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THE INFLUENCES OF HVAC DESIGN AND OPERATION ON RADON MITIGATION OF EXISTING SCHOOL BUILDINGS

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ABSTRACT

A number of public school buildings in Maryland and Virginia have been qualitatively surveyed to assess the various school characteristics that may influence radon entry and potentially impact radon mitigation system design and performance. Results indicate that one of the most significant factors contributing to elevated radon levels in schools is room depressurization caused by the HVAC system exhausting more air from a room than the supply fan is furnishing to the room. Conversely, if the HVAC system pressurizes the room, radon entry can often be prevented as long as the fan is operating.

Four Maryland schools with varying types of HVAC systems have had mitigation systems installed to reduce elevated levels of indoor radon. Mitigation techniques include depressurization of the area under the slab (sometimes accompanied by the sealing of cracks and holes), and the temporary reduction of radon levels by pressure control through the HVAC system. These systems were effectively reducing radon levels following their installation during the summer of 1988, and fall charcoal canister measurements made in a few of the schools showed continued system effectiveness. The radon levels in these schools are now being monitored to assess system performance during the 1988-89 heating season.

This paper discusses the various school characteristics identified as influencing radon entry, the design and operation of the installed mitigation systems in four schools, and the success of these systems in reducing school radon levels.

INTRODUCTION

In late 1987, radon levels exceeding the Environmental Protection Agency (EPA) guideline of 4 picocuries per liter (pCi/L, 1 pCi/L = 37 Bq/m^3) were identified in several rooms of a school in Fairfax County, VA. This led to extensive radon measurements in schools in Fairfax County in addition to other counties in Virginia and Maryland. More than 30 schools in these counties were visited by the EPA and, based on previous work on radon mitigation in houses, school characteristics that potentially influence radon entry and impact mitigation system design and performance were identified. Mitigation systems were then installed in several of these schools by school personnel with some assistance from the EPA and an experienced radon diagnostician. The details of the mitigation systems installed in four of the Maryland schools are discussed.

Although these schools may not represent the most challenging aspects of school radon mitigation, they do represent the successful application of subslab depressurization, a well-established radon mitigation technique for houses. In addition to subslab depressurization, sealing of suspected radon entry routes and pressure control through the heating, ventilating, and air-conditioning (HVAC) systems were studied in a few of these schools. These mitigation approaches are aimed at preventing radon entry into the schools; consequently, the health concerns associated with exposure to radon daughters are not addressed.

The paper is organized into two parts. Part I summarizes the important characteristics relative to radon entry in schools, and Part II discusses case studies of mitigation systems installed in four schools.

IMPORTANT SCHOOL CHARACTERISTICS RELATIVE TO RADON

To identify and better understand the various characteristics that may influence radon entry into schools and to develop a testing program to efficiently and effectively study various radon control options for schools, more than 30 schools were visited. These schools were inspected in cooperation with the directors of facilities maintenance in Fairfax County in Virginia, and Prince Georges, Montgomery, and Washington counties in Maryland. To confirm, quantify, and develop a better understanding of the characteristics common to schools throughout the U.S., the study will eventually be expanded to characterize a larger number of schools in many geographic areas. It is anticipated that this information will also be applicable to many other similar structures such as office buildings, retail establishments, and public buildings should they require radon mitigation. The information collected thus far has already been useful in providing school districts with guidance on radon-resistant new construction.

If elevated levels of radon are present in the soils beneath a school, characteristics such as HVAC system design and operation, substructure type, building size and configuration, and location of utilities can influence indoor radon levels and consequently impact mitigation system design and performance. The interaction between these characteristics and radon entry and mitigation is discussed below.

HVAC SYSTEMS

The size and complexity of large building HVAC systems is a problem not previously encountered in mitigation of houses. In fact, a significant factor contributing to elevated levels of radon in schools is building or room depressurization caused by the HVAC system. If the HVAC system induces a negative pressure in the building relative to the subslab area, radon in the soil gas can be pulled into the building through floor and wall cracks or other openings in contact with the soil. Similarly, the natural stack effect can also cause radon-containing soil gas to be pulled into the school. If the HVAC system pressurizes the building (a common finding in properly designed and operated systems), it can prevent soil

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gas entry as long as the air-circulating fan is running. However, school HVAC systems are frequently set back or turned off during evenings and weekends, and indoor radon levels can build up during these periods.

