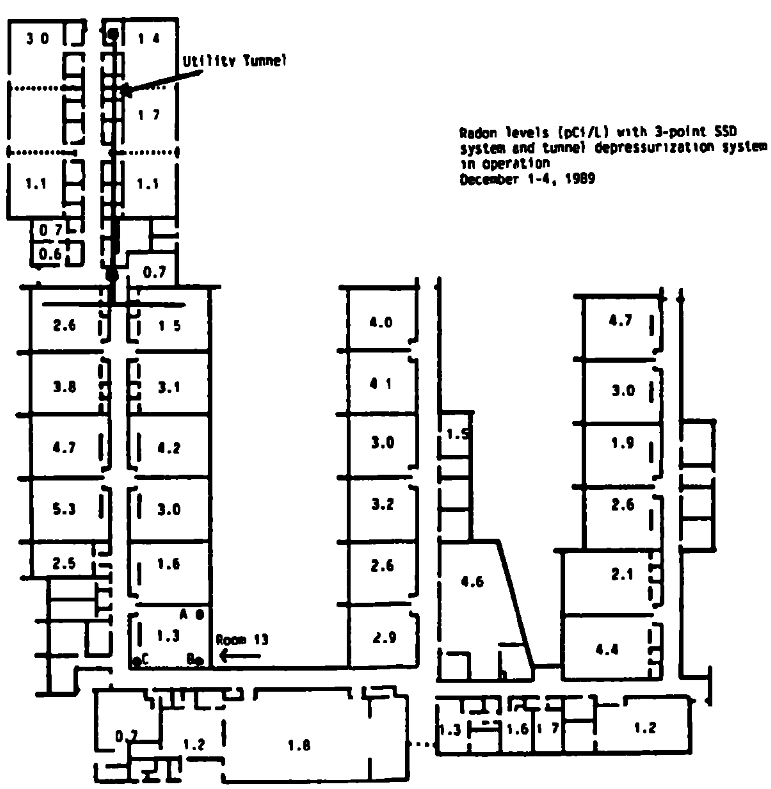


Figure 2. Radon levels in School A with SSD and tunnel depressurization systems in operation.

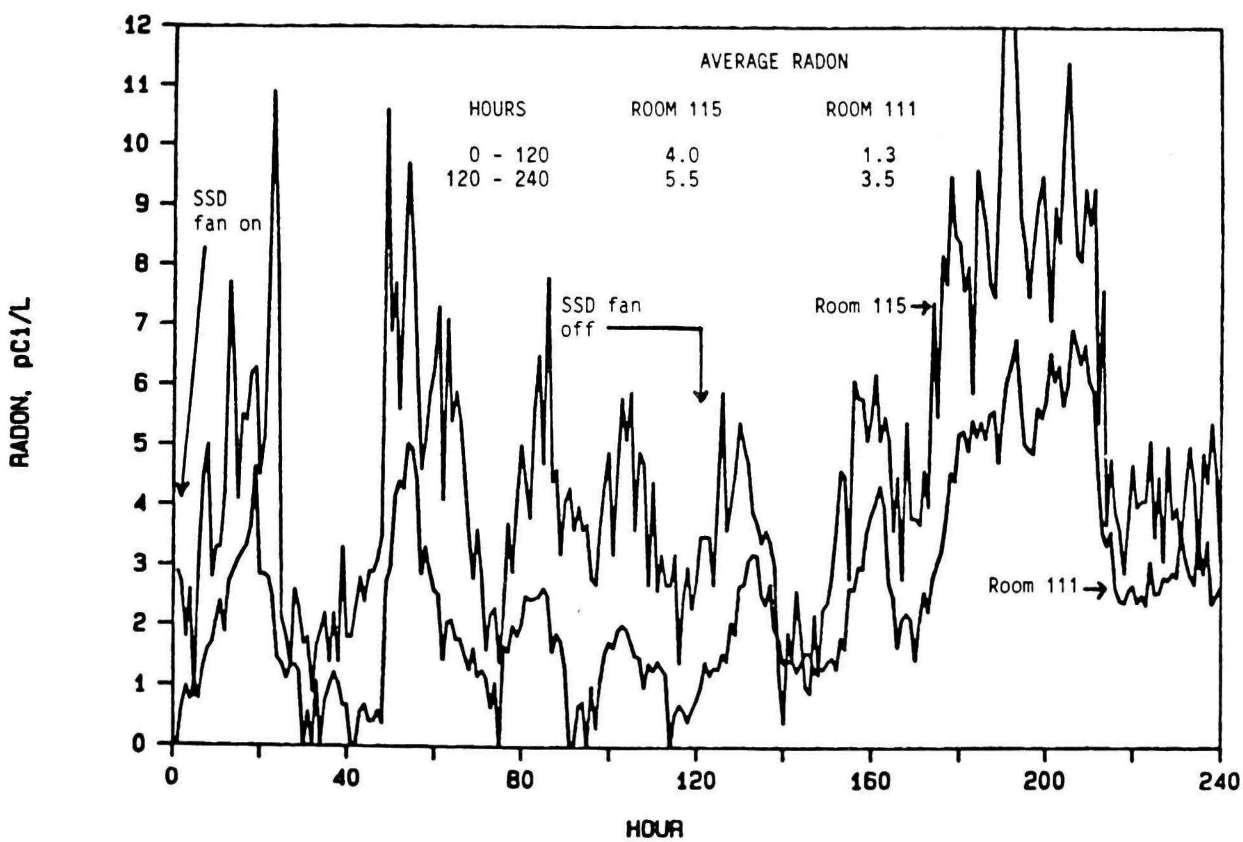


Figure 3. Continuous radon measurements in Rooms 111 and 115; SSD fan in Room 111 on and off (12/1-11/89).

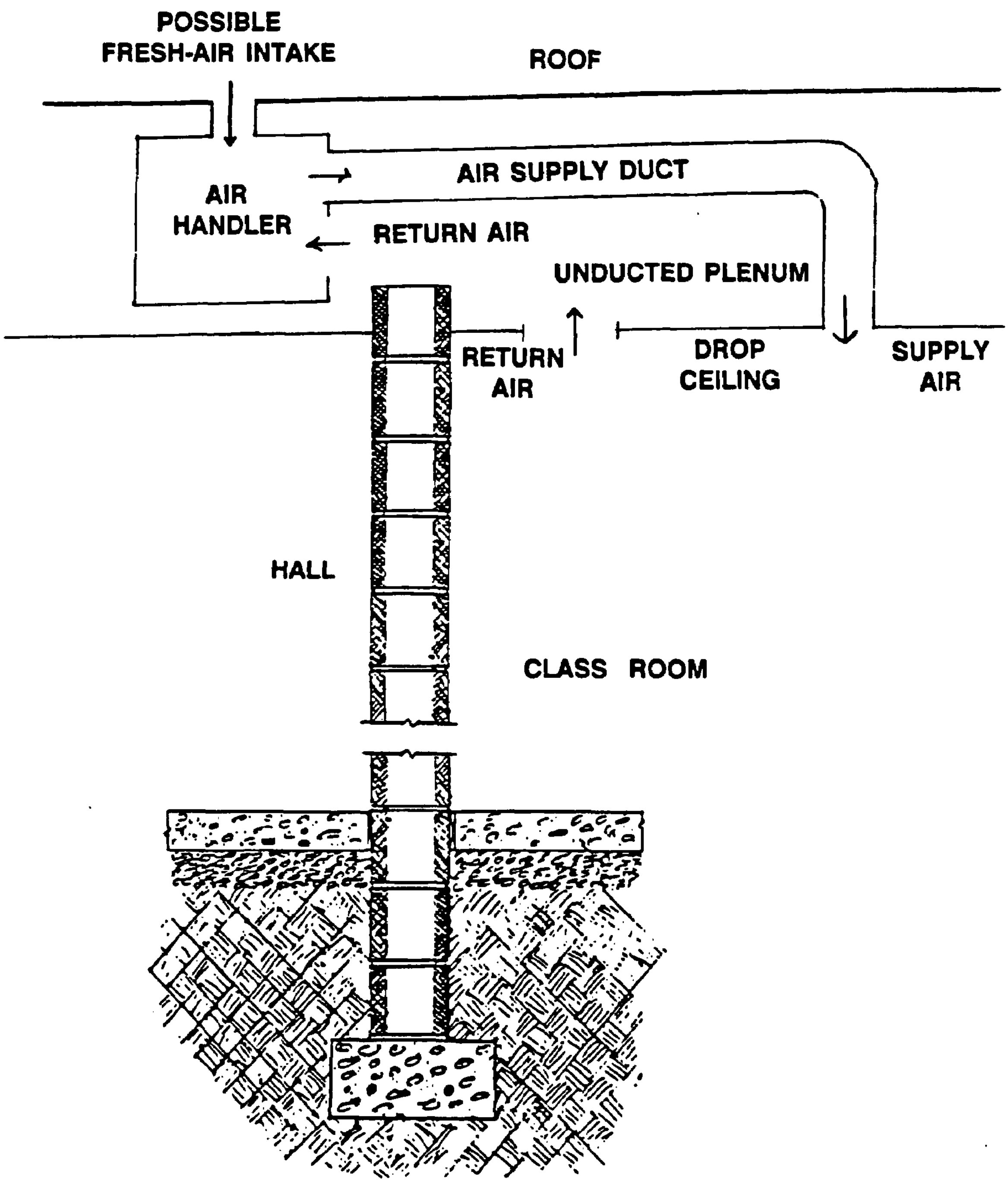
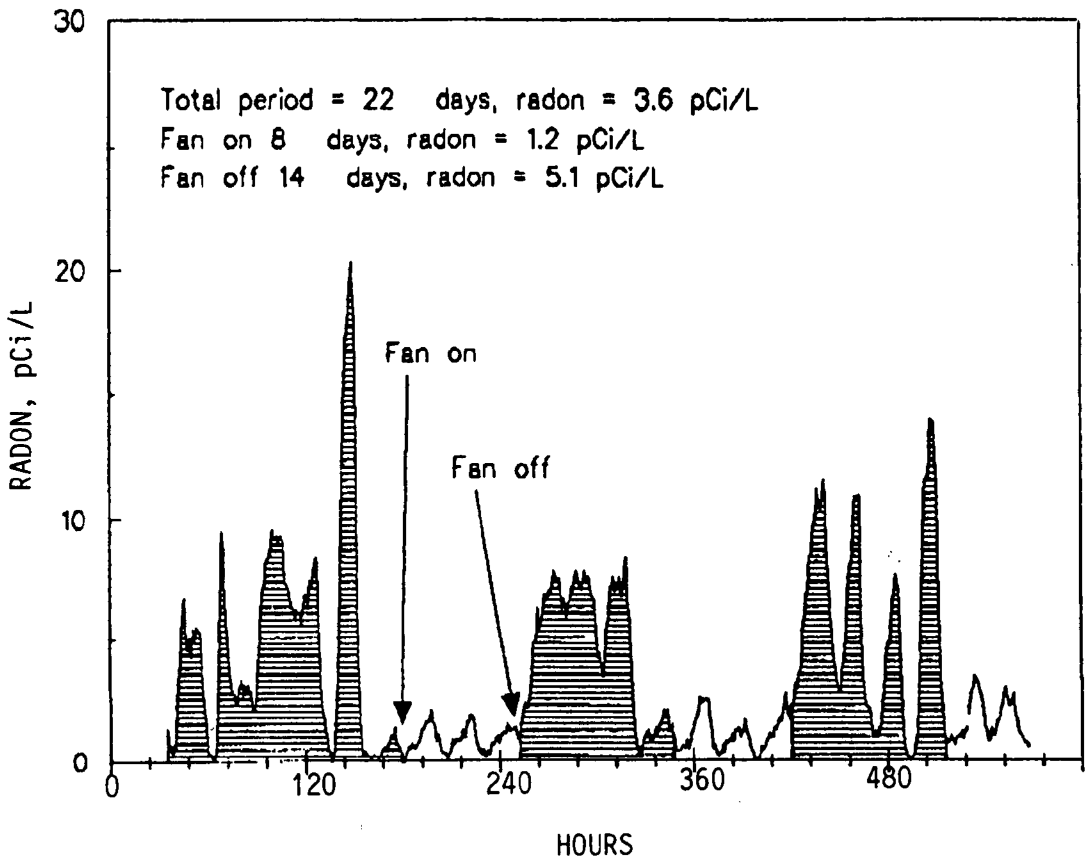


Figure 4. Example of school with unducted return-air plenum in drop ceiling.



