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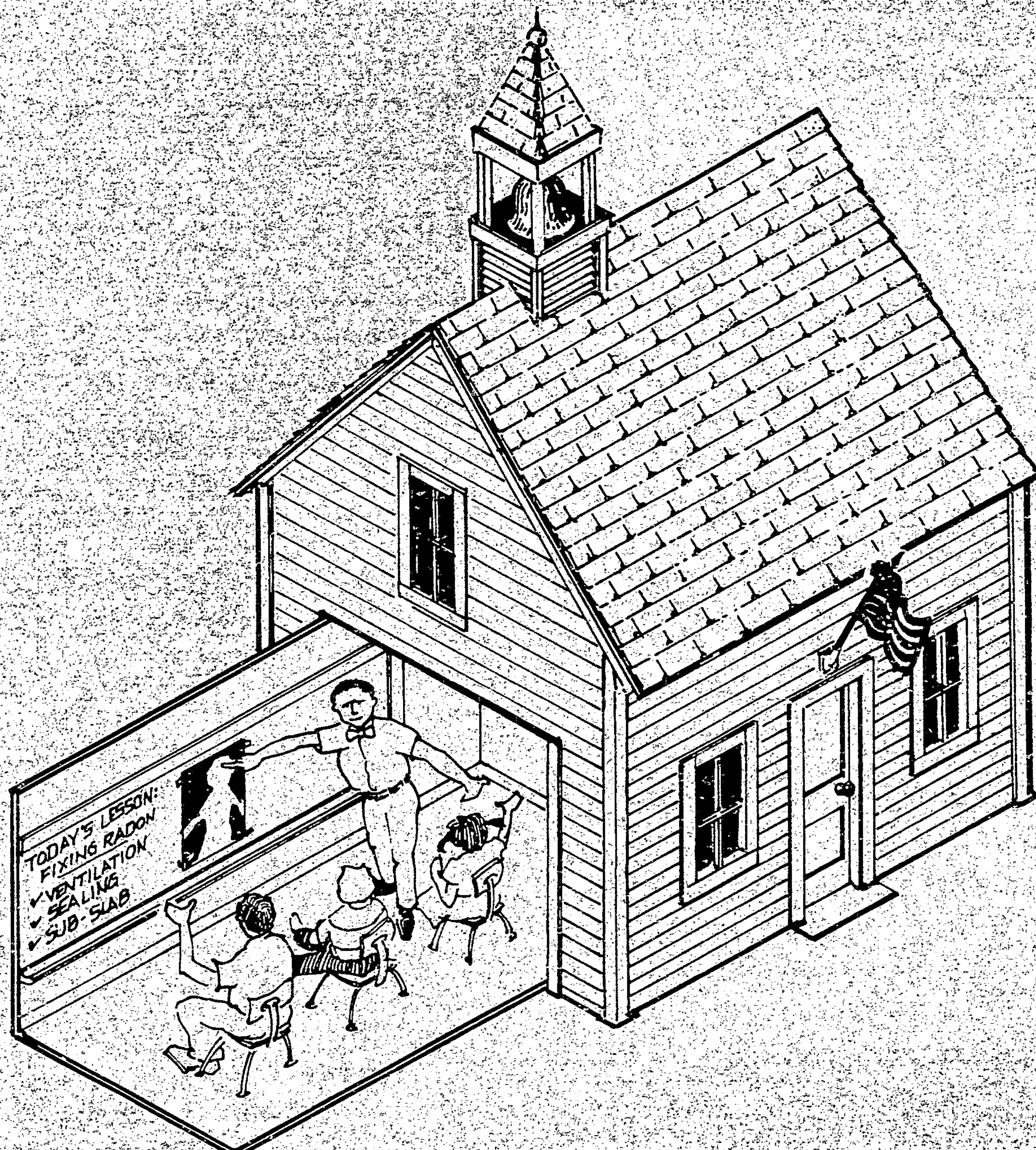
RADON REDUCTION TECHNIQUES IN SCHOOLS

Interim Technical Guidance



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Office of Air and Radiation
and
Air and Energy Engineering Research Laboratory
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1. INTRODUCTION

1.1 PURPOSE

This technical document is intended to assist school facilities maintenance personnel, State officials, and other interested persons in the selection, design, and operation of radon reduction systems in schools. School officials should work in conjunction with a person experienced in radon mitigation, preferably in schools, to diagnose the problem and determine which mitigation options are feasible. School officials can contact their State Radon Office or EPA Regional Office for guidance on selecting a qualified radon mitigation contractor. (See Appendix C.)

The guidance contained in this document is based largely on research conducted in 1987 and 1988 in schools located in Maryland and Virginia. In these initial efforts, researchers from the U.S. Environmental Protection Agency (EPA) adapted radon reduction techniques proven successful in residential housing and installed them in eight schools. Results indicate that radon mitigation and diagnostic techniques developed for houses can be applied successfully in these schools. The applicability of these mitigation approaches to other schools will depend on the unique characteristics of each school.

Because school design, construction, and operation patterns vary considerably, it is not always possible to recommend "standard" corrective actions that apply to all schools. Costs for radon reduction will also be school specific and will depend on the initial radon level, the extent of the radon problem in the school, the school design and construction, the design and operation of the heating, ventilating, and air-conditioning (HVAC) system, and the ability of the school maintenance personnel to participate in the diagnosis and mitigation of the radon problem. With the guidance of an experienced radon mitigator, maintenance personnel may be able to install radon reduction systems themselves.

This technical document covers background information on radon and radon mitigation experience, important school building characteristics relative to radon entry and mitigation, problem analysis, radon diagnostic testing, and radon mitigation system design and installation. Appendices include technical information, case studies of the Maryland and Virginia schools mitigated, and lists of State Radon Offices and EPA Regional Radiation Program Offices.

It is important to understand that this is preliminary guidance. A major research program is under way in the Air and Energy Engineering Research Laboratory in EPA's Office of Research and Development, and guidance on recommended radon reduction actions for schools will be updated as soon as possible.

1.2 ADDITIONAL SOURCES OF INFORMATION

The publications listed below are available from State Radon Offices or from EPA Regional Offices. (See Appendix C.)