In a single-fan system, the air is supplied to the rooms (under pressure) by the air-handling fan, and the return air is pulled back by the same fan. A separate exhaust system may exist or air may exfiltrate due to overpressurization by the supply fan. While operating, a single-fan system can pressurize the school and help reduce radon entry.

Larger air-handling systems often have two fans: a supply fan and a smaller return fan. If the return fan pulls more air from any room than the supply fan is furnishing, the room can be under a negative pressure relative to the subslab area, causing soil gas to enter the room through openings to the soil beneath the slab. Consequently, proper balance is imperative in a two-fan system.

Air-handling systems normally have provision for fresh air intake; however, due to increased energy costs, these systems are not always operated. Older schools sometimes have no mechanical ventilation system. In some schools with either individual unit ventilators in each classroom or with radiant heat systems, ventilation is accomplished only by exhausting air. If the air is exhausted with power fans, the rooms are frequently found to be under significant negative pressure relative to the subslab area, greatly increasing the potential for radon entry. In one of the schools visited that had unit ventilators for HVAC, the fresh air intake in at least one room was open to the soil in the concrete block walls, allowing easy soil gas entry through the unit ventilator.

The air return system can also cause significant depressurization and, consequently, contribute to elevated radon levels. The drop ceiling over the hall, commonly referred to as a plenum, is frequently used for air return with no return ducting. As a result, the entire ceiling plenum is under negative pressure relative to the subslab area. Many of the block walls intersecting the plenum also penetrate the slab and rest on footings under the slab. Radon-containing soil gas under the slab may travel up through the core of the block wall to the return air system in the ceiling plenum and be distributed throughout the building by the air-handling system.

Although most observed return air systems are overhead, a number of systems have air returns under the slab. If the surrounding soil contains elevated radon concentrations, this will create a very difficult mitigation problem, since soil gas will be drawn into the ducts and be distributed throughout the building. Since the discovery of elevated indoor radon levels, 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 increase indoor radon concentrations.

SUBSTRUCTURE TYPES AND BUILDING SIZE AND CONFIGURATION

Construction plans of 10 of the slab-on-grade schools—the most prevalent substructure of the schools profiled to date—were examined: all showed aggregate under the slab. As a result, it should be possible to mitigate these schools using subslab depressurization, a radon-reduction technique proven successful in many residences. However, it is anticipated that older schools may not always have aggregate under the slab. Where this is the case, problems will arise for mitigation using subslab depressurization, and other mitigation approaches may be necessary.

Since schools are commonly much larger than houses, they often have interior footings and subslab foundations that can reduce airflow between areas. The location of these subslab barriers will depend on the configuration of the building, and foundation plans should be carefully examined for siting of subslab depressurization points.

OTHER FACTORS INFLUENCING RADON ENTRY INTO SCHOOLS

The location of entry points for utility supply lines can also influence radon entry in schools. Supply line locations depend on many factors such as substructure type, HVAC system, and architectural needs or practices. Utility supply lines located overhead should not cause significant radon entry problems, and overhead is the preferred location as far as radon entry is concerned. However, utility penetrations from the subslab or crawl space area to individual rooms are often not completely sealed, leaving openings between the soil and the building interior. This is commonly the case with sanitary sewer lines, where there is potential for radon entry around the commode ring. In some slab-on-grade schools, the utility lines are located in a subslab utility chase that follows most of the perimeter of the building. The chase has many openings to the soil beneath the slab-on-grade and, consequently, can be a potential radon entry route. Risers to unit ventilators frequently pass through unsealed penetrations in the floor so that soil gas in the utility chase can readily enter the rooms. If the surrounding soil has elevated levels of radon, a utility chase could be a major radon entry route in schools. However, future research will address the possibility of using the utility chase as a radon collection chamber for a subslab depressurization system.

As with houses, floor and wall cracks can also be significant radon entry points in schools. Sometimes these entry routes may be difficult to identify. Carpeting, for example, may conceal cracks in a concrete slab. If the building is under negative pressure, as discussed in the HVAC Systems section, radon can be pulled into the school through these cracks. Fibrous expansion joints that tend to be widely used in school construction can also serve as radon entry routes.

MITIGATION CASE STUDIES IN SCHOOLS

Following the qualitative assessment of school characteristics relevant to radon entry, mitigation systems were installed in several schools in Maryland and Virginia. Case studies of four of these installations follow.