Depressurization fan on (Wednesday noon to Saturday noon)
Depressurization fan off (Saturday noon to Wednesday noon)

Figure 5. Continuous radon measurements in School A with utility tunnel depressurization fan on and off (9/27 - 10/22/89).

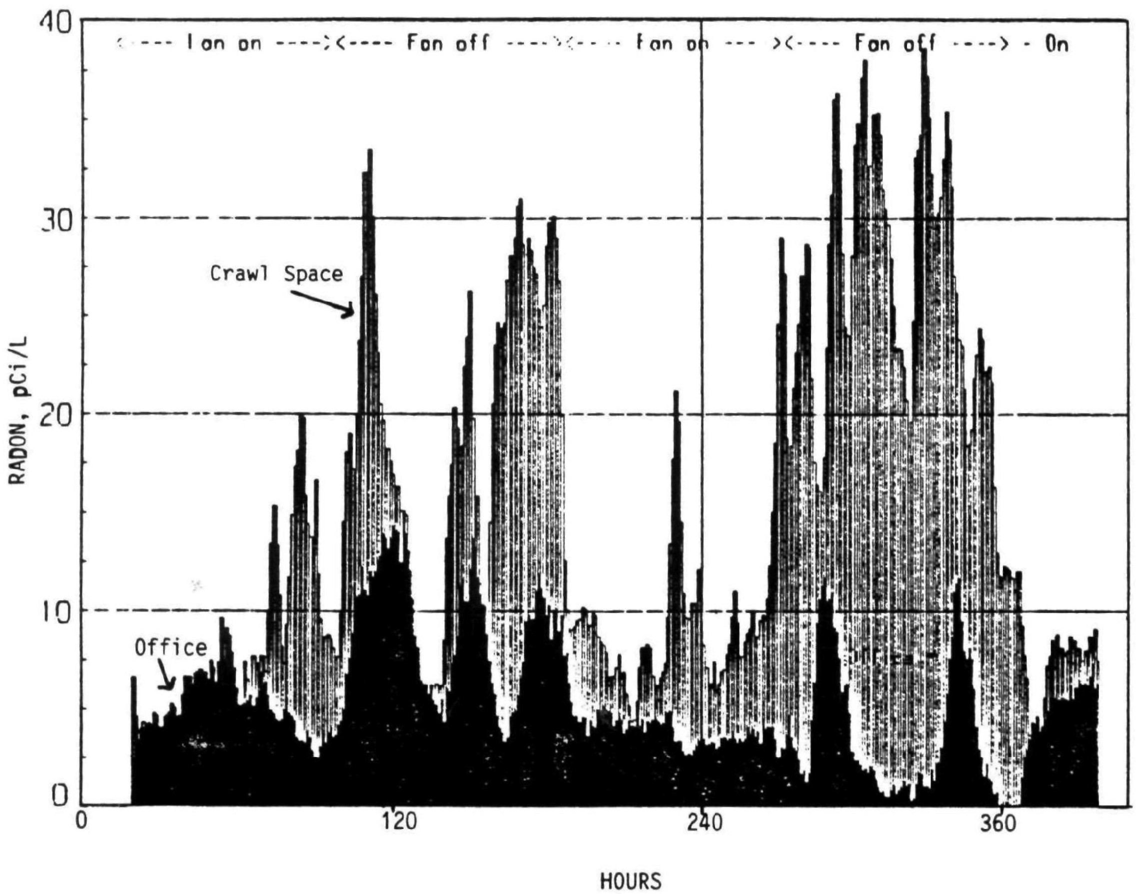


Figure 6. Crawl space depressurization in School C with fan on and off (12/22/88 - 1/7/89).

AIR PRESSURE DISTRIBUTION AND RADON ENTRY PROCESSES IN EAST TENNESSEE SCHOOLS

L. D. Sinclair*, C. S. Dudney**, D. L. Wilson, and R. J. Saultz

Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6113

ABSTRACT

Many building characteristics have been found to influence radon entry, including building size and configuration, substructure, location of utility supply lines, and design and operation of the heating, ventilation, and air conditioning (HVAC) system. One of the most significant factors is room depressurization resulting from the HVAC system exhausting more than it supplies. This paper represents a preliminary assessment of HVAC characteristics and how they may relate to radon entry. During the summer of 1989, a limited survey was made of air pressure and radon levels in four schools in eastern Tennessee. Short-term samples of radon and pressure were made in all rooms in contact with the soil using alpha scintillation cells and an electronic micromanometer, respectively. The pressure differences and radon concentration changes induced by operation of the building ventilation system varied among sites within individual schools.

* Permanent address: Lexington High School, Lexington, SC 29072.

** Author to whom correspondence should be addressed.

INTRODUCTION

Radon-222 is a radioactive, colorless, odorless, chemically inert gas with a half-life of 3.8 days. It is the parent of several short-lived, alpha-emitting radionuclides that occur naturally in the environment and have caused lung cancer in some exposed human populations (1). Recent attention has focused on radon in schools because of legislation passed by the U.S. Congress (2).

Radon studies have been conducted in schools in 13 states. Elevated radon levels have been found in many of these schools. Although there are no studies to determine whether children are more sensitive to radon than adults, some studies of other radiation exposures indicate that children may be more sensitive (3). Consequently, children exposed to radon could at greater risk than adults from exposure to radon. Indoor radon in large structures such as schools is a topic of concern to the U.S. Environmental Protection Agency (EPA), the U.S. Department of Energy, and various public health officials in all levels of government. It now appears that the benefits of making schools more energy efficient by sealing up cracks and cutting back on HVAC operation must be evaluated against the substantial risks associated with decreased indoor air quality. In addition, Saum et al. (3) have shown that air pressure varies significantly between rooms in a single elementary school in Maryland. We suspect that at the time of initial installation, the HVAC system is balanced for each room (i.e., the system is adjusted so that supply exceeds exhaust by a small amount), and there is positive pressure in every room. As the system ages, some rooms come under negative pressure. In rooms with negative pressure, some of the air that is drawn into the room comes from cracks in or near the floor. The source of most radon is uranium in the soil(4). So if a schoolroom is both under negative pressure and connected to a portion of the soil with elevated radon concentrations, the room may have elevated radon levels. Therefore, the purpose of this study was to monitor HVAC operation, pressure, and radon concentrations at selected sites in four school buildings to gain greater insight into the variations and relations among these variables in large structures such as school buildings.

EXPERIMENTAL MATERIALS AND METHODS

The primary criteria used to select the four schools were:

1. Some rooms with radon levels above 4 pCi/L, were expected based on earlier surveys (6,7),

2. Schools were under normal or near normal operation due to summertime use of the building,

3. Schools were similar in size, construction, and design, and

4. The full range of public school grade levels were represented.

School A is a high school, constructed in 1969. It is a block and brick veneer structure built on a concrete slab with underlying aggregate. It consists of a two-story classroom wing containing 40 compartmentalized rooms, a one-story gymnasium wing with perimeter classrooms, and a one-story auditorium wing which also houses the band and chorus facilities. The three wings are connected to a center commons area which contains the cafeteria, library, and administrative offices. The HVAC system consists of individual unit exchangers in the classroom wing. These exchangers allow air to pass through heating and cooling coils. The heat is furnished by hot water from a central boiler and cooling is furnished by chilled water from a central chilled water unit. Air returns are located in the exchanger. In the auditorium wing, air is split into two streams after the air supply fan: one stream is heated by hot water coils, and the other is chilled by cold water coils. The two streams are carried in parallel ducts to each room. A mixing box in each room controls the percentage of heated and cooled air entering the room depending on the room thermostat. Returns were located in the wall or in the slab. There are three ventilation systems. One (roof mounted) for the first and second story classroom wing, one for the office and cafeteria area, and a third for the auditorium areas. There exists a sub-slab ventilation system (return) unique to the band practice room area located between the band and chorus rooms. Other returns in this area (assembly) were located in the wall.

School C is an elementary school, constructed in 1968. It is a two-story block and brick veneer structure of modified open space design. The lower level includes three clusters (pods), each consisting of five classrooms and a teacher planning center. A maintenance corridor is located along the back side. Since this school was built into the side of a hill, the lower level classrooms are walk-out basements and are in contact with the soil on three sides. The upper level consists of three pods identical to and directly above the lower level. There is also a one-story gym, cafeteria, media center, and office area which fronts the school. The HVAC system is of the dual air supply design with returns located in special light fixtures that have a chamber around them for exhausting air to the ceiling plenum. It is turned on locally at 6:30 a.m. and off at 2:30 p.m. The system is shut down at 2:30 on Friday for the weekend.

School D is a junior high school, constructed in 1954. Also of block and brick veneer construction, it consists of a separate two-story classroom building with 35 self-contained classrooms, library, and offices. Another separate building contains the gym and still another two-story building contains the cafeteria, auditorium, and basement level shop classrooms and storage. The classroom building is built into the side of a hill and has one wall in total contact with the soil. The basement level has no air conditioning. A dual air supply system provides both heated and cooled air (added in 1988) in both the two-story building and in the auditorium-cafeteria level of the other building. The gym area has forced air heat exchangers but no air conditioning. The HVAC system is turned on at 6:30 a.m. and off at 3:30 p.m. and is shut down for the weekend.