PUBLICATIONS ON RADON IN SCHOOLS

For guidance on how to measure radon levels in schools, you should consult "Radon Measurements in Schools - An Interim Report" (EPA 520/1-89-010).

OTHER PUBLICATIONS ON RADON

EPA has been studying the effectiveness of various methods of reducing radon concentrations in houses. Although this work is not yet complete, considerable progress has been made over the last several years, and a number of EPA publications have been issued. A general familiarity with these publications on radon reduction in houses will be useful in understanding and reducing elevated radon levels in school buildings.

"A Citizen's Guide to Radon: What It Is And What To Do About It" (EPA OPA-86-004) provides general background information for the homeowner on radon and its associated health risks. It should be noted that this guide is being updated, and the next edition should be available in mid-1990.

"Radon Reduction Methods: A Homeowner's Guide" (Second and Third Editions) (OPA-87-010 and OPA-89-010) describe in general terms the various radon reduction methods available to homeowners.

"Radon Reduction Techniques for Detached Houses: Technical Guidance" (Second Edition) (EPA/625/5-87/019) is a reference manual providing information on the sources of radon and its health effects as well as detailed guidance on the selection, design, installation, and operation of radon reduction systems.

"Application of Radon Reduction Methods" (EPA/625/5-88/024) supplements the second edition of the technical manual (above) as a decision guidance document directing the user through the steps of diagnosing a radon problem and selecting a radon reduction approach. Mitigation system design, installation, and operation are also detailed.

"Radon Reduction in New Construction, An Interim Guide" (EPA OPA-87-009) and "Radon-Resistant Residential New Construction" (EPA-600/8-88-087) provide information on radon prevention techniques for new construction.

1.3 RADON FACTS

1.3.1 Radon Gas

Radon is a colorless, odorless, and tasteless radioactive gas which results from the decay of uranium. Since uranium occurs naturally in small quantities in most rocks and soil, radon is continually released into soil gas, underground water, and outdoor air. Radon is chemically inert, and it moves freely without combining with other materials. In outdoor air the radon emitted from the soil is quickly diluted to very low concentrations. However, relatively high concentrations of radon can accumulate inside buildings if radon-containing soil gas infiltrates into the building through openings such as cracks, building joints, and utility penetrations. Normal building ventilation may dilute the incoming radon gas, but depending on the soil gas radon levels and the amount of soil gas entry, the radon concentration in the building may accumulate to high levels. Since radon source strengths vary and radon entry routes are so unpredictable, testing each building is the only practical way to determine the extent of the problem.

EPA currently recommends taking action to reduce radon levels in homes where the annual average concentration of radon exceeds 4 picocuries per liter (pCi/L). (As a comparison, average outdoor radon concentrations tend to range from about 0.1 to 0.2 pCi/L.) The greater the reduction in radon, the greater the reduction in health risk. Consequently, an effort should be made to reduce radon levels in all buildings as far below 4 pCi/L as possible. It should also be noted that the 1988 Indoor Radon Abatement Act establishes as a national long-term goal that the air within buildings be as free of radon as the air outside of the buildings.

1.3.2 Health Effects

Radon differs from most other carcinogens in that human epidemiological evidence links radon to lung cancer, and this evidence is well supported by laboratory studies and experimental research. Although uncertainties remain and considerable research is continuing in this field, the health risks of radon have been clearly recognized by the National Academy of Sciences, the U. S. Public Health Service, and EPA.

Lung cancer is the only health risk which significant data clearly associate with radon. Radon gas decays into other radioactive elements (often referred to as radon decay products or radon progeny) which can lodge in the lungs. Bombardment of sensitive lung tissue by alpha radiation released from the decay products can increase the risk of lung cancer. It is estimated that radon causes roughly 20,000 lung cancers each year in the United States.

It should be emphasized that estimates of the number of lung cancers resulting from radon vary widely, but even the lowest estimate represents the largest cause of lung cancer for non-smokers. Not everyone exposed to elevated levels of radon will develop lung cancer. However, most scientists believe that children are at an equal or greater risk from exposure to radon than adults and that smokers are at a greater risk from exposure to radon than nonsmokers. There is also consensus among scientists that the risk of developing lung cancer increases as the concentration and length of exposure increase.

2. RADON MITIGATION

Since 1984, when elevated levels of indoor radon were discovered in the Reading Prong area of Pennsylvania, many thousands of houses have had radon reduction systems installed. In many areas of the United States, it is not uncommon to find a contractor with house mitigation experience. In fact, many states maintain lists of radon mitigation contractors. (See Appendix C for a list of State Radon Offices.)

Radon mitigation experience in schools is relatively recent. However, initial research indicates that radon reduction technologies proven successful in houses are applicable to some schools. The applicability of these mitigation approaches to other schools will depend on the unique characteristics of each school.

2.1 RADON ENTRY

Radon normally enters a building 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 and radon is present in the soil, the 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, and the number and size of the radon entry routes.

2.1.1 Causes of Pressure Differentials

Pressure differentials that contribute to radon entry can result from operation of an 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 much greater impact on radon levels than do heating and air conditioning systems in houses. 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, thermal stack effects can induce localized negative pressure at the base of the building causing radon-containing soil gas to be pulled into the school. As air inside the structure is heated, it becomes less dense, and rises, exiting out through openings in the top of the structure. Cooler air is drawn into the building to replace the warm air leaving at the top of the structure. This phenomenom, which acts much like a chimney, is referred to as the stack effect.

If the HVAC system pressurizes the building, which is common 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 adequately reduced. Adjustment of the setback timing may, in some cases, achieve acceptable indoor radon levels during periods of occupancy. Measurements with continuous radon monitoring equipment in each classroom with elevated radon levels are necessary to determine the appropriate setback configuration in such situations.

2.1.2 Radon Entry Routes

Typical radon entry routes include cracks in the slabs and walls, floor/wall joints, porous concrete block walls, open sump pits, and openings around utility penetrations. Radon accumulated in crawl spaces may also enter a building. In addition, many schools have other radon entry points such as slab pour joints (control joints) and subslab utility tunnels. These are discussed in more detail in Section 4.3, Location of Utility Lines.

In houses, radon problems caused by radon emanations from building materials or by radon released from radon-contaminated water (normally well water) occur in isolated instances. We would expect few schools to have this type of radon problem.