DATA COLLECTION METHODOLOGY

To assist in understanding radon entry into the schools and to design effective mitigation systems for the schools, continuous data were collected as part of the diagnostic measurements. A portable data monitoring system recorded Julian Day, hour, differential pressure (three sensors), and temperature (four sensors). Radon data were collected with a continuous radon monitor (CRM). There was no interface between the CRM and the data logger, and software was developed so that the CRM and data logger data could be merged in a computer for further analysis. Hourly data averages were computed from sensor readings collected approximately every five seconds. This system allows for approximately two weeks of unattended data storage. Not all of the sensors were used during each experiment, and the positioning of sensors varied according to building size and configuration.

In addition to continuous data, five-minute radon grab samples were occasionally collected with the CRM during visits to the schools. Spot pressure differential measurements with a micromanometer were also made in a few cases when set-up of the data logger was not possible. To determine the coverage of subslab depressurization systems, pressure field extension measurements were sometimes made. One-quarter-inch (in, 1 in = 25.4 mm) holes were drilled at various distances and in various directions from the suction holes, depending on building size and configuration, and the resulting test hole pressure measured with a micromanometer. Radon grab samples were occasionally collected through these test holes.

CASE STUDY A: PRINCE GEORGES COUNTY, MD

Radon levels in this school were initially measured in February 1988 with charcoal canisters: one classroom tested above 40 pCi/L, a teachers' lounge tested above 20 pCi/L, and several other classrooms tested between 4 and 20 pCi/L. The building is slab-on-grade construction with a large two-fan air-handling system. The HVAC system had a rated capacity of 51,000 cfm (1 cfm = 0.47 L/s) of air supply and 34,000 cfm of return air. Louvers regulate the amount of fresh air and recycled air in the system. This would result in positive pressure in all rooms if the system were properly balanced. However, continuous radon and pressure measurements indicated that many of the rooms were under negative pressure relative to the subslab area when both the supply and return fans were in operation. As seen in Figure 1, there was a good correlation in all rooms between negative pressure (in the room relative to the hallway) and radon, with the highest radon levels in the rooms with the highest negative pressures.

The room with the highest radon level (usually 10 to 20 pCi/L) typically measured between 0.06 in and 0.08 in negative pressure relative to the subslab. When the return air fan was turned off, the pressure in the room became positive, and radon levels decreased to less than 2 pCi/L. Examination of the air-handling system showed that the air supply fan had been damaged, resulting in a significant capacity loss. As a result, the supply fan was actually supplying less air than the return air fan was removing, causing a negative pressure in many rooms.

This same room with the highest radon level and the highest negative pressure also had a very large floor-to-wall crack along one wall. This particular crack was an expansion joint where two parts of the building were joined. The material in the expansion joint had disintegrated, and the parts appeared to have separated, leaving a 1-in gap between the floor and wall. This gap was concealed by an aluminum angle iron installed when the building was built. When the return fan was operating, initial tests in this room showed a large flow of radon-containing soil gas out of this crack. The radon level was about 500 pCi/L in the soil gas entering the room through the crack, the same measured under the slab in the middle of the room. When the return air fan was turned off and the room was pressurized by the air supply fan, room air flowed into the crack and consequently no soil gas was entering. The pressure in the room relative to the subslab increased to about 0.01 in, and radon levels in the room quickly dropped below 2 pCi/L. The floor-to-wall crack was sealed with backer rod and urethane caulking. This sealing decreased radon levels only slightly when both fans were off, indicating other soil gas entry points in the room.

The influence of HVAC operation on the pressure differential between this room and the subslab area and the resulting radon levels in the room are displayed in Figure 2 for a seven-day period. (The return air louvers were closed during these measurements.) While the HVAC system is operating, the room is at a higher pressure than the subslab area and, consequently, radon entry is reduced. However, when the HVAC system is turned off during night and weekend setback, pressure in the room becomes negative relative to the subslab area and radon levels increase.

As a temporary solution to reduce radon levels, the return air fan was left off and the HVAC system operated with only the air supply fan. Under these conditions, all rooms showed positive pressure and had radon levels below 2 pCi/L during HVAC operation. The damaged supply fan has now been replaced and the air supply and air return systems are being balanced.

As a precaution to reduce radon entry when the air handlers are not operating during night or weekend setback, two fan-assisted subslab depressurization points have been installed. It is anticipated that this will be an effective mitigation system since the school was constructed on 4 in of subslab aggregate. Follow-up testing was initiated during the 1988-89 heating season.