Constructed in 1976, School E is a high school and is constructed of a slab on grade with block walls and a veneer of bricks. The main building consists of two stories of classrooms with a hexagonal commons area, cafeteria, and administrative offices at the center. This building was built into the side of a hill and portions of it have all areas in contact with the soil. The lower west wing was situated considerably below grade. In fact, the hallway leading to it is inclined. A separate building contains the gymnasium-auditorium complex. It has a basement (girls and boys locker and shower rooms) and a first and second floor (balcony level). The HVAC system consists of roof mounted ventilators and individual room air exchangers that differ from those at school A in that they are on the outside wall and vented to the outside. They bring in fresh air as well as circulate room air. The operation of the HVAC is under computer control from the district office and operates from 6:30 a.m. until 3:30 p.m. on weekdays during the summer with some provision for manual override at the school. The vocational complex was not studied because of time limitations. However, it has construction and location characteristics that would make it of interest.

From June 22 until August 14, 1989, four schools were surveyed for radon using several measurement methods. Results reported here were all obtained with a Pylon AB-5 monitor operating with room air flowing through a 163 cm^3 Lucas cell at about 1 L min^{-1}. After steady state conditions were achieved within the Lucas cell, at least ten consecutive 1-minute readings were recorded and averaged. The efficiency (CPM per pCi/L) of each Lucas cell was determined in a chamber at ORNL using instruments that had been compared with instruments at EPA's Eastern Environmental Radiation Facility or instruments at DOE's Environmental Measurements Laboratory. During any day in which data were collected, the operation of the instrument was checked with a ^{226}Ra source and the background count rate was determined by sampling outdoor air for at least ten minutes. Background count rates were subtracted from observed count rates before calculating radon concentrations. The sampling was performed according to established EPA guidelines, in that, sampling was done in the center of the room, away from windows, doors, corners, and HVAC ducts.

Pressure readings (referenced to the air mass in a central hallway) were recorded for each location with a digital micromanometer. The micromanometer was turned on and, after a warm-up period, the zero point was established by connecting the two pressure connections together with tubing. For differential pressure measurements, the micromanometer was connected to a length of tubing inside the room to be tested, and to an identical length of tubing that was placed under the closed door and opened into the adjacent hallway. The instrument was electronically zeroed immediately before each measurement. Data were recorded after allowing a few seconds for the instrument readings to stabilize. The position of the HVAC return and supply in the room was noted and whether or not the HVAC system was on or off in that particular location.

RESULTS AND DISCUSSION

Figure 1 and Table 1 summarize the results from the survey. The highest ^{222}Rn concentrations were seen in School A in the auditorium wing during periods of HVAC operation. Moderately elevated concentrations were also seen in Schools A, C, and E when the HVAC was not operating. Lower concentrations were observed in School D. In Schools A and D, the cases of elevated ^{222}Rn were generally limited to those instances when the pressure was low (see Figure 1), similar to what has been reported in a school in Maryland (4). A similar trend may be present in the data from School E, but because the ^{222}Rn concentrations are lower, the signal to noise ratio is lower and no conclusive statements are possible. There is no apparent correlation between radon and pressure data from School C, where the ^{222}Rn concentrations are lowest on average among the four schools.

In School A, we observed considerable variation among zones of the building. For further evaluation of this phenomenon, we divided the building into zones. Zone U consisted of all rooms not in contact with the soil. Zone A consisted of the auditorium and music rooms. Adjoining Zone A was Zone B, consisting of the cafeteria and nearby rooms. Adjoining Zone B was Zone C, consisting of the central office and nearby rooms. Zone D adjoined both Zones C and E and consisted of the ground floor of the classroom wing. Zone E was the gymnasium and shop areas. Figure 2 summarizes the means of all ^{222}Rn and pressure measurements made in these zones during periods of HVAC operation and non-operation. There is much variation among zones with regard to the mean levels of ^{222}Rn and pressure. There is also considerable variation among zones as to both the magnitude and algebraic sign of the change induced by operation of the HVAC system.

Results in this paper confirm and extend the observations of Craig and his coworkers (4). These results strongly suggest that the impact of HVAC operation on radon entry processes in schools and other large buildings is very important and can vary considerably within a building.

These results have important implications for the design of surveys of ^{222}Rn in large buildings. This study shows that care must be taken in the analysis of results from surveys of large buildings to reflect the status of the HVAC system during the survey in comparison to its status during normal occupancy. To reduce costs, some survey designs may include only sparse sampling of rooms within a large building using passive monitors. Such survey designs have limited ability to reduce the occurrence of falsely negative findings (i.e., cases where buildings are falsely declared "radon-free"). An alternative approach may be to screen a building with a manometer and to place radon monitors in known low-pressure rooms.

ACKNOWLEDGEMENTS

The authors are very grateful to the staff of the schools in which these data were collected. Without their patience, this study would not have been possible. One of us (L. D. S.) was a Teacher Research Associate at Oak Ridge National Laboratory under the auspices of a program sponsored by the Office of

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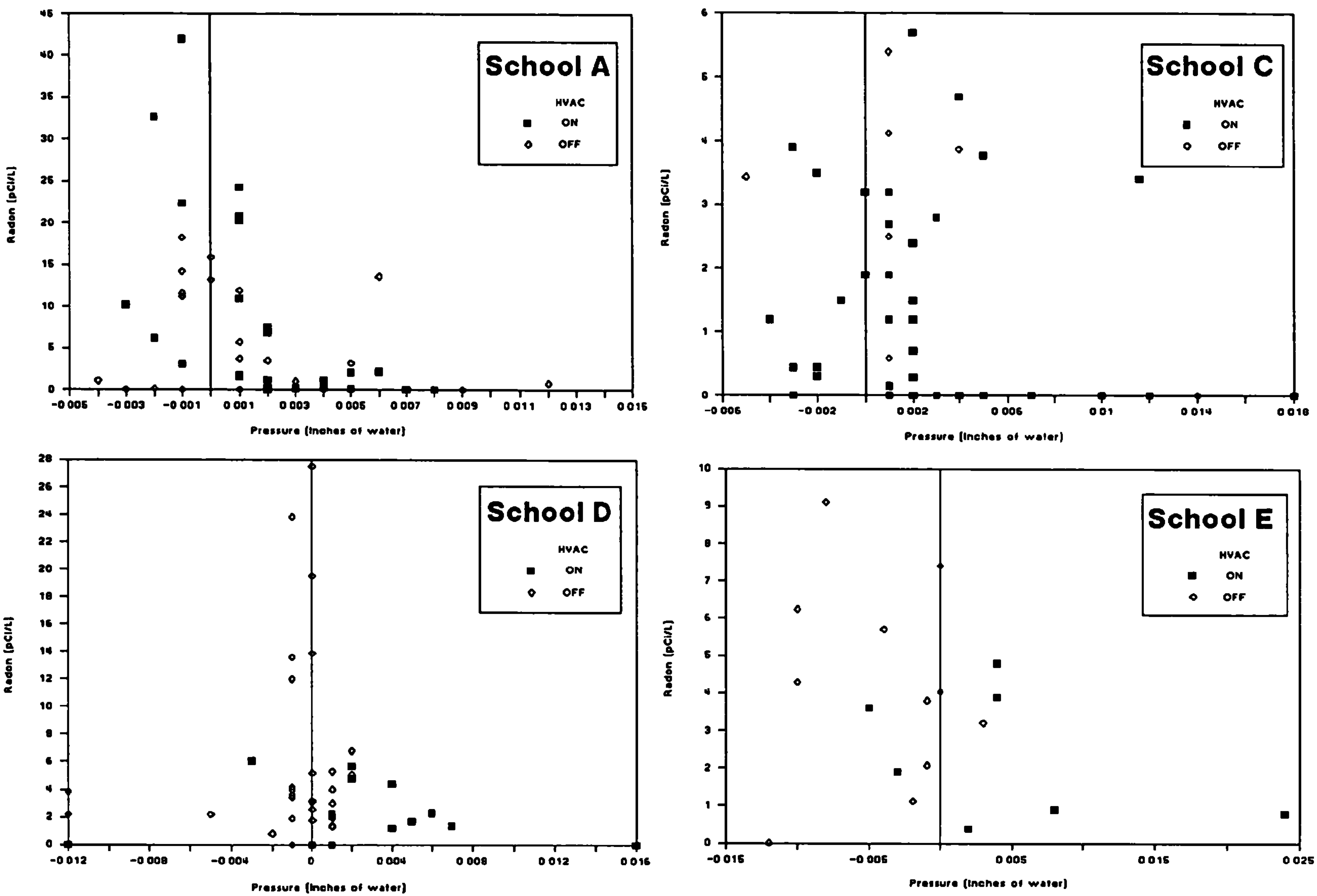

Figure 1. Results from ^{222}Rn and pressure measurements made at several sites in four schools.

RADON IN SCHOOLS OF MASSACHUSETTS

by: Lee Grodzins
NITON Corporation, Bedford, MA 01730
Massachusetts Institute of Technology

ABSTRACT

NITON Corporation has completed the testing of more than 7,000 classrooms in about 500 buildings of more than 80 public and private school systems in Massachusetts. This paper presents our protocols and summarizes our results based on about 5,000 of the tests. Only 6% of the rooms had radon levels, measured in weekend screen tests, above 4 pCi/L, a factor of 3 smaller than found in a recent EPA survey. Our protocols are similar to those recommended by the EPA, with three exceptions: 1. Long-term tests that include nights, weekends and school vacations are never carried out; they are manifestly unrealistic measures of radon levels during occupancy. 2. Follow-up tests of elevated measurements are made during hours of occupancy; i.e., during the daytime when schools are in use. 3. Successful screen tests, with the buildings closed and unoccupied and with ventilation systems dampened or off, are carried out in warm weather.

INTRODUCTION

We treat our children differently from ourselves. We set for them a higher standard. Their environment must be ultra-clean, whether ours is or not. So we demand that their schools be free from asbestos, free from lead paint, free from radon.

A few states have passed laws requiring that schools be tested and mitigated, if necessary. Most states will probably follow. But schools cannot and are not waiting. Massachusetts, for example, has no radon testing law, nor is one imminent. Nevertheless, thousands of classrooms of Massachusetts have already been tested, for school administrators are all too aware that the wide knowledge of the risks of radon have, de facto, made the schools accountable.

We report here on the testing of more than 5,000 classrooms in some 70 school systems. NITON's basic protocol is a three-stage procedure similar to that advocated by the EPA[1]. We begin with a broad-coverage screening test using charcoal, liquid scintillator, passive detectors. The tests are carried out under "worst case conditions," over a week-end or during a vacation. The initial test is followed, where necessary, with tests carried out when the school is in session, again using liquid scintillation, passive charcoal detectors. Finally, in those cases where there are elevated radon levels during occupancy, we make diagnostic tests with electronic radon monitors to recommend mitigation procedures.

Schools are different from houses, but two generalizations are much the same: There is yet no way of telling, a priori, which school buildings, or which rooms in a given building, will have a high radon level; every frequently occupied room on or below grade must be tested. And the mitigation of elevated levels is idiosyncratic; there are few commonalties and no magic bullets that will solve the radon problem in all schools.