2.2 RADON VARIATIONS WITHIN SCHOOLS

Experience has shown that there can be large differences between radon levels in classrooms on the same floor. Causes for these room-to-room differences are thought to include variations in the soil under the class rooms, variations in the construction between rooms, variations in the number and size of cracks in different rooms, and variations in the design and operation of the HVAC system. This room-to-room variability makes it difficult to detect and mitigate all the rooms with high radon levels unless every classroom on or below ground is tested.

2.3 MITIGATION TECHNIQUES

Although the selection of the most appropriate radon mitigation technique depends on the unique characteristics of each building, five mitigation approaches have been common in house mitigation, either alone or in combination. These include: subslab depressurization (SSD), submembrane depressurization (SMD) in crawl space areas, sealing, pressurization, and natural and mechanical ventilation. (For additional details on these and other mitigation techniques for houses, refer to the technical manuals previously referenced.)

These techniques and their applicability to schools are briefly discussed below. Because current radon mitigation experience in schools is largely limited to SSD, this guidance document focuses on that approach. Where available, guidance for other techniques is also given. The reader should review Sections 5 and 6 for more detail.

EPA feels that many of the radon reduction approaches for houses will be applicable to school mitigation, and research is in progress to conduct additional testing of these techniques in school buildings. It should be understood that in many types of schools there is little or no experience in radon mitigation. Examples of schools that may be difficult to mitigate include: schools with poor subslab permeability (explained under SSD); schools with subslab ductwork; schools with exhaust fans to increase fresh-air infiltration (potentially causing large negative pressures and increased radon entry); and schools constructed over crawl spaces.

2.3.1 Subslab Depressurization (SSD)

SSD has been the most successful and widely used radon reduction technique in slab-on-grade and basement houses. Installation of an SSD system involves inserting pipes through the concrete slab to access the crushed rock or soil beneath. A fan is then used to suck radon-containing soil gas from under the slab through the pipes, releasing it outdoors. SSD works by creating a negative pressure field under the slab relative to the building interior; this interior/exterior pressure relationship prevents radon-containing soil gas from entering the building.

The material under the foundation slab must be permeable enough to allow air movement under the slab so that adequate suction can be induced across the entire slab. (Subslab permeability or air flow is often referred to as subslab "communication" or "pressure field extension.") When subslab pressure field extension is inadequate, additional suction pipes may be able to increase the area that can be depressurized.

Initial results indicate that SSD can successfully reduce radon levels in some schools by over 90 percent if crushed aggregate or other permeable material is under the slab to allow for adequate pressure field extension. However, schools with poor subslab communication and those using return-air ductwork beneath the slab may require an alternative mitigation approach to SSD.

2.3.2 Submembrane Depressurization (SMD)

A variation of SSD, often referred to as submembrane depressurization (SMD), has been very successful in reducing radon levels in houses constructed over crawl spaces. A polyethylene or rubber membrane is laid over the earth floor and sealed to the crawl space walls and internal piers. Suction is applied to the soil underneath the membrane and the soil gas is exhausted to the outdoors. EPA has not yet researched this method in schools; however, SMD may prove more difficult in many school crawl spaces because of all the internal foundation walls, the large areas to be treated, and the possible presence of asbestos.

2.3.3 Sealing

The effectiveness of sealing alone as a radon reduction technique is limited by the ability to identify, access, and seal major radon entry routes. Most buildings have so many radon entry routes that sealing only the obvious ones may not result in a significant degree of radon reduction. Complete sealing of all radon entry routes is often impractical. In some buildings, certain areas will be difficult, if not impossible, to access and/or seal without significant expense. In addition, settling foundations and expanding floor cracks continue to open new entry routes and reopen old ones. Typical initial radon reduction from extensive sealing in houses is usually about 50 percent.

2.3.4 Pressurization (Through HVAC System Control)

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. There may also be potential moisture and condensation problems if pressurization is implemented in very cold climates.

2.3.5 Increasing BuildingVentilation (Without HVAC System Control)

An increase in building ventilation rate, by opening lower-level windows, doors, and vents or by blowing outdoor air into the building with a fan, reduces radon levels by diluting indoor air with outdoor air and by minimizing the pressure differentials that draw radon into the building. However, EPA's preferred radon reduction strategy has been to prevent radon entry into buildings, rather than to reduce radon levels once it has entered. Experience has shown that it is usually impractical to lower radon levels in houses much more than 50 percent through increased ventilation. Therefore, in most climates, reducing radon levels through ventilation should only be considered as a temporary measure.

3. ANALYZING THE PROBLEM

Understanding a school radon problem and developing a mitigation strategy involves a careful review of all radon testing data, a walk-through audit, and a review of relevant building documents. Applicable critical building components (as discussed in Section 4) should be examined. These include the building structure, the HVAC system, and the location of utility lines. Special radon diagnostic tests will also be useful. These might include continuous monitoring of radon levels during various building operating conditions, mapping of subslab radon, and measuring subslab communication and pressure field extension to determine if SSD is applicable. Diagnostic tests are discussed in more detail in Section 5. A general outline of the steps involved follows.

STEP 1: REVIEW RADON TEST RESULTS

Write down all radon test results on copies of the school floor plan so that rooms with high readings can be correlated. Test data should include type of measurement device, length of measurement period, HVAC operating conditions, school occupancy, and weather conditions during the test period. In developing a mitigation plan, emphasis should be on the confirmatory measurements rather than the screening measurements, as described in "Radon Measurements in Schools - An Interim Report". (See Section 1.2, Additional Sources of Information.)

STEP 2: WALK-THROUGH AUDIT

Thoroughly examine all parts of the building in contact with the soil. (In a basement school, examine both the basement and first floor.) Note the presence of possible radon entry routes such as floor/wall cracks and other openings to the soil and determine if they correlate with areas having elevated radon levels.

STEP 3: EVALUATE HVAC SYSTEM

Depending on the design and operation of the HVAC system, relatively strong indoor pressures (either positive or negative) can be exerted during system operation. Where possible, obtain a complete description of the HVAC system design and operation from the building facilities personnel and determine if HVAC operation is causing any negative pressures in the building relative to the subslab area. If the original school has any additions, be sure to note if there are different types of HVAC systems, as well as structural differences between the additions. In some cases, consultation with a qualified firm experienced in HVAC system design may be useful in understanding possible sources of HVAC depressurization.