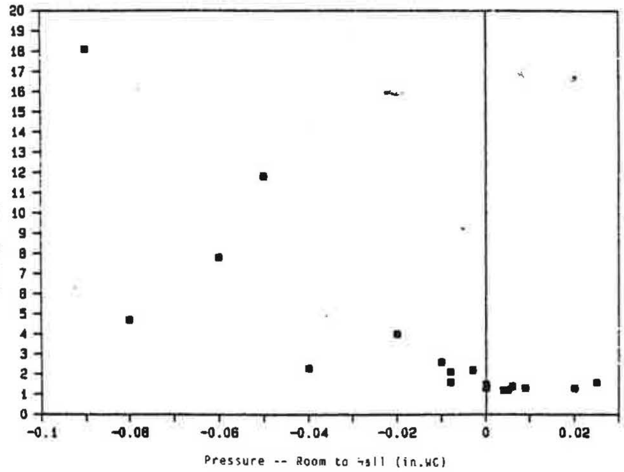

Figure 1 Correlation between room pressure—relative to hall—and radon level (Case Study A)

CASE STUDY B: WASHINGTON COUNTY, MD

This is a small school built on the side of a hill with a walkout basement along the lower side. The unexcavated area is slab-on-grade with the slab extending over the basement area and resting on steel bar joists. The foundation walls are concrete block. The interior wall of the basement supports the end of the bar joists and the slab. This wall is not painted or waterproofed on either side. Building plans specify 4 in of subslab aggregate.

The HVAC system consists of a single-fan system on each floor. A fresh air intake into the return air duct is under negative pressure during fan operation. Pressure measurements indicate that the building is under positive pressure even when the fresh air intake is set for minimum supply. However, since the HVAC system is normally set to run only when heating or cooling is required, the system may not operate during mild weather. In addition, the temperature in the below-grade part of the school is often buffered and, consequently, the basement HVAC system does not run as often as the upstairs system.

Radon levels in all rooms were measured with charcoal canisters over a weekend in May 1988 with air handlers off. Measurements ranged from 78 to 82 pCi/L in the basement and from 18 to 33 pCi/L on the first floor. Subslab and block wall grab samples measured as high as 1500 pCi/L.

Continuous radon measurements were made on both floors of the school during all phases of mitigation. Before mitigation, radon levels rose dramatically at night if the air handlers were off but did not rise during continuous operation. Pressure measurements indicated that operation of the air handlers produced a slight positive pressure in the building relative to the subslab area, thus reducing soil gas entry. In the hottest part of the summer, radon levels rose dramatically overnight when the air handlers were off. It is suspected that a night stack effect resulted since the hot inside daytime temperatures did not decrease as rapidly at night as the outdoor temperature. Overnight levels as high as 150 pCi/L were reached in the basement and levels as high as 100 pCi/L were reached on the first floor when the air-handling fans were off during hot weather. Continuous operation of the HVAC reduced radon levels to less than 4 pCi/L within an hour.

As a temporary solution, the HVAC system was run continuously while the school was occupied. For a permanent solution, subslab depressurization points were installed in phases in both the basement and on the first floor. Due to the high radon levels and complex foundation, it was anticipated that several suction points would be needed.

A 1-ft-diameter (0.305 m) subslab suction pit was installed in the basement with a 4-in-diameter pipe, and radon reduction was about 50% with the subslab pressure field extending less than 30 ft. The suction pit was excavated further to a diameter of about 3 ft with an additional decrease in radon levels and an increase in pressure field extension. The suction fan was replaced with a larger fan, resulting in additional reductions in radon levels. This also increased pressure field extension to 40 ft. This basement suction point also caused some measurable depressurization under the first floor slab, indicating some communication between the slabs.

To evaluate the effectiveness of the single-point subslab suction system in this school and to investigate the effects of the single-fan HVAC system on mitigation performance, Figure 3 shows radon and pressure measurements in the school over a 10-day period. The first-floor single-fan HVAC system was operated continuously during the school week to reduce radon levels while the school was in session on the first floor. Since the basement was unoccupied during the monitoring period, the basement HVAC system was not operated. Over the weekend (day 156), the HVAC system and the single-