This report begins by reviewing those differences in construction and usage that bear on the protocols one should use. Section III describes the NITON detectors and our early results for a few school systems that led us to adopt the protocols described in Section IV. Section V presents the full results of our school tests. Case studies give examples of different classes of school buildings, demonstrate the differences between radon levels found over weekends and during week days, and between daytime and nighttime concentrations, and give examples of successful mitigation. The final section presents our conclusions relevant to this conference.

II. SCHOOLS ARE DIFFERENT FROM HOUSES

The upper section of Table 1 summarizes the main differences in construction, ventilation and usage that bear on the radon problem. In particular, the almost universal use of on- or below-grade rooms in sprawling, decentralized schools make a strong case for testing every such occupied room.

The lower section of Table 1 summarizes the obvious differences in the profiles of occupancy between a home and a school, differences that argue compellingly that long-term, uninterrupted radon testing is inappropriate for schools.

Table I.

Houses	Schools
Small Footprint.	Very Large Footprint.
Basements often not used.	Ground Floors almost always used.
Basements usually isolated from the first floor.	Ground floor often open to upper floors through wide stairwells.
The rooms of a given floor are generally open to each other.	Classrooms, especially in the lowest grades, are often isolated, with rooms closed for extended periods.
The stack effect of the furnace is a paramount concern in the winter.	The boiler room has little relevance to the radon problem.
N.E. homes are rarely on slab.	Schools are often on slab.
N. E homes usually have 2 floors plus a basement and attic.	Schools are often single or two story; on or below grade.
No ventilation code.	Mass. code requires 10 cfm of fresh outdoor air per person.
One type of heating system.	Usually a complex HVAC system.
----------------------------------	----------------------------------
Occupied day and night, especially at night.	Occupied during the day. Rarely at night.
Occupied on weekends.	Used sparingly on weekends and then only during daytime.
Occupied during the summer.	Used sparingly during the summer.

School construction is remarkably varied. Some buildings are built on slab, some over crawl space. Old buildings may still have fieldstone foundations. A school may have one to several additions, each constructed years apart under different codes and designed by different architects.

Schools are supposed to have ventilation systems operating whenever the building is occupied. Massachusetts, for example, requires that schools supply at least 10 cfm of fresh outdoor air for each occupant; for most classrooms that is about 2 air exchanges per hour. To meet this code, some schools have central HVAC but many have complex, hybrid systems. Modern schools in our area often have central ventilation plus independent univent heating systems in every classroom to heat fresh make-up air. Nevertheless, the ventilation system is often the offender when a radon problem is found in a school. One reason is that older school buildings generally have antiquated ventilation systems, or none at all. Another can be traced to the 1970's when the sharp increase in the cost of energy prompted many custodians to minimize the amount of fresh air brought in during the colder months.

Finally, we note that the stack effect can be important in every building, but the causes and consequences are different in a school and a home. In particular, unrelated parts of a large, one-story school may exhibit widely different stack effects and, hence, widely different radon concentrations.

III. Early Results and Protocols

All screening measurements have been carried out with our patented NITON Liquid Scintillation detectors. These small vials, weighing about half an ounce, contain a perforated plastic container filled with activated charcoal and desiccant. The adsorption time constant makes them appropriate for sensitive testing from 8 to 72 hours. Removing the cap exposes the charcoal to the ambient air; screwing the cap back on seals the gasket and completes the test. The detectors are highly resistant to problems of high humidity and air movements.

We carried out radon tests of several school systems in the fall of 1988. Fig. 1 shows the extreme variations that one can encounter in different school buildings of the same town. School A had no radon level above 1 pCi/L; School B had a few isolated high radon values, difficult to find without a thorough test; the majority of the rooms in School C had radon levels above 2 pCi/L, though no room had a serious problem; the majority of tests in school D were greater than 10 pCi/L.

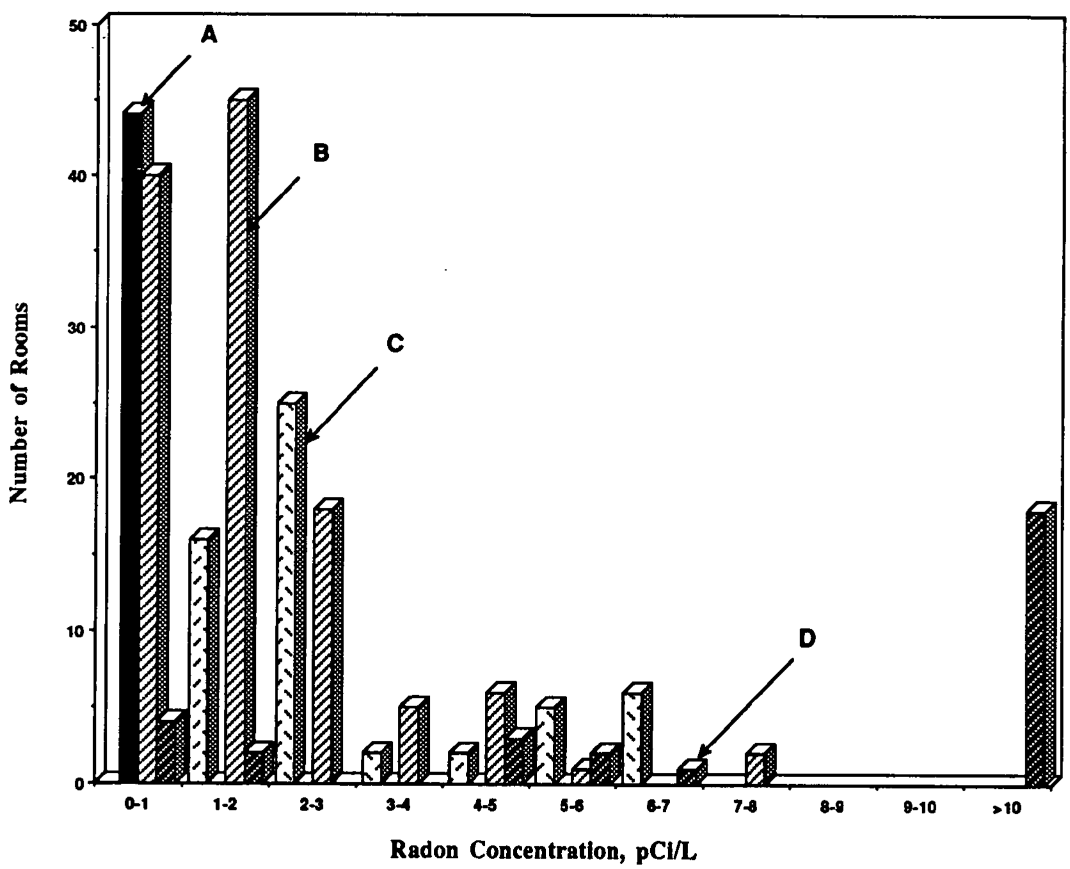

Figure 1. Radon Screen Test Results in 4 School Buildings

In one town, we worked closely with a superintendent who had an excellent custodial staff and was himself conversant with the construction and use of every building. He had also done his radon homework. When we walked through the system, he knew where he wanted the detectors to be placed. One modern school in particular was especially suspect, being built into a granite ledge so as to be surrounded on two sides by stone up to the top floor. Another, a modern, one-story, well-ventilated school, situated on top of a knoll would, he felt, be no problem. However, former school building had a radon distribution similar to School A of Figure 1, no radon levels above 2 pCi/L. The latter school building had the radon distribution of School D.

When these results were confirmed with a second weekend test, in which the radon concentrations reached 100 pCi/L in one classroom, the superintendent considered shutting the school down until the radon levels were mitigated. William Bell of the Mass. Department of Public Health and I persuaded him to allow us to first carry out some long-term, time-dependent radon tests. These results, which are commented on more thoroughly below, are shown in Fig. 2. The radon levels in that school were varying from day to night by more than a factor of 25; on one day the variation was close to a factor of 50.

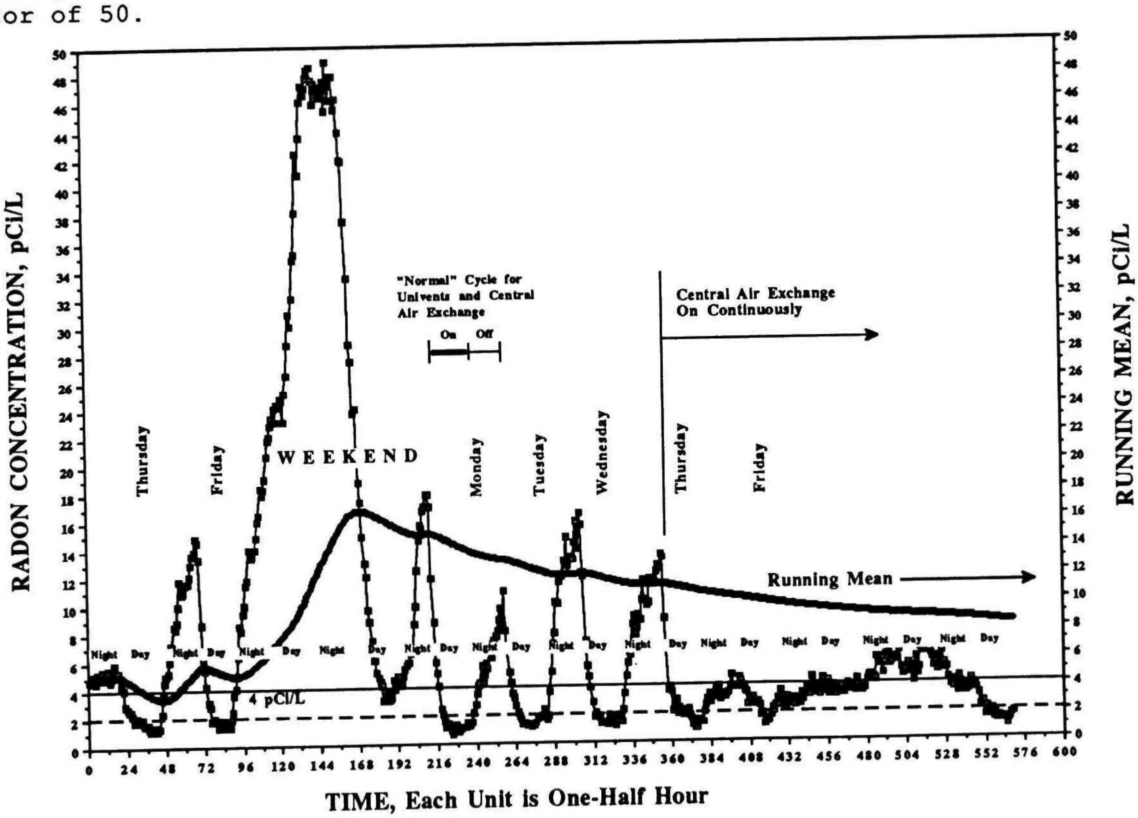

Figure 2. 12 Days of Radon Tests in One Classroom in School D.