STEP 4: REVIEW BUILDING PLANS

Study the foundation plans and specifications for information on aggregate or gravel beneath the slab, for the layout of footings and subslab walls that could limit subslab communication in an SSD system, and for the presence of subslab ductwork.

STEP 5: CONSULT EXPERIENCED MITIGATORS

School personnel with little experience in radon reduction should use experienced or certified radon mitigation firms to gain the advantage of their experience and specialized knowledge of local problems. These firms may also be able to provide specialized equipment such as continuous radon monitors, core drills, and sensitive pressure gauges. Since radon mitigation in schools is a relatively new field, it is probable that mitigators in many parts of the country will be more experienced in mitigation of houses than schools.

Local and state health departments and EPA regional offices maintain lists of persons who have attended EPA mitigation training courses. Several states have initiated programs for certification of radon mitigation companies, and several trade associations have been offering membership or educational courses for professionals in the field. In 1990, EPA will publish a national list of mitigators who have met the requirements of the Radon Contractor Proficiency Program.

STEP 6: PLAN MITIGATION STRATEGY

Radon mitigation is not an exact science. In schools it is often best to proceed in phases: install the simplest system that promises the biggest payback and re-test to determine effectiveness; then use this information to proceed with subsequent phases, as necessary. The phased approach should be especially helpful in schools because experience is limited and the buildings tend to be more complex than houses. Because we often do not know all the radon entry routes or forces drawing radon into the building, the first phase of mitigation can usually provide valuable information. The following sections cover the critical building components relative to radon entry and mitigation, the design and installation of SSD systems, and other mitigation approaches. The case studies in Appendix B are examples of the phased approach to mitigation.

4. CRITICAL SCHOOL BUILDING COMPONENTS

For help in understanding the causes of elevated radon levels in schools and to better design school mitigation systems, three building components are of primary concern: the building substructure(s), the design and operation of the HVAC system(s), and the location of utility lines. This section discusses how these aspects of school buildings relate to house mitigation experience, how these building components tend to affect radon entry in schools, and how they may impact mitigation system design and operation.

An understanding of these critical building components and how they relate to a specific situation are important when designing a school mitigation system.

4.1 SCHOOL SUBSTRUCTURES

The three basic substructure types are slab-on-grade, basement, and crawl space. The majority of substructures in the school districts studied thus far were slab-on-grade. Schools often have one or more additions, and each addition may have a different type of substructure.

Because of larger building and room sizes, schools often have interior footings and subslab foundation elements. These may create subslab communication barriers between areas. The location of subslab barriers and their influence on subslab communication will depend on building size and configuration, and on architectural preferences for carrying roof load. The locations of these barriers may affect the number and placement of SSD suction points in a slab-on-grade or basement structure, and foundation plans, if available, should always be examined when selecting suction point locations. This increases the opportunity for all areas with elevated radon levels to be adequately treated by the SSD system.

4.1.1 Slab-on-Grade

Since current research indicates that SSD is the most successful technique for reducing radon levels in slab-on-grade schools with good subslab communication, the construction documents should be checked for information on the type and amount of subslab gravel or aggregate. Even if aggregate is specified, the air-flow resistance of different aggregate types has been found to differ significantly. Subslab communication measurements and visual inspections are often necessary to efficiently design an SSD system.

Interior footings and rolled footings (grade beams) may pose substantial barriers to communication between areas; therefore, it is necessary to carefully examine the foundation plans when designing an SSD system. Depending on the type of subslab barrier and the material underneath the barrier (e.g., clay, sand, gravel) there may be limited communication, if any, across these barriers. Often, it may be necessary to locate additional subslab suction points if areas to be mitigated do not communicate across subslab barriers. In other cases, coverage of the SSD system may be increased if a larger fan and/or pipe diameter are used. Evaluation of subslab communication, as discussed in Section 5.2, will indicate the effect that these subslab barriers will have on SSD system design.

4.1.2 Basements

Schools with basements may present a difficult problem because a large area is in contact with the soil. Some school basements are completely below-grade and others are walk-out basements. Walk-out basements are commonly used as classrooms or workspace. Many full basements in older buildings have also been converted to classroom space. Below-grade walls, the slab, and floor/wall cracks can be significant sources of radon entry. If there is adequate subslab communication, SSD is probably the most desirable approach to radon mitigation in most basement schools. All of the comments on SSD systems in the above section on slab-on-grade schools are applicable to basement schools. In addition, any asbestos in the basement should be removed or encapsulated according to the Asbestos Hazard Emergency Response Act

(AHERA) before attempting any radon reduction activities in the basement.

4.1.3 Crawl Spaces

Most crawl space schools tend to be constructed on concrete slabs supported by periphery and internal foundation walls, although schools with conventional wood joist and floor construction over a crawl space and "portable" classrooms do exist. Crawl spaces are usually divided into compartments that are all interconnected by open passages allowing access to utility pipes. To avoid freezing of inadequately insulated pipes, some school crawl spaces have no vents. As a result, high levels of radon may collect in the crawl space. (Elevated levels of radon can accumulate in a vented crawl space as well.)

Increasing natural ventilation by opening crawl space vents may be a possible solution as long as the changes in temperature do not cause problems such as freezing pipes, condensation, or cold floors. Whether this will adequately reduce radon levels will be school specific. Depressurization of the crawl space has been more effective in reducing radon levels in houses than natural ventilation of the crawl space; again, experience in schools has been limited. Submembrane depressurization (SMD) has also been successful in reducing radon levels in houses built on crawl spaces. However, SMD has not yet been researched by EPA in any schools. It is possible that the application of this technique may be difficult in many schools because of the large area to be treated and complicating interior crawl space walls.

More detailed guidance on these approaches for schools will be available following further research. In any case, any asbestos in the crawl space area should be removed or encapsulated according to AHERA before attempting any radon reduction activities in the crawl space.