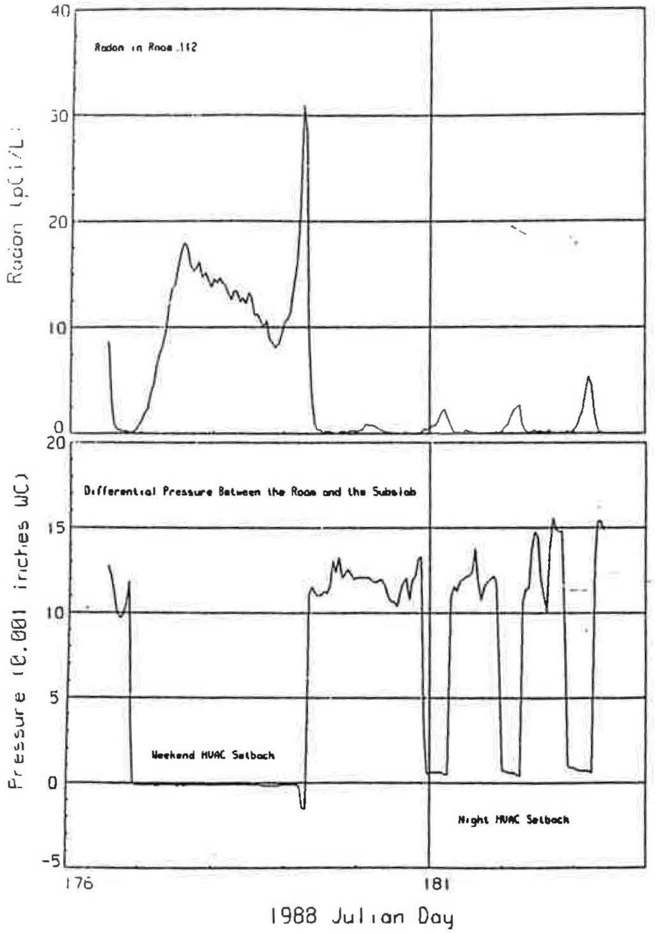

Figure 2 Influence of HVAC operation on radon levels (Case Study A)

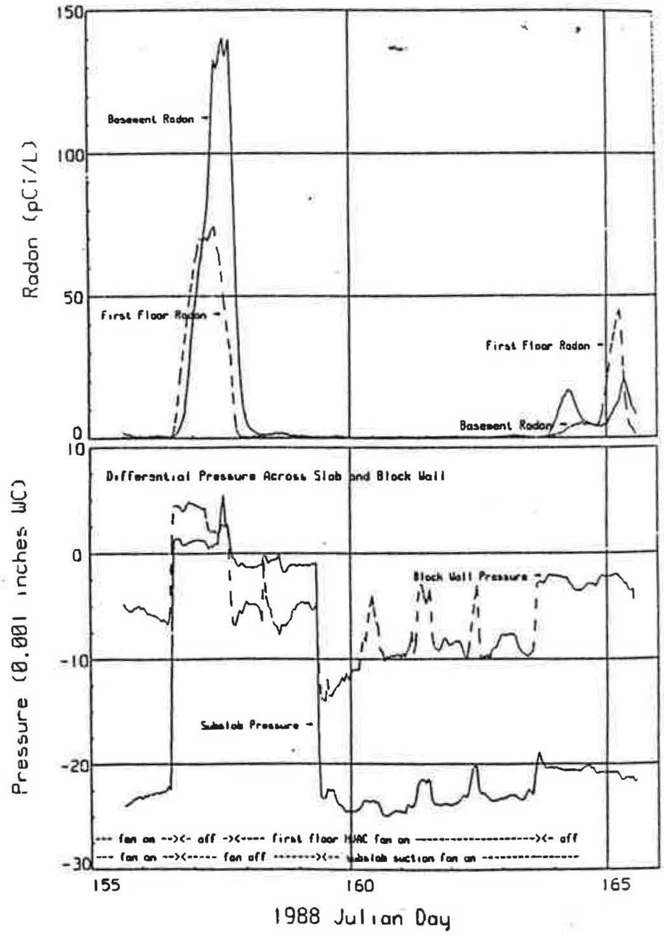

Figure 3 Influence of HVAC operation and single-point subslab depressurization on radon levels and pressure (Case Study B)

point subslab suction system on the first floor were turned off, and the radon levels rose quickly to more than 70 pCi/L on the first floor and 140 pCi/L in the basement. On day 157 the subslab suction system remained off, but the first-floor HVAC system was turned on. Radon levels on both floors dropped, and the differential pressure under the slab and within the block wall became slightly negative relative to the room. On days 158-163, both the HVAC system and subslab suction system were operating, and radon levels remained low. On days 164 and 165, the subslab suction system was operated and the first-floor HVAC system was off. This resulted in an increase of first-floor radon levels to 40 pCi/L, indicating that one suction point was not adequate if the HVAC system was not operating.