A careful examination of our results convinced us that we could neither predict which buildings nor which rooms in a given building might show high concentrations of radon. School B, with 5% of its rooms above 4 pCi/L, showed that every occupied room on grade should be tested, or one can miss the odd room or the special wing that might be seriously polluted.

The results of School D also made evident that follow-up tests must measure the radon concentrations during occupancy; we care minimally about the concentrations when no one is in the building to be at risk.

Our early conclusions have been confirmed and strengthened by a year of testing school systems. The protocols outlined in the next section are designed to uncover problems and obtain insight into a mitigation strategy.

IV. NITON PROTOCOLS

1. THE INITIAL SCREEN TEST: A screen test is a short-term test carried out in such a manner as to create "worst case" conditions. The radon concentration found in the screen test should be higher than the radon concentration in that location averaged over an entire year of occupancy.

The key word is occupancy. Schools are typically occupied by a given staff member for no more than 25% of the hours of the year; a child is in school for no more than 15% of the year. It is the radon levels during these fractions of a year that we seek to screen.

The data in section V show that a "closed school" test almost always yields a higher elevated concentration than that found during a school day.

2. WHEN TO TEST: Start the test on a Friday afternoon, harvest them Monday morning. By Saturday morning, the school building will have had closed conditions for about 12 hours; by Monday morning, a charcoal diffusion detector, which gives greater weight to the radon levels in the later times of the tests, will give a good measure of the radon concentrations.

A Friday to Monday test is not written in stone. Two-day tests during vacation periods or tests pulled early because of impending school functions or stormy weather are also successful. But a weekend test is generally the most economical, requiring the minimum overtime pay for the custodians.

Winter or Summer? The EPA states that "radon screening measurements in schools should be made in the colder months (October through March) when windows and doors as well as interior room doors are more likely to be closed and the heating system is operating." We know of no evidence to support this recommendation. Indeed, one can generally get better "closed conditions" in the summer since schools are often completely closed during parts of the summer. The remaining justification for cold weather screen testing presumes that the heating system exacerbates the radon problem. Our view is that the emphasis on the heating system is misplaced. The proper emphasis should be on the fresh air input systems, required by Massachusetts and most states. If such systems are shut off, and the school is closed and unused, then a screen test is likely to be as "worst case" in the summer as in the winter. NITON tested several large school systems this past summer. We expect to retest a number of the buildings this winter with the hope that the data will provide convincing evidence for or against year round screen testing of schools.

3. WHERE TO TEST: Every frequently occupied room on or below grade should be tested. Closed rooms that are occupied for only short periods -- file rooms, storage rooms, boiler rooms and the like -- should be tested only with full knowledge that acceptable levels can exceed 4 pCi/L without undue risk.

Cafeterias, gymnasiums, libraries and other large open rooms seem to have higher radon levels than do classrooms. Perhaps it is because they are seldom well sealed against soil gas. Auditorium stages, for example, are sometimes built directly over the ground. We recommend one detector for every 2,000 square feet of floor space; that is, a 60 by 60 room would have 2 detectors.

Washrooms and showers. These tend to have elevated concentrations due to gaps around pipes that go through the floor. But a given individual spends little time in these rooms, so that testing should be done with insight.

Upper floors: The open structure of schools expose the upper floors to a radon problem if it exists in the ground floor. A thorough screening of the on-grade rooms should uncover the problem. We recommend that a few upper floor rooms be tested in every wing.

4. CONDITIONS FOR TESTING: We all agree that the school should be closed as much as is practical during the weekend test. And no one disagrees that high winds and stormy weather should be avoided, if at all possible. There is, however, disagreement on the matter of the operation of the HVAC system and on summer time versus winter time testing. I will take up the latter point again in the last section. On the question of the operation of the HVAC system, NITON prefers to make the tests with the ventilation system throttled so as to bring in the least amount of fresh outside make-up air and provide a better "worst case" screening test. The EPA, however, recommends that the heating system be kept on during the entire weekend, a procedure that produces a "worst case" only when the ventilating system is not bringing in outside air.

5. WHO SHOULD DO THE TESTING? A school can save a great deal of money by putting out and harvesting the tests themselves. The testing procedure itself is simple. So too are the directions for placement. If one can handle taking a pill from a child-proof bottle, one can conduct a passive radon test. But our experience shows that there are no free lunches here. The school superintendent must decide whether there are competent custodians who will responsibly put out and harvest the tests and, most important, keep proper records of what they have done. If not, we believe that the school will benefit from having a professional radon expert who will assume all responsibilities; in any case, the expert will be needed if problems are uncovered. On the other hand, the budgets of many schools preclude hiring an outside professional for the first screen test. In that case, NITON provides a number of aids:

a. Clear written instructions as to how to make the test.

b. Record-keeping sheets so that each custodian will provide us with the basic information of location and testing periods.

c. Where practical, we hold a meeting of the custodial staff to explain radon, hand out material, demonstrate the test, stress the need for record keeping, accuracy, promptness and diligence, and answer questions.

d. A successful strategy is to give a free test to custodians so that they could test their own home to become familiar with the entire procedure.

FOLLOW-UP TESTS:

1. <u>Criteria:</u> What should be the criteria for retesting? At what screening level do we pronounce a room cleared? There are no one-line answers. Prudence dictates that we recognize that radon levels can fluctuate markedly from day to day, from week to week, from season to season, and that a screening test is not invariably a "worst case."

NITON asks for follow-up tests whenever:

a. A room has a radon concentration above 3 pCi/L.

b. A cluster of rooms has radon concentrations above 2 pCi/L.

c. An entire school has a mean radon level above 1 pCi/L.

The isolated high-radon-level room may be a fault of the test, but we have found that the problem is almost always real and often caused by a faulty ventilation unit or a unique radon entry point. Isolated rooms with elevated radon levels should be tested with two detectors placed side-by-side.

Areas of radon concentrations exceeding 3 pCi/L should be retested thoroughly, with additional tests in rooms above or adjacent to the area. Duplicate tests are satisfying but not necessary since the tests validate each other.

Clusters of rooms that have weekend values between 2 and 4 pCi/L point to a problem that could be serious in another season or year. We highlight this region and ask for early follow-up tests on most of these rooms.

Some school buildings show no radon concentration greater than 3 pCi/L, but yet are far from being radon free. These buildings must be watched. We begin with follow-up tests of about 20% of the rooms.

Having determined which rooms to retest, we now must decide how to make the tests in the most direct, economical manner possible. Follow-up tests can simply repeat the initial screening test to confirm their findings. NITON has long since discarded this approach since we found that we rarely failed to confirm the earlier findings. Our preferred follow-up tests address the radon problems directly.

The NITON follow-up tests are carried out during school days when the rooms are occupied. The tests are done with our LS vials so as to differentiate between radon levels in the daytime and those in the nighttime.

2. The Day versus Night Follow-up Test: We seek to know the radon concentration that students and staff are exposed to. We thus need to measure the radon concentrations during a weekday, from roughly 7 A.M. to 7 P.M; the duration depends on the school use. Continuous monitors, in place for at least one day, would give the most complete information, but such monitors are expensive and the first follow-up tests, like the initial screening, often involve a number of rooms.

We prefer to make the tests using our inexpensive NITON LS detectors. We have carefully calibrated the sensitivity and accuracy of these detectors for periods ranging from 8 to 72 hours. The sensitivity at 8 hours is more than adequate; a 10 minute liquid scintillation count is sensitive to 0.4 pCi/L with an uncertainty of 25%. The accuracy of an 8 hour measurement, as determined from tests at a National Radon Facility, is well within 15%; the typical precision of multiple tests is about 10%. Both the accuracy and the precision are considerably worse than we generally obtain with a 2 day test, but they are quite acceptable for screening tests of elevated radon values.

Consistency checks of this procedure are constantly made by exposing, in classrooms, three sets of detectors: one during the day; a second set during the night; a third set for the full 24 hours.

The custodial staff (now expert in handling our detectors) or a professional exposes one set of detectors from, typically, 8 A.M. to 6 P.M. and another set from 6 P.M. to 8 A.M. An equivalent combination is a daytime exposure together with an overlapping 24 hour exposure.

DIAGNOSTIC TESTS:

Daytime concentrations are generally 30% to 50% smaller than the "worst case" screen tests. Thus, many of the rooms found to have screen-tested radon levels in the 2 to 6 pCi/L range, are found, with daytime testing to have acceptable values during occupancy. These rooms must be checked periodically but need not be mitigated.

The rooms that have elevated radon concentrations during occupancy must be dealt with expeditiously. Section V gives a few examples.

V. Results

SCREENING TESTS:

Fig. 3 presents the results of 5,200 screening tests carried out in 350 school buildings in 68 school systems of Massachusetts, mainly public, during the past 12 months. Most of the tests were conducted during the period from November, 1988 to May, 1989 but every season of the year is represented. Most of the screening tests were carried out by the school custodians. An additional 2,000 screening tests (not shown) were carried out by professionals in private schools in this area. The results are shown on a semilog plot to show the overall trend to high radon values. The abscissa values above 10 pCi/L are grouped in 5 pCi/L bins, shown as 5 identical vertical bars. Some overall results:

61% of the rooms had radon levels below 1 pCi/L.
6% of the rooms had radon levels above 4 pCi/L.
1.1% of the rooms had radon concentrations above 10 pCi/L.
0.7% of the rooms (37) had radon concentrations exceeding 20 pCi/L.

The elevated radon concentrations are far less frequent than found in the recent EPA study of 3,000 classrooms.[2] In that study, 20% of the school rooms had radon levels exceeding 4 pCi/L, and 3% had radon levels above 20 pCi/L. We have no explanation for the factor of 3 to 4 between the EPA results obtained in 130 schools and the Massachusetts school results.

Radon Distribution in 5,200 School Rooms in Massachusetts.