4.2 HEATING, VENTILATING, AND AIR-CONDITIONING (HVAC) SYSTEMS

Understanding the school's HVAC system often plays an important role in determining the source of, and the solution to, the radon problem. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62-1981R "Ventilation for Acceptable Indoor Air Quality" should be consulted to determine if the installed HVAC system is designed and operated to achieve recommended minimum ventilation standards for indoor air quality. 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. It is advisable to achieve the recommended minimum ventilation standards in a school in conjunction with or in addition to installation of a system for radon reduction. Consultation with a qualified HVAC firm or a registered Professional Engineer experienced in HVAC system design is recommended for evaluating the HVAC system both in terms of radon mitigation options and indoor air quality.

HVAC systems in the school districts initially researched by EPA include: central air-handling systems, room-sized unit ventilators, and radiant heat. Unit ventilators and radiant heat can exist with or without a separate ventilation system. Central air-handling systems and unit ventilators tend to be most prevalent in newer schools, particularly if air-conditioned. Often, because of additions, schools may have more than one type of HVAC system.

4.2.1 Central-Air Handling Systems

In many buildings with air-conditioning, the HVAC system contains some type of central air-handling system. The systems can vary widely in size and configuration, and the different types of systems will tend to have unique effects on radon entry and subsequent mitigation. Three types of central air-handling systems common in schools are summarized below: single-fan systems, dual-fan systems, and exhaust-only systems.

In single-fan systems the air is distributed to the rooms (normally under pressure) by the air-handling fan, and the return air is brought back by the same fan. These systems are similar to forced-air systems in houses, except that fresh air can usually be mixed with the return air. The air-handling fans may operate continuously during the day, or they may operate only when heated or cooled air is required, cycling on and off throughout the day with thermostat control. In any case, the systems are normally set back or turned off during evenings and weekends. These single-fan systems are normally designed to generate neutral or positive pressures in all rooms. In a single-fan system, stale air leaves the building either through a separate exhaust system, by relief, or by exfiltration through cracks and openings due to overpressurization by the fan (if fresh air is brought into the system).

Larger air-handling systems often employ a dual-fan system: an air-distribution fan and a smaller return-air fan. The return-air fan allows for forced exhaust of return air. Louvers regulate the amount of fresh air brought into the air supply and the amount of return air that is exhausted. Dual-fan systems are usually designed so that they generate positive pressures in all rooms when operating; however, if the return-air fan pulls more air from a room than the supply fan is furnishing, then the room can be run under negative pressure causing soil gas to enter the room through openings to the soil beneath the slab. The fans usually operate continuously during the day and are either set back or turned off during evenings and weekends.

Although single- and dual-fan 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.

The third type of central air-handling system is an exhaust-only system in which no supply air is provided mechanically. Such systems are generally used for ventilation in schools that heat with radiant systems or unit ventilators and have no central air-handlers. The fans exhaust air through a central ceiling plenum above the rooms or with roof mounted exhausts in many locations. These systems are designed to draw fresh air into the rooms by infiltration through above grade cracks and openings; however, radon can enter through below grade cracks and openings. The fans in exhaust-only systems usually are normally off at night but may operate continuously during the day. This can generate a negative pressure in all rooms and, consequently, increase the potential for radon entry.

4.2.2 Unit Ventilators

These self-contained units provide heating and/or air-conditioning in individual rooms. They are usually installed on outside walls with an enclosure which contains finned radiators and/or coils. They can also be located overhead in each room and are sometimes above the drop ceiling. Unit ventilators normally contain one or more fans and a vent to the outdoors so that fresh air can be pulled in by the fan(s). An adjustable damper allows a variation in the mix of recycled room air and fresh air fed to the circulating fan. Fresh-air intake can be minimal because of obstruction of the outdoor vents due to poor maintenance or energy conservation practices. (Units that do not provide any outdoor air by design are referred to as fan coil units, not unit ventilators.)

In some cases there is a central-building exhaust-fan system in schools with unit ventilators, as discussed above. This exhaust fan is intended to provide ventilation by pulling air in through the unit ventilators (if their fresh-air vents are open), but it also creates a significant negative pressure in the room. This negative pressure can pull radon into the rooms with the soil gas. If fresh-air intakes in the unit ventilators are blocked for any reason, operation of exhaust-only fans will increase the negative pressure in the building relative to the subslab area.

Radon mitigation strategies in schools with unit ventilators might include (1) opening the fresh-air vents to improve ventilation and running the unit ventilator fans continuously 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 an 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), SSD, would be the most practical strategy if there is good subslab communication.

4.2.3 Radiant Heat Systems

Radiant heat systems in schools tend to be of three types: hot water 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 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.

If SSD is under consideration as a mitigation option in a school with intra-slab radiant heat, the building plans should be carefully studied to avoid damaging any piping when placing the SSD points. An infrared scanning device can be used to help locate the exact position of subslab pipes. Satisfactory locations for SSD pipes may be very limited in such schools.

4.3 LOCATION OF UTILITY LINES

The location of entry points for utility lines can have a significant influence on radon entry in schools since they can provide an entry route from the soil into the indoor air. Utility line locations depend on many factors such as substructure type, HVAC system, and architectural needs or practices. Utility lines located above grade should not cause significant radon entry problems.

In slab-on-grade and crawl space schools, the utility penetrations from the subslab or crawl space area to individual rooms are frequently not completely sealed, leaving openings between the soil and the building interior. For example, there is a potential for radon entry around plumbing penetrations and electrical conduits.

If utility lines, such as electrical conduits and water and sewer pipes, are located under the slab, their exact locations should be carefully noted from the plans, and caution should be taken when drilling holes through the slab during diagnostic measurements. This is discussed in more detail in Section 5.

In some slab-on-grade schools, the utility lines are located in a subslab utility tunnel that tends to follow the building perimeter or central hall. Utility tunnels often have many openings to the soil beneath the slab-on-grade and, consequently, can be a potential radon entry route. In addition, risers to the unit ventilators frequently pass through unsealed penetrations in the floor so that soil gas in the utility tunnel can readily enter the rooms. If the surrounding soil has elevated radon levels, a utility tunnel could be a major radon entry route in schools.

It is possible that the utility tunnel could be used as a radon collection chamber for an SSD system, and this approach will be studied. Any asbestos in the utility tunnel should be removed or encapsulated according to AHERA before attempting any radon reduction activities in the tunnel.