To ensure acceptable radon levels on the first floor while the HVAC system was not in operation, another suction point with a 3-ft-diameter suction pit was installed on the first floor. Addition of this suction point reduced levels on the first floor although radon levels on both floors still rose above 10 pCi/L at night with the HVAC system off.

Pressure field extension measurements made with these two suction points operating indicated incomplete coverage of both floors. Consequently, two additional suction points with 1-ft-diameter suction pits were installed in the basement, and a fifth suction point with a 1-ft-diameter suction pit was installed on the first floor.

Nine pressure field extension measurements showed overlapping fields between suction points in the basement area, indicating that all of the basement subslab was adequately depressurized. Basement radon levels measured less than 2 pCi/L with the air handlers off and the mitigation systems operating; however, first-floor radon levels still rose above 4 pCi/L at night with the air handlers off.

Based on mapping of subslab radon levels in more than 20 test holes on the first floor, three additional suction points were installed, each with a 6-in-diameter pipe and a 1-ft-diameter subslab suction pit. Two points were manifolded to a single fan, and a separate fan was installed on the other suction point. After installation of these last three suction points, radon levels stayed below 4 pCi/L on both floors, except for occasional brief excursions at night. A larger fan was installed, and this appears to be reducing radon levels satisfactorily. More than 10 pressure field extension measurements made on the first floor showed little variation in the short-term when the first-floor HVAC system was turned off. This indicates that the present system is achieving adequate coverage even when the HVAC fan is not operating.

Although subslab suction was effective in solving a serious radon problem at this school, it was surprising that it took eight suction points. Aggregate under the slab was confirmed visually at every suction point; however, the aggregate used was probably unscreened "crusher run" containing a great deal of fines. This tends to confirm the belief that screened, coarse aggregate (3/4 to 1 1/4 in), essentially free of any material less than 1/4 in diameter, is preferred for optimal operation of subslab depressurization systems.

CASE STUDY C: WASHINGTON COUNTY, MD

This entire school building is slab-on-grade with block walls and no utilities below grade except sanitary sewers. The original building was constructed in 1956 and has four area air handlers for heating and ventilating with a central boiler room. A classroom wing was added in 1968 and unit ventilators are in each room. None of the building is air-conditioned. Construction plans specified 4 in of subslab aggregate under the entire building. Elevated radon levels were found in the locker rooms on each side of the gymnasium in the original building and in the new classroom wing. Mitigation of each of these areas is discussed separately.

Original Building—Locker Room Mitigation

Although the locker rooms and gymnasium are on the same air handler, the gymnasium measured 2 pCi/L; the girls' locker room, 5 to 6 pCi/L; and the boys' locker room, 5 to 19 pCi/L. Further examination indicated that each locker room area had large exhaust fans to remove odors and shower steam. Differential pressure measurements (using a micromanometer) with the air handler and exhaust fans operating correlated with the radon levels showing that the gymnasium was slightly positive, the girls' locker room area slightly negative, and the boys' locker room area significantly negative.

Construction plans showed that each locker room area was a continuous slab over aggregate. As a result, a subslab suction point, using a 6-in pipe, was placed in each locker room area with a 1-ft-diameter suction pit. Both locker room areas measured less than 4 pCi/L with the exhaust fans and the subslab depressurization systems operating, indicating that the subslab suction systems effectively overcame the negative pressures caused by the exhaust fans.

New Classroom Wing

Weekend charcoal canister measurements were made in April 1988 in this wing with the unit ventilators off. All but one room measured above 4 pCi/L: a room in the northeast corner measured 27 pCi/L. Levels decreased from north to south in this wing, as did subslab radon levels. A CRM was placed in the room with the highest radon levels. When the unit ventilator was off, levels above 20 pCi/L were reached nightly but remained below 2 pCi/L when the unit ventilator was run continuously. Pressure measurements with a micromanometer confirmed that the unit ventilator was pressurizing the room slightly.

Since the unit ventilators are off at night (except in extremely cold weather, when they are cycled), it was decided to install two subslab depressurization points in the wing. These 4-in suction pipes were installed in the hall and manifolded with an above-ceiling 6-in pipe running to a fan at the north end of the building. One suction point was installed with a 3-ft-diameter suction pit about 20 ft from the east end of the hall and the other suction point was installed with a 1-ft-diameter suction pit about 40 ft west of the first point. Pressure field extension measurements indicated that the two fields overlapped, and all of the wing was depressurized to the outside walls except for the southernmost classrooms.