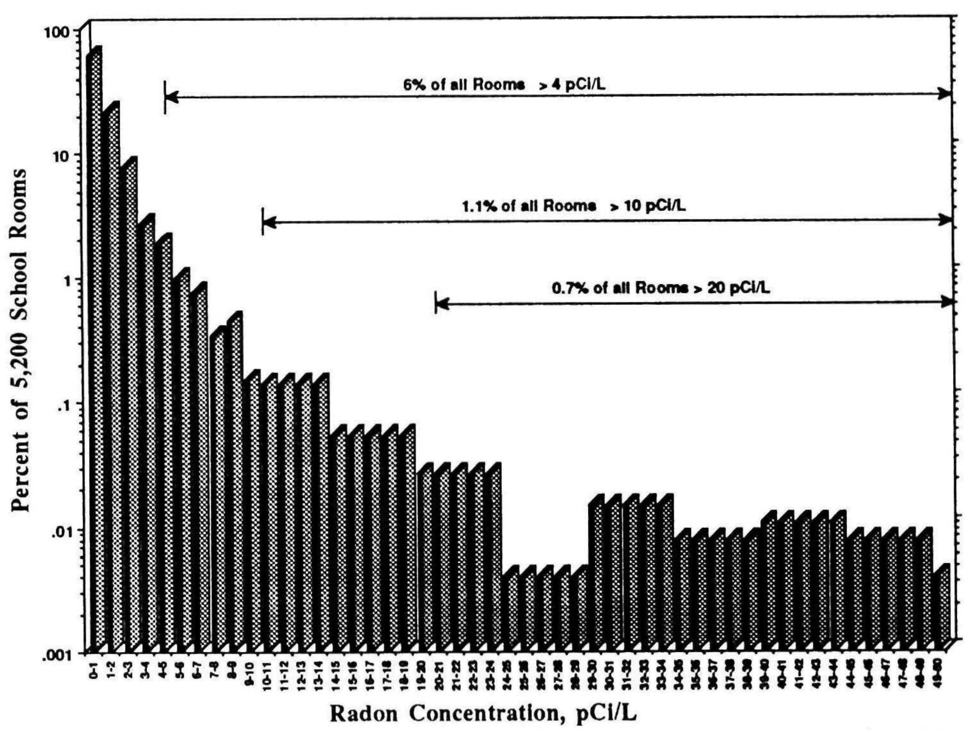

Figure 3. Radon Distribution of 5200 School Rooms in Massachusetts

The gross averages tell little about the individual schools, which have widely different distributions, as Figure 1 illustrates. The point is emphasized by noting that 25% of the buildings accounted for all of the radon levels exceeding the EPA "action level" of 4 pCi/L. Said the other way, 260 buildings, that is, 75% of the total, had no "elevated" radon concentration. And 25 school buildings, 7% of the total, accounted for all of the radon concentrations above 10 pCi/L. Some of these "high radon" buildings were old, most were not. Some were built on slab, some were not. Some were in towns that have higher than average radon levels, others were not. No pattern has emerged so far.

The elevated levels found in the weekend tests are only indicators of possible problems. Before one rushes to mitigate, one must confirm that the results apply to people when they occupy the building.

DAY-NIGHT FOLLOW-UP TESTS:

Radon concentrations observed during a regular school day are almost always lower than the values found either on the weekend or at night. An example of our observations is given in Table 2, which shows the results obtained for two school buildings in one system. The second column gives the values found over a weekend in October. The third column gives the values found a few weeks later during the daytime (12 hours) of a school day; the fourth column gives the concentration found during the following night (12 hours.)

Table 2. Weekend, Daytime and Nighttime Tests in One School System

Room	pCi/L, Weekend	pCi/L, Daytime	pCi/L Nighttime
E: 13	6.8	3.0	2.8
E: Gym	5.5	2.3	2.9
E: 10	6.2	1.9	3.0
E: Library	6.4	2.9	3.8
E: 16	5.2	2.5	2.9
F: Teachers Room	7.0	1.8	7.9
F: Cafeteria	5.1	2.5	6.4
F: Spec. Ed	3.6	1.5	7.1
F: 11	3.6	1.2	3.6
F: 10	5.4	2.1	6.0
F: Janitor	10.0	2.4	6.1
F: Girls Room	5.4	2.1	6.0

In building E, the daytime and nighttime values are similar, and both are about a factor of 2 less than the weekend results. In this building, the ventilation system was never turned off on weekdays.

In building F, the nighttime concentrations are similar to those found on the weekend, and both are about a factor of 2 higher than the daytime concentrations. In this building, the ventilation system is damped at night.

The results of 40 such tests are summarized in Figure 4; four sets in which a ratio exceeded 1.5 have been excluded to emphasize the main body of data. On the Y axis, we have plotted the ratio of the daytime to the weekend concentration; on the X axis is the ratio of the nighttime to the weekend concentration. (The division of the two values gives the ratio of the daytime to nighttime concentrations.)

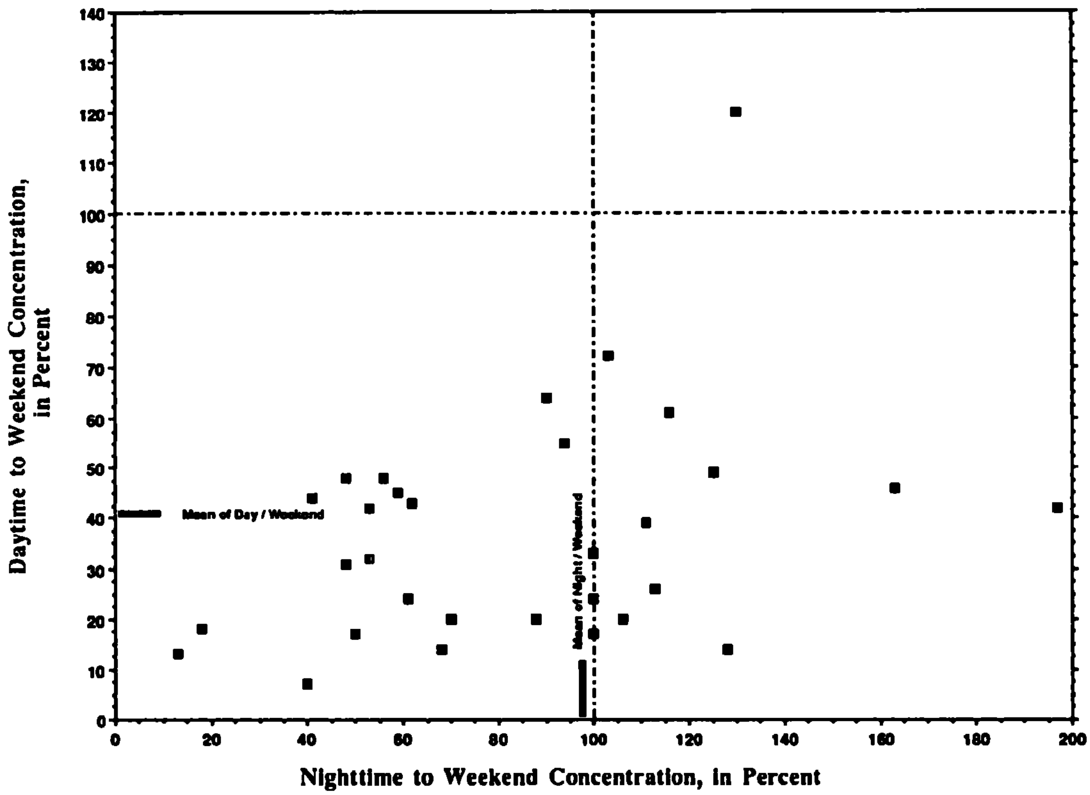

Figure 4. Day to Night to Weekend Concentrations of Radon.

The scatter of both ratios is wide. But on average, using all data from tests of some 60 rooms, the daytime concentrations were 42% of the nighttime concentrations, with a standard deviation of 32%; on average, the nighttime concentrations were 97% of the weekend results; $\sigma = 55\%$

A few daytime values exceeded those found on the weekend. In every case, however, the weekend value was considerably higher than 4 pCi/L, so that the weekend test did not miss the elevated concentration.

A long-term radon test is heavily weighted by the nighttime and weekend concentrations. Such a test for Building F would show a radon concentration well above 4 pCi/L. In fact, the radon concentration during the daytime in Building F was only about 2 pCi/L.

FURTHER COMMENTS ON THE RESULTS FROM SCHOOL D:

The elevated radon readings found in the first screening, Fig. 1, were confirmed the following weekend. A few days later William Bell and I put a monitor into one of the classrooms and recorded radon levels over 30 minute durations for 12 days in December, 1988. The results are shown in Fig. 2.

The radon concentration in the classroom of School D ranged from less than 1 pCi/L, found during the daytime, to a high of 48 pCi/L, found on the weekend. The precipitous decline in the concentration, observed each weekday morning, was well correlated with turning on both the central air exchange and the room univents. The sharp rise in the evening was correlated with the systems being turned off. When the air exchange system was left running all the time, the maximum values dropped to just below 4 pCi/L. The univent system lowered the radon levels to below 2 pCi/L.

The one-week average for the radon concentration in School B was approximately 11 pCi/L, far above the EPA guideline, and a demand for mitigation. But the one-week average of the radon concentration from 8 A.M. to 6 P.M was only 1.9 pCi/L, well within the EPA guideline.

LONG-TERM TESTS

In every school building we have investigated, a long-term test that includes the nighttime and weekend concentrations would give a totally erroneous representation of the radon exposure to the occupants.

EXAMPLES OF MITIGATION

1. The Odd High Radon Level. We frequently find that a building has only one room or a limited area with an elevated concentration. Such problems are often easy to diagnose and correct. An example was the multi-winged, one-story school built on slab. An examination uncovered two problems.

The ventilation system was defective. For one thing, the air returns inside the classroom closets were so covered with books and paraphernalia as to be ineffective. For another, the make-up air brought in by the univents and central ventilation system had been deliberately restricted years ago to reduce the cost of heating. When the returns were cleared, the radon problem in the rooms of one wing disappeared.

But the radon problem in two end rooms of another wing not only persisted but remained well above 10 pCi/L during the daytime. Further tests with the LS detectors, carried out by the custodians, showed that the back of one of the classrooms was about 20 pCi/L - almost twice the concentration found in the front of the room.

When William Bell and I investigated, we found that the radon was gushing in from the clearance space around the sink drain pipe. Foaming this space solved most of the remaining radon problem.

2. School D. School D, the modern grade school building of Figs. 1 and 2 is a one-story building built over a crawlspace whose height ranges from about 3 to more than 6 feet. Service ducts and pipes form a tangle above the dirt floor. The radon concentration in the crawl space was very high and clearly the cause of the radon problem in the school.

Sealing the dirt floor, with the possibility of pumping under the seal, was and remains an expensive option. Instead, the decision was made to mitigate by controlling the cycles of heating and ventilation. The air exchange system is kept on during the week to supress excessively high concentration. The univent systems are turned on by 6 A.M. and turned off around 6 P.M., later if there is an evening activity. We periodically monitor the building and have advised installing a permanent radon monitor.

VI. Conclusions:

NITON has tested some 7,000 classrooms in about 500 buildings in more than 80 school systems. The first measurements were screen tests carried out over a weekend under "worst case" conditions. The follow-up tests were carried out during school session; daytime and nighttime concentrations were obtained separately. Finally, where necessary, diagnostic tests were conducted with electronic sniffers and monitors to determine the origin of the

radon infiltration. We draw the following conclusions from these data:
1. A week-end test, beginning Friday afternoon and ending Monday morning, when carried out under closed building conditions, provides a reliable screening measurement. The radon concentrations are, with few exceptions, higher than concentrations found during occupancy.

2. The ventilation system in the school should be restricted during the screening test if one is to simulate "worst case" conditions.