5. DESIGN AND INSTALLATION OF SUBSLAB DEPRESSURIZATION (SSD) SYSTEMS

5.1 APPLICATION

Experience has shown that SSD is the most successful radon reduction technique in houses that have aggregate or permeable soil beneath the slab. There is much less experience with SSD in schools; however, the results to date, although limited, have been promising in schools that have aggregate or clean, coarse gravel under the slab. Current guidance on radon reduction in schools is focused on designing and installing SSD systems, since experience in mitigating schools using other techniques (Section 6) is very limited.

Experience to date has identified certain types of schools where SSD may not be applicable. These include:

- Schools that do not have crushed aggregate, coarse gravel, or permeable soil underneath the slab. (Experience has shown that SSD systems perform best when the subslab material is approximately 3/4 to 1-1/4 inches in diameter, with few fines.) An SSD system may work in other situations if enough suction points are installed to create a sufficient pressure field. However, in other cases an alternative mitigation approach will be necessary.

- Schools with subslab ductwork. In house mitigation, the subslab ductwork is sometimes sealed off and replaced with new above-slab ductwork. This could be difficult and expensive in many schools, and impossible in others.

- Schools with crawl space construction. Depending on crawl space size and configuration, increased crawl space ventilation, crawl space depressurization, or submembrane depressurization (SMD) may be applicable provided no asbestos is present.

Future school mitigation studies will research radon reduction strategies for mitigating these types of schools, and technical guidance will be published as soon as possible. If diagnostic test results or other reasons indicate that an SSD system is not appropriate for a given school or if an SSD system can not be installed as soon as desired, refer to Section 6, <u>Other Approaches to Radon Reduction</u>.

5.2 DIAGNOSTIC TESTING

Diagnostic measurements will help to better understand the nature of the radon problem so that an effective mitigation strategy can be developed. Aggregate inspection and subslab communication testing are the simplest, least expensive, and most important diagnostics to determine the applicability of an SSD system. Other diagnostics require more expensive equipment and may be more difficult to interpret, but they also may be required to understand the complex radon problems associated with larger buildings and HVAC system operation. Diagnostics that have proven useful in school mitigation are described below.

5.2.1 Evaluation of the Footing Structure

It is important to determine the types and locations of potential subslab barriers, such as footings, subslab walls, and grade beams and how they may impact subslab communication and mitigation system design. The presence of building walls does not necessarily indicate the position of a footing or grade beam because not all walls are load-bearing. The building plans (foundation drawings) are the best source of information on the location of footings. Note that thickened areas of the slab (called "grade beams") are sometimes found in schools to support a block wall. Their effect on subslab communication will depend on the depth of aggregate or gravel under them.

Experience to date has shown that, in some cases, subslab communication will reach across these barriers. However, in many cases, areas surrounded by footings, subslab walls, or grade beams may each need at least one suction point. (This is why the subslab communication test, which follows, is important in confirming the presence, extent, and effects of subslab barriers.)

5.2.2 Evaluation of Subslab Communication

The most important parameter in assessing the applicability of SSD is subslab communication or pressure field extension. Permeable aggregate, screened, coarse, and approximately 3/4 to 1-1/4 inches in diameter, is preferable. Building plans and specifications have been found to be generally accurate in determining the presence of aggregate, but the aggregate quality must be determined by inspection. If aggregate is not mentioned in the specifications, it may not be present even though it is shown on the foundation drawings.

Subslab communication can be evaluated by using a shop-type vacuum for suction at one larger hole (normally located at the potential SSD point) and pressure sensors at other smaller holes. The suction hole should be at least 1-inch in diameter or larger, and the test holes should be approximately 3/8-inch in diameter and should be located at various distances and in various directions from the suction hole, depending on building size and configuration. This approach will indicate the feasibility of developing a pressure field under various parts of the slab and will also help to identify the influence of subslab barriers such as grade beams or below grade foundation walls. It will also help to indicate competing pressures or excessive leakage from subslab ductwork which would inhibit pressure field development in an SSD system.

Experience has shown that the size of the area that can be mitigated by each SSD point varies from a few hundred to several thousand square feet. The coverage will be dependent on subslab communication, the flow capacity of the fan and pipe, the presence of subslab barriers, and on the strength of the building pressures and leakage that the system must overcome. Of course, if subslab permeability is limited, then the pressure field may extend only a few feet and many SSD points may be necessary to adequately treat the entire area.

Pressures at the primary (1-inch plus) suction point are typically measured at suctions of about 8, 6, 4, 2, and 0 inches WC. The pressures at the test hole can be measured either qualitatively (with a smoke stick) or quantitatively (with a pressure gauge). If communication testing indicates a pressure of 0.001 inch WC (0.25 Pascal) or lower at a given test hole or if smoke stick tests show that air flows into the hole, it may be possible that an SSD system will be able to reach the area.

This procedure requires an electric-pneumatic hammer drill, a vacuum, and a sensitive pressure sensor. Before drilling into the slab, utility pipes and conduits should be noted from the plans and confirmed to avoid drilling through them. Refer to Section 7.2 on worker protection for safety suggestions.

Aggregate quality can also be inspected by drilling at least one hole in the slab, large enough (at least 4-inches in diameter) to extract a sample. Holes larger than 4-inches will allow for a better estimate of the depth and porosity of aggregate, but holes of this size may also cause more damage to floor tiles and be more difficult to repair. Again, proper precautions should be taken when drilling through the slab. Although this approach will indicate the presence of subslab aggregate and the potential for subslab communication, it will not indicate the extent of pressure field development that is possible with the communication test.

5.2.3 Evaluation of Pressure Differentials

If the radon tests were made with the HVAC system or other ventilation fans on, it may be useful to re-test the rooms (at least the ones in question) with all fans turned off in order to isolate the major sources of radon and to determine if HVAC operation is influencing radon levels. Changes in radon levels due to HVAC operation may indicate the significance of the pressures (both positive and negative) generated by HVAC operation and the potential for mitigation by HVAC modifications (See Sections 4.2 and 6). Pressure differentials and air flow measurements in classrooms can be used to identify any HVAC flow imbalances that may cause negative pressures in the building relative to the subslab area. These measurements require sensitive pressure gauges and/or air flow meters. Qualitative information can be obtained by using a smoke stick to indicate the direction of air flow.