Since the pressure field extension around the 1-ft-diameter suction pit was not as great as around the 3-ft-diameter suction pit, the 1-ft-diameter suction pit was increased to 3 ft in diameter. This extended the measurable depressurization area by 10 ft to the south (enough to reach the last two classrooms) and about doubled the amount of depressurization in the test holes in all directions around the suction point. With the subslab depressurization system operating and the unit ventilator fans off, radon levels were less than 4 pCi/L in all classrooms.

CASE STUDY D: WASHINGTON COUNTY, MD

The original building of this school was built in 1958 and is heated with hot water radiant heat in the slab. In 1978 a kindergarten room was added to the original building, and a separate building (referred to as Building B) was built, containing four classrooms, a library, a teachers' workroom, a conference room, and restrooms. The kindergarten room is heated with hot water radiant heat, and the new building is heated with unit ventilators. Office space in the original building is air-conditioned with a window unit. No other area of either building is air-conditioned.

The original building has two 3600-cfm roof-mounted fans that could be used to exhaust air in plenums over the hall ceiling. Each room has a ceiling vent connecting to these hall plenums. However, the exhaust fans are never used. Consequently, the building has no active ventilation system. Plans showed that the original building had 6 in of aggregate under a 6-in-thick slab (containing hot water pipes) and Building B had 4 in of aggregate under a 4-in slab.

All rooms in both buildings were tested with charcoal canisters over a weekend in mid-April 1988. The eight rooms in Building B measured between 17 and 20 pCi/L. It is believed that the unit ventilators were off during the testing weekend, but this could not be confirmed. Seven tests in the classrooms, library, and multi-purpose room in the original building measured between 12 and 23 pCi/L. Mitigation of the two buildings is discussed separately.

Building B (Unit Ventilators)

A CRM was placed in one of the classrooms in Building B to measure the effects of unit ventilator operation on radon entry. It was found that radon levels would rise overnight to more than 20 pCi/L with the ventilator off but would remain below 2 pCi/L with the ventilators on. Again, this shows that this type of ventilator can pressurize the room slightly, preventing radon entry when run continuously.

Since the ventilators are off during night setback, a four-point subslab depressurization system was installed. Four 4-in-diameter pipes were connected to two 6-in manifold pipes above the drop ceiling with a common suction fan. (Two vertical pipes are manifolded to each overhead pipe.) Pressure field extension measurements indicated that depressurization extended 50 ft, the minimum distance necessary to reach all parts of the slab.

With the subslab system operating and the unit ventilators off, all rooms remained below 4 pCi/L. However, based on the pressure field extension measurements, the system may be marginal during cold weather. If radon levels rise above 4 pCi/L, it is believed that subslab depressurization can be improved by sealing the floor-to-wall opening. (One-half-in expansion joints around all of the slabs in the building are deteriorating, leaving significant openings to the subslab. This probably leads to some short-circuiting of the subslab depressurization system.)

Original Building (Intra-Slab Radiant Heat)

Subslab suction on this intra-slab radiant-heated building was a challenge since construction plans showed that the hot water pipes in the slab were 15 in or less apart over the entire building. As a result, it was difficult to locate an area where a 6-in subslab suction point could be placed without damaging a hot water pipe. A 3-ft-square area without water pipes was finally located in each room. A hole was successfully cut through one of these areas. The plans indicated that the aggregate was a minimum of 6 in deep, much deeper than at any other school examined. A 6-in-diameter suction pipe was installed with a 3-ft-diameter pit. Pressure field extension was far greater than expected, and depressurization could be measured as far as 90 ft from the suction hole. These results were surprising since the aggregate appeared to be some type of "crusher run" aggregate with a certain amount of fines. However, in leveling the aggregate before pouring the concrete, it is probable that most of the fines had sifted to the lower portion of the aggregate bed, leaving a fairly thick area of large-diameter aggregate immediately under the concrete. It is believed that this layer of coarse stone made for a much greater pressure field extension and will be studied further. Preliminary follow-up tests indicate that this one suction point will solve the radon problem in the original building.

To analyze the effectiveness of a single-point subslab suction system and to investigate the pressures that control radon levels in schools during hot weather, radon, pressure, and temperature were monitored continuously in one classroom, as shown in Figure 4. The classrooms were kept closed during this period of very hot weather, and there is no ventilation system in this building. When the subslab suction system was turned off from day 222 through day 225, the radon levels quickly rose and followed a diurnal cycle that seems to match the temperature cycle. When the outdoor temperature was coolest relative to indoor temperature, the radon levels were highest. This can be expected from the stack effect, as discussed in Case Study B. Although a small positive pressure was measured across the slab during this period, it does not show significant diurnal variation. The differential pressure across an outside classroom wall does not show much correlation with the radon levels, except for a sharp dip in the middle of day 224 that may be due to wind.