3. Follow-up tests of elevated readings should distinguish daytime and nighttime radon concentrations. Such tests can be carried out economically using passive LS charcoal detectors.

4. Long-term testing of radon that includes nighttime, week-end and vacation concentrations produces manifestly improper measurements of the radon exposure to humans. EPA's insistance in suggesting alpha track and long-term EPERM measurements as a preferred alternative for screening measurements weakens their entire program for schools.

The results of a long-term test can be dangerously wrong if radon levels at night and weekends are much lower than those during the daytime. In that case, a serious radon problem may be missed. The more likely scenario is that the higher radon concentrations generally found on weekends and nighttimes will result in a falsely high radon concentration. Schools will then be compelled to spend considerable funds to "fix what ain't broke."

5. We are now testing whether warm-weather testing gives erroneously low radon results, as is implied by the EPA recommendation to test only in cooler months. We hope to present the data at the conference.

6. Our data reinforces the EPA's conclusion that one cannot predict which buildings, or which rooms in a given building, will have a radon problem. Every occupied room on or below grade should be tested.

7. Finally, we emphasize that school buildings differ from one another in construction and usage. Testing them for radon is now a straightforward protocol. Mitigation of serious radon problems is, however, not well understood. We do not yet know how to systematically approach a radon problem in buildings with complex, hybrid heating and ventilating systems.

Acknowledgements

The data described here was obtained by the technical staff of NITON Corporation, whose watchful and meticulous work is deeply appreciated. I would also like to thank William Bell, with whom I did most of the early diagnostic measurements; his teaching and advice are of continuing benefit.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and therefore the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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RADON GAS TESTING IN KENTUCKY SCHOOLS: SUMMER TESTING PRAGMATIC CONCERNS AND PRESSURE / HVAC CONSIDERATIONS

by: Patrick Holmes
Alpha Spectra of KY., Inc.
Louisville, KY 40243

ABSTRACT

This study examines the radon gas levels and related mechanisms in elementary, middle, high and special schools. The Jefferson Co. Project consists of 4,000 to 5,000 screening data points on 158 sites in Louisville, Kentucky. The primary instruments consist of short-term electret perms and open-face design AC canisters with CRM's as cross-checking devices.

Due to political, operational and financial considerations, this project was mandated to be initiated and completed in summer 1989. Modifications and specific concerns were addressed, in order to adhere as closely as possible to EPA's Interim Guidelines for school testing (see summary).

RADON SURVEYS IN LARGE BUILDINGS: THE UCF RADON PROJECT

Ralph A. Llewellyn
Department of Physics
University of Central Florida
Orlando, FL.32816

ABSTRACT

Documented protocols for surveying the distribution of radon in large buildings do not currently exist. Those developed for one/two family residential structures and draft versions of those being developed for schools provide inadequate guidance for investigators and diagnosticians charged with determining radon levels throughout large office buildings or interconnected multi-building complexes. To support the development of protocols for large buildings, the UCF Radon Project has completed the initial phase of a detailed data collection and analysis program. Measurements of radon levels were made under known, controlled conditions in twelve large buildings ranging in size from 25,000 sq.ft. to 225,000 sq.ft. and up to five floors above ground. An average of more than 100 radon measurements were made per building. Results from the study indicate that (i) radon levels often do not decrease as expected in the upper floors of multistory buildings and (ii) sampling rates currently being proposed for the above ground-level floors of large buildings may be too low.

INTRODUCTION

As is the case in several states, Florida is currently in the throes of developing a building construction code intended to make all structures, from single family residences through schools to high-rise office towers, resistant to the intrusion of radon gas. A legislatively mandated team drawn from the Florida State University System has been working with pertinent state agencies since September 1988 on the drafting of the comprehensive code. At the outset of their task the group recognized that existing experimental data that could provide the basis for a radon-resistant construction code which could apply to large buildings was exceedingly meager. Even the most fundamental knowledge, such as characteristic concentrations, radon movement pathways, and the extent of exposures to occupants, was (and is) not yet available in the literature. Indeed, standard protocols to govern the conduct of radon surveys and follow-up measurements for large and/or high structures do not exist. As a consequence of the dearth of information, the drafting of codes and regulations pertaining to the prevention of radon hazards in large structures must await additional measurements and research.

UCF RADON PROJECT

In mid-1989 the small environmental physics group at the University of Central Florida initiated a research program, the UCF Radon Project, directed toward filling a small part of the information gap. The project is organized in three phases:

Phase 1: Baseline determination. Collection and analysis of detailed radon concentration data in a number of large buildings. Development of a computer program and database to aid the analysis and to facilitate diagnostic measurements and interpretation.

Phase 2: Study the effects on radon concentrations and transport of changing the environmental control settings in selected structures. Extend computer programs to include the results of phase 2 work.

Phase 3: Utilize the results to develop a draft protocol for radon analysis of large buildings.

The University's complex of large buildings of varying numbers of floors, up to 5, and areas, up to 225,000 sq.ft. (20,900 m^2), provided a convenient and in many ways ideal "laboratory" for the project. All of the buildings are of masonary construction and relatively new, the oldest just over 20 years and the newest less than a year. Types of building utilizations include exclusively offices, mixtures of offices and laboratories, a library, and exclusively residential suites. The HVAC of all but the latter are controlled by a central computer system on a floor-by-floor basis. Table 1 identifies 12 of the buildings used in Phase 1 of the study as to their size and type of utilization.

DATA COLLECTION

The data collection for the project was to serve a dual purpose. First, it was to provide research data pertaining to large buildings that would assist in the development of future measurement protocols and construction codes. Secondly, it was to provide the University with timely information regarding the levels of exposure to radon gas received by its employees and student body. To this end, all rooms were assigned to one of four categories based on occupancy time, ranked in order of

TABLE 1. BUILDING DESCRIPTIONS

Building No.	Name	Utilization type (a)	Number of floors	Gross area (sq.ft.)
1	Administration	A	4	87,700
2	Library	B,A	5	226,500
5	Chemistry	D,A	3	49,100
12	Physics	D,C,A	4	106,500
14	Phillips Hall	A,C	4	64,600
18	HFA	A	5	84,000
20	Biology	D,A	4	62,800
21	Education	A,C	3	110,300
29	CCII	A,D	2	23,400
32	Seminole Hall	E	4	42,100
40	CEBA I	D,C,A	4	130,900
45	CEBA II	A,C	4	119,700

à Key to utilization type: A = offices; B = library; C = classrooms; D = laboratories; E = residence suites

measurement priority. They were: 1 - offices, 2 - residential suites, 3 - laboratories and classrooms, and 4 - mechanical and service areas. Elevator shafts were initially of high priority interest and were included in category 1.

Data collection and measurements were carried out on the basis of an a priori draft "UCF Radon Measurement Protocol" (1) for large structures, the detector deployment and measurement procedures of which were based closely on pertinent USEPA documents (2)(3)(4). The resources available to the project have thus far enabled screening measurements to be made in all first priority rooms (offices) and some second priority rooms (residential suites). A total of approximately 1500 measurements have been completed to date.

Radon samples were collected using charcoal canisters[1] exposed from 48 to 72 hours. The radioactivity of each exposed canister was measured using one of two 3 in x 3 in (7.6 cm x 7.6 cm) NaI(Tℓ) scintillation detectors, ORTEC electronics, and an IBM PC/XT configured as a 2048-channel analyzer operating in four 512-channel segments. The individual analyzer segments were programmed to record gamma rays from radon daughters in the energy range from 0.25 MeV to 0.61 MeV. Typical operational characteristics of the two detector systems are recorded in Table 2.

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1 F&J Specialty Products, Inc. model RA40V

TABLE 2. DETECTOR CHARACTERISTICS

Channel	Resolution %	Efficiency	Error % b	Minimum Detectable Activity(pCi/liter) a
A	6.0	0.263	7.7	0.27
B	6.0	0.272	7.3	0.25

a At the level of 3 standard deviations.
b At the level of 2 standard deviations for a 4.0 pCi/liter result.

DATABASE

The net gamma ray counts measured for each canister were entered into a specialized database (UCFRADON), together with information that enabled the program to calculate the radon concentration in pCi/liter according to the procedures outlined in reference 4. Its design is especially 'user friendly! Information is also entered that permits relating the radon results to the HVAC status of the building maintained by the University's indoor environmental control computer. File structures in UCFRADON have been arranged to facilitate analysis on a building-by-building, floor-by-floor, and room-by-room basis.

There are currently approximately 1500 records in the UCFRADON data files. The data retrieval routines currently provide a variety of options, including, e.g., printouts of rooms with radon concentrations exceeding user selected levels. Additional options under study include floor-by-floor contour plots and 3-dimensional building-wide concentration histograms to aid in radon transport analysis. The existing data and any added subsequent to this writing is available to interested individuals on request.

RESULTS

ELEVATION DEPENDENCE

Initial analysis of the data collected in the first phase of the UCF Radon Project has yielded some interesting results. That fickle predictor, conventional wisdom, tells us that the concentration of radon should decrease as we move upward in a multistory structure. Assuming that any radon in the building emanates from the ground rather than from the materials used in the construction, it is easy to understand physically why the concentration should decrease with elevation.

Treating radon diffusion in air as a random walk problem, let's consider some concentration of radon, n(z,t) atoms/m^3, which is introduced at the ground level slab where z = 0[1] at time t = 0. Straightforward application of statistical mechanics leads to the conclusion that

$$\overline{z^2} = (1/3)\overline{v^2}\, t\, \tau \qquad (1)$$

where $\overline{v^2}$ = mean square velocity of the atoms and τ = mean free time between collisions (5).

Equation 1 implies that the standard deviation of the z component of the displacement vectors of the radon atoms $\Delta z = (\overline{z^2})^{1/2}$ is proportional to $t^{1/2}$, where t is the time after the radon was introduced. Figure 1 shows curves for the concentration n(z,t) vs z for three different times $0<t_1<t_2<t_3$. Table 3 shows Δz values for four specific times, two of which are specifically pertinent to radon diffusion, namely, the half-life of 3.8 days and 20 days, the approximate time over which a given sample has totally decayed.

TABLE 3. ΔZ RESULTS

Time t	Δz (meters) a,b
1 hour	0.17
10 hours	0.53
3.8 days	1.58
20 days	3.60

a At 300K, the rms velocity of radon atoms is 184 m/s and the $\tau = 7 \times 10^{-10}$ seconds.

b 1 m = 3.28 ft.

The random walk calculation results in Table 3 agree very closely with those calculated by ordinary diffusion theory. For example, the molecular current J = net flow of atoms per unit area per unit time, given by (6)

$$J = -D(dn/dz) \qquad (2)$$

where D = diffusion coefficient, yields the mean vertical displacement of the atoms introduced at z = 0, t = 0 to be 1.64m when t = half-life of radon.