If the HVAC system pressurizes the building, it can prevent soil gas entry as long as the air-circulating fan is running. However, installation of an SSD system may still be necessary if radon levels build up to unacceptable levels inside the school when the fans are off and it takes too long to reduce the radon to acceptable levels when the system is turned back on.

If HVAC system operation or the natural stack effect exerts a negative pressure in the building relative to the subslab area, then a successful SSD system must overcome this negative pressure. Recent experience with SSD in a limited number of schools indicates that a well-constructed SSD system can provide considerable reductions in radon despite strong HVAC counter pressures. However, it may be difficult for an SSD system to overcome the negative pressures exerted by return-air ducts located under the slab.

Continuous radon measurements (typically averaged over 1-hour intervals) collected for several days will show variations in radon levels. These variations can result from changes in HVAC operation, diurnal effects, weather conditions, and occupancy patterns. These data may lead to a greater understanding of the pressure dynamics in the building; however, a relatively expensive continuous radon monitor is required. Continuous differential pressure measurements (inside/outdoor/subslab) collected concurrently with the continuous radon measurements, are also extremely useful in understanding HVAC system influence on radon entry.

5.2.4 Measurement of Subslab Radon Levels

Subslab radon measurements are used to map radon source strengths so that the suction point(s) can be placed near the major sources. The subslab radon measurements can be collected through the 1/4-inch diameter holes drilled into the slab in the subslab communication test detailed above. To obtain the most representative results, the subslab radon levels should be measured prior to the communication test. This diagnostic technique requires a hammer drill and a continuous or grab radon monitor that can pump air samples into a measuring chamber. Before drilling into the slab, utility pipes and conduits should be noted from the plans and confirmed to avoid drilling through them.

5.3 DESIGN AND INSTALLATION

Installation of SSD systems is primarily a matter of plumbing because of the extensive use of PVC pipe. Electrical work, concrete work, and roof work are often also involved. Due to the nature of the work, it is important that the installer take into account all applicable codes that may affect construction and/or modifications to school buildings. Typically, these may include electrical, mechanical, fire protection, plumbing, and building codes (Section 7).

A typical SSD system for a school is shown in Figure 1 and should be referred to throughout the section.

5.3.1 Suction Hole Location

The location of the suction hole is selected once an area or room to be treated has been identified based on radon measurements, subslab communication tests, and any other diagnostic measurements. For optimum mitigation it would be best to locate the suction hole closest to the highest known radon source. Of course, if the rooms with higher radon levels are widely separated, then they are probably independent and must be treated separately. Often, the source may be widespread or unidentified or the suction hole may need to be located in an out-of-the-way place that will cause minimum disruption to the room occupants.

Another consideration when locating suction points is the accessibility of the exhaust pipe and exhaust fan. In many cases the suction hole position is chosen on the basis of aesthetics, fan

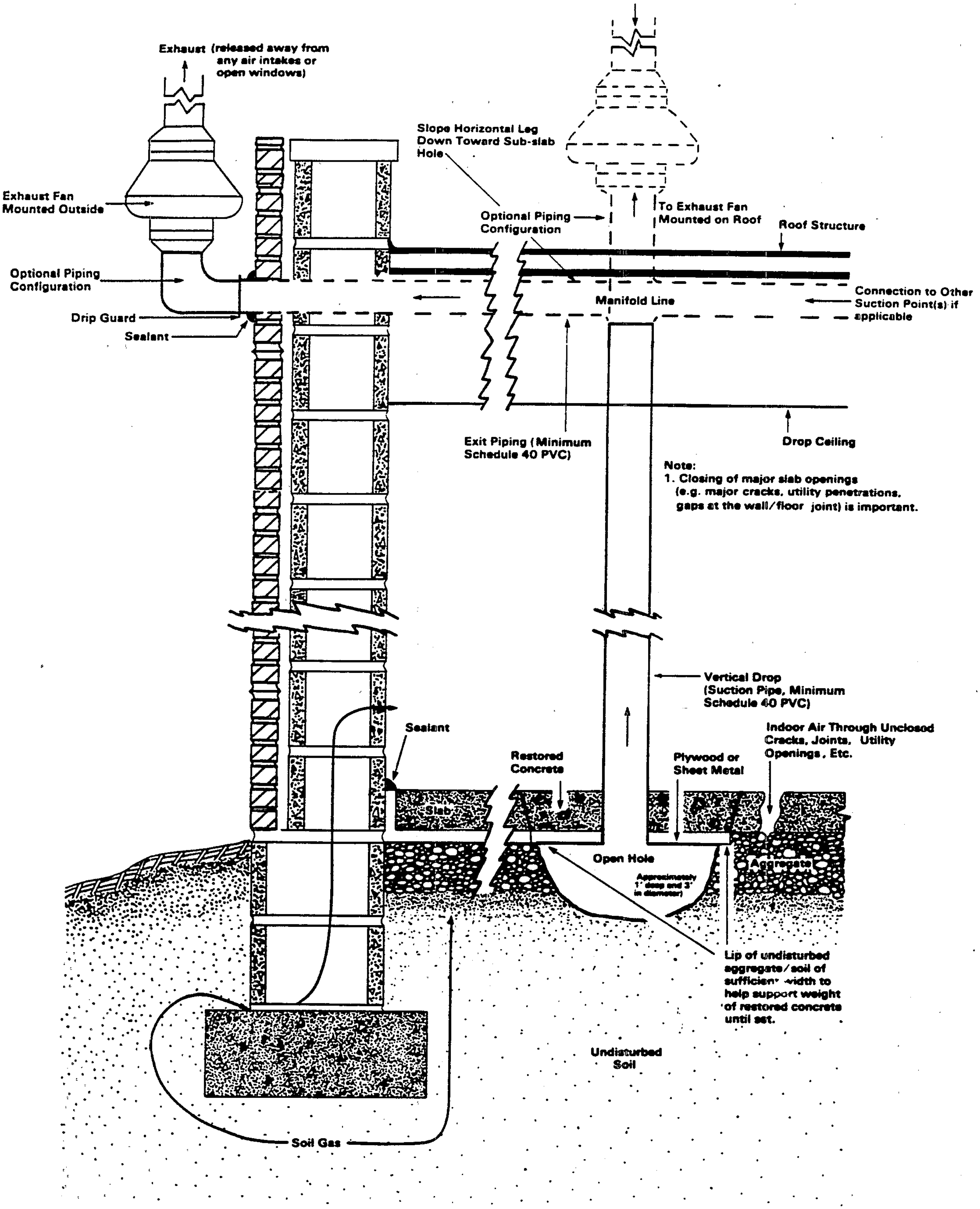

Figure 1. Typical Subslab Depressurization (SSD) Design for a School

location, or exhaust pipe routing. Often a location equidistant from both outside walls, such as a hall or a closet on the hall side of a classroom, is a good location if subslab communication is sufficient.

5.3.2 Pipe and Fan Layout

In order to adequately depressurize school slabs, which may be much larger than house slabs, larger fans and larger pipes to carry the increased air flows are typically used. Appendix A contains information on fan and pipe selection which lists a number of fans with the capability of drawing over 300 cubic feet per minute (cfm) at 3/4-inch WC (which may be three to four times the capacity of home mitigation fans).

The typical 4-inch pipe used in most home mitigation systems may have too much flow resistance when used with this larger fan; therefore, 6-inch pipe is often used. The piping used should be fire-rated (minimum Schedule 40 PVC).

If the permeability of the aggregate is high, then a single 6-inch suction point can be used with the larger pipe and fan. However, with typical aggregate permeability, a wider area can be mitigated by using two or three suction points manifolded to one of the more powerful fans. The location for the SSD point(s) should be selected based on the results of the diagnostic measurements. A typical manifold system might consist of a 6-inch PVC pipe running horizontally within a dropped ceiling and extending 20- to 60-feet between vertical drops. Connected to the manifold would be an exterior mounted fan, and 4-inch PVC vertical pipes which penetrate the slab and transmit vacuum to that area of the floor slab. This arrangement can be used to mitigate a long classroom wing with the suction points located in the central corridor or on the corridor side of a classroom. Experience in schools has shown that locating the suction points remote from the outside wall will help to reduce short circuiting (satisfying fan demand for air) of the system.

If any of the pipe is either outside the building or in an unheated section of the building, then condensation may form inside the pipe because of the high moisture content of the exhausted subslab soil gas. The pipes should always be slanted so that this condensation can drain back into the subslab cavity where it originated. (The in-line fans should be mounted vertically to prevent water accumulation in the bell-shaped housings.) Experience has shown that SSD systems in homes can fail due to a buildup of condensation in improperly oriented fans and pipes. In humid climates, condensation will also form on the outside of pipes in exposed areas, and insulation or boxing in may be necessary. Rain entry into uncapped exhaust pipes has not been reported as a problem, probably because the volume of rain is small compared to the volume of condensation that is continually flowing back down the exhaust pipes. Ice buildup on the fan or on the exhaust stack has not been reported as a significant problem, probably because the soil gas is warm enough to melt any ice or to prevent it from forming.

5.3.3 Suction Point and Pipe Installation

Once the location of a suction point is determined, a hole must be drilled through the concrete slab. Typically, the slab hole diameter corresponds to the pipe's outside diameter, usually slightly larger than 4- to 6-inches. The hole must be large enough to accommodate the suction pipe and to allow the excavation of a cavity beneath the slab. Before drilling into the slab, utility pipes and conduits should be noted from the plans and confirmed to avoid drilling through them. Recommended concrete drill types are discussed in Appendix A. Alternatively, core drilling companies can be hired to drill this type of hole. If a school district anticipates mitigating a large number of schools using SSD, they should consider purchasing a drill. Worker protection should include respirators and eye protection, in addition to ventilation of the work area to dilute radon that is released by opening up the subslab.

An open hole or cavity, as seen in Figure 1, should be excavated beneath the slab with a diameter of approximately 3-feet and a depth of about 1-foot. Experience has shown that when 1-foot diameter cavities have been enlarged to

2- to 3-feet and the depth increased to 1-foot, the negative pressure fields have often doubled because of the decreased resistance. Although performance improvements have been variable, this larger cavity size has proven most worthwhile in nonporous soils (where the most improvement is sought). Aggregate can sometimes be removed from the subslab either by hand or with a powerful shop vacuum. If the aggregate is packed tightly, a crowbar and hand excavation may be necessary. Large subslab cavities may require opening up a larger slab hole just for aggregate removal. This hole will have to be resealed with concrete.

The exhaust pipe should be well supported so that it will not be knocked loose if it is jostled. In school environments it is advisable to enclose the pipe for both security and aesthetics.

5.3.4 Fan Installation

The EPA recommends that SSD fans be installed outside the building because of the chance of leakage of highly concentrated radon from the fan or the pipe exhausting from the fan into the building interior (since the fan and exhaust pipe are under positive pressure). Figure 1 shows two possible fan mounts. In houses the fans are usually placed in attics, but in schools they have been placed on the roof or on the upper sidewall of the building exterior. (See Appendix A for a discussion of SSD fan installation variations.) Wall penetrations are usually preferable because roof penetrations may lead to roof leaks. Several fan configurations are possible: in-line mounts that couple to pipes, pedestal mounts with a vertical discharge, and pedestal mounts with a horizontal discharge. However, the piping configuration and fan placement must be guided by building codes in addition to practical considerations.

The system should exhaust above the roofline to prevent high concentrations of radon from re-entering the building. A location should be chosen which provides a reasonable distance between the discharge point and HVAC fresh-air intakes, windows, doors, or any other openings to the building interior.

5.3.5 Sealing of Radon Entry Routes

To enhance the performance of the SSD system, an effort should be made to seal as many radon entry routes as possible. This increases the strength and extent of the negative pressure field and also reduces the amount of treated indoor air that will be drawn into the SSD system. Entry routes that should be sealed include cracks in the slab and walls, the floor/wall joint, the surface of porous concrete block walls, and openings around utility penetrations. Fibrous expansion joints, that are commonly used when the slabs are poured, can also serve as radon entry routes. These and all other cracks and porous surfaces should be properly prepared and sealed with a suitable sealant.

5.3.6 Troubleshooting

Troubleshooting SSD systems may involve taking a number of diagnostic measurements. If radon levels are not adequately