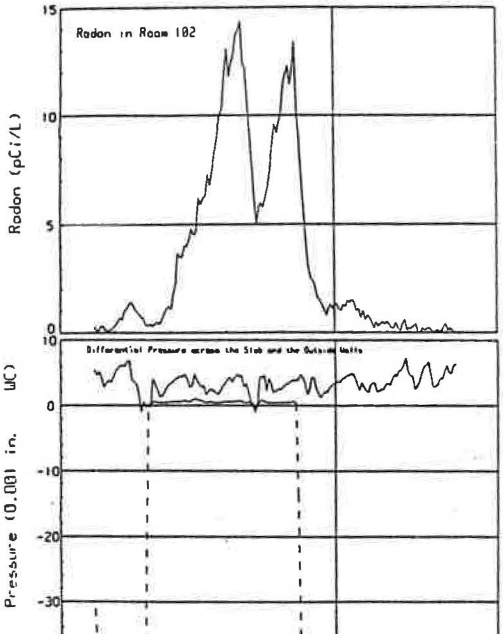

Figure 4 Effect of single-point subslab depressurization on radon levels (Case Study D)

Kindergarten Room

Since the kindergarten room is an addition, the subslab area does not communicate with the original building. Consequently, a suction point was put in a closet adjacent to a restroom where the hot water pipes were spaced 24 in apart to clear the sewer line of the commode. This suction point lowered radon levels to less than 2 pCi/L. No pressure field extension measurements were made for fear of damaging a heating water pipe.

CONCLUSIONS

The following tentative conclusions can be drawn from the EPA's experience in assisting in the installation of radon mitigation systems in Maryland schools. These tentative conclusions are based on limited studies and will be verified and expanded with further research.

1. One of the most significant factors contributing to elevated levels of radon in schools and influencing the mitigation approach is the design and operation of the HVAC system. The complexities of large building HVAC systems present problems not previously encountered in house mitigation.
2. Pressure control through continuous HVAC fan operation can often be an effective temporary solution to reduce elevated radon levels in schools, depending on HVAC system design. Whether such a technique is a feasible long-term solution depends on factors such as the proper operation of the system by maintenance personnel, variations in outside environmental conditions, and any additional maintainance costs and energy penalties associated with increased operation of the HVAC system.
3. A subslab depressurization system can usually overcome negative pressures induced by HVAC operation in schools if there are no return air ducts under the slabs. As with houses, subslab depressurization is more successful (and requires fewer suction points) when the slab is poured over clean, coarse aggregate.
4. Effective mitigation of schools using subslab depressurization requires greater fan capacities and suction pipe diameters than does mitigation of houses. The capacities of the fans used in these school installations were typically at least 300 cfm (at 0.75 in WC) compared to capacities of about 150 cfm (at 0.75 in WC) for fans commonly installed in house subslab depressurization systems. Suction pipe diameters of 4 in to 6 in often proved successful in these installations, compared to pipe diameters of 4 in or less typically used in houses.

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DISCUSSION

Carl N. Lawson, LRW Engineers, Tampa, FL: In any of your school work, have you studied any multi-level projects? If so, what were the results?

K.W. Leovic, U.S. EPA, Research Triangle Park, NC: The only multi-level school we studied was a basement/slab-on-grade school (where the basement was used for classroom space). This is in case study B.

We have not yet studied any other multi-level schools. Controlling radon entry at the lowest level in contact with the soil—and ensuring that the HVAC system does not distribute radon to upper levels—will probably be the best approach.

Marian Heyman, Hartford Steam Boiler Inspection and Insurance Co., Hartford, CT: Are there any guidelines and/or recommendations for testing floors higher than basement/first floors for radon in schools? The question is asked in light of recommendations to test the second floor of homes, especially homes using wellwater. Radon aerosolized through water taps and showerheads can contribute significantly to radon concentrations in a home. Can any of this information be applied in schools?

Leovic: Current EPA guidelines, "Radon Measurements in Schools—An Interim Report," recommend that measurements be made in all rooms frequently used on or below the grade level. Since schools tend to use public water supplies, rather than private wells, radon in water will probably be less applicable in schools than in residential housing.