Based on these calculations, one would not expect to find much radon anywhere above the ground floor. The problem with that expectation is

1 The z-axis is the vertical, or elevation axis; it is positive upward.

that the air in buildings circulates, to a certain extent due to natural forces, but mainly because of very effective HVAC systems. Still, the expectation has always been that the radon concentration will decrease as we move upward through the building. The few sampling protocols that have been drafted for large structures seem based on that assumption (7). However, results of experimental measurements on the large buildings studied in the UCF Radon Project suggest strongly that the expectation is not well founded. Results for the five largest buildings studied, graphed in Figure 2, show that in 80% of the cases the average concentration on the 2nd and 3rd floors substantially exceeds that on the 1st floor, as do more than half of the cases at the 4th floor level. For the two buildings with 5 floors, the average radon concentration on the top floor was still 40% of that on the ground floor.

These results, if substantiated by further work, have serious implications for the development of protocols intended to guide the accurate assessment of the health risks to occupants of large buildings arising from long-term exposure to radon gas. They also have something to say about the design of big buildings. Namely, the way to reduce radon intrusion into floors above the ground level would be to isolate the ground floor HVAC system from that of the rest of the building. Our interest here, however, is in the first of the implications, which will be discussed briefly in the next section.

SAMPLING FREQUENCY

Draft protocols currently being discussed for measuring radon concentrations in large buildings specify sampling rates on floors above the ground level that are much lower than that for the ground floor. For example, reference 7 specifies a 20% sampling rate for second floors and 10% for the third floors. However, the results shown in Figure 1 suggest that such low sampling rates will not yield a reliable profile of the radon concentration distributions on the upper floors. The large number of measurements made during this study enabled a test of that suggestion.

Using a number of floors in the larger buildings for which 100% of the first priority rooms had been measured, a χ^2 'goodness of fit' test was done for random samples at several sampling rates from 20% to 80%. This test answers the question, "What is the probability that the sample distribution agrees with the parent, or actual distribution?" (8). Table 4 records the results of the test for three floors in two of the large buildings studied. Figure 3 shows the curves of probability of goodness of fit used in evaluating the reliability of the random samples. Clearly, a 20% sampling rate on the 2nd floor of CEBA I provided a poor representation of the actual distribution of radon. Indeed, sampling rates in excess of 60% were necessary in order to achieve probabilities of 'good fit' in the 0.7-0.8 range. While these numbers are in part a function of the statistical uncertainties of the relatively low radon concentrations in the University's buildings, they suggest that sampling rates defined by protocols be considered with great care.

TABLE 4. RELIABILITY OF SAMPLE [a]

Building and Floor	Sampling Rate %				
	20	33	50	67	80
CEBA I, 2nd	0.02	0.05	0.18	0.75	-
CEBA I, 3rd	0.01	0.01	0.11	0.75	-
HFA, 4th	-	-	0.01	0.25	0.85

a Tabulated values are probabilities of agreement between sample and parent distributions.

CONCLUSION

Based on the results discussed above, it would be prudent for those developing protocols for guiding radon measurements in large structures to assess very carefully the sampling rates proposed for floors above the ground level in large buildings. Assumptions typically made regarding radon concentrations and adequate sampling rates that are implicit in current draft protocols may be seriously in error and could well lead to substantial underestimation of the radon exposures received by occupants of large buildings.

The work described in this paper was not funded by the U.S. Environmental Protection Agency and, therefore, the contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

ACKNOWLEDGEMENTS

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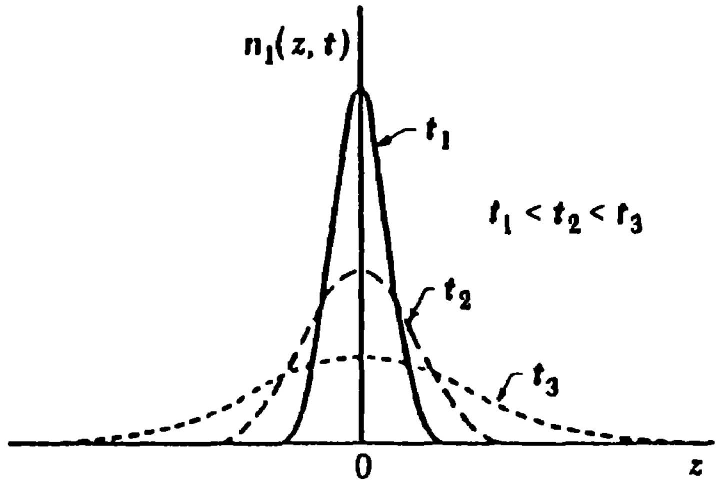

Figure 1. Concentration n(z,t) vs z for various times after t = 0.

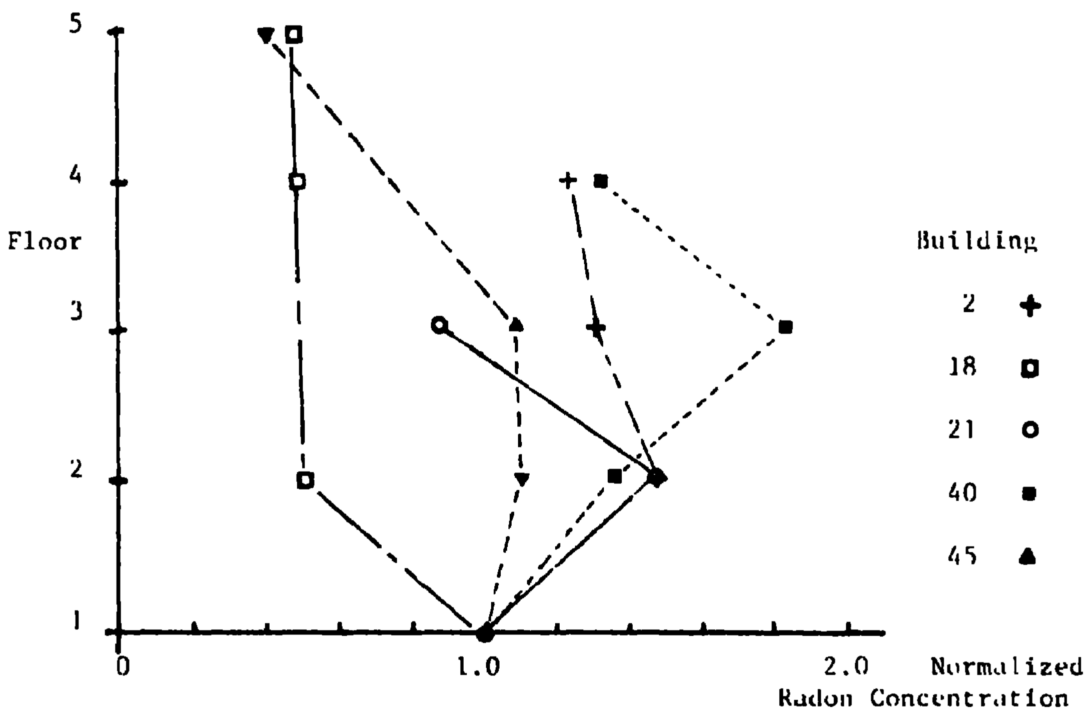

Figure 2. Radon concentration vs elevation in 5 large buildings.

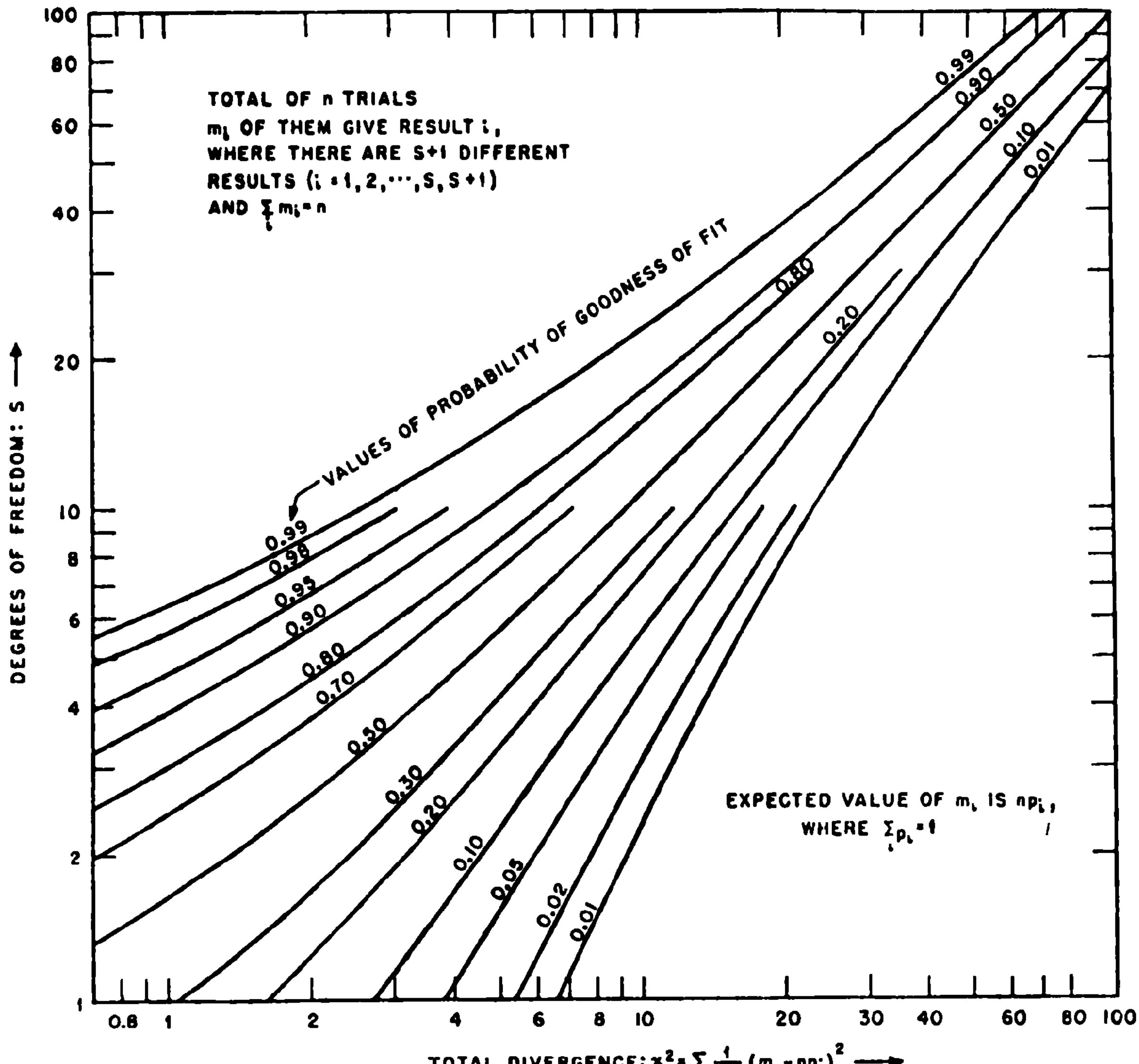

Figure 3. Contours of probability for goodness of fit. (9)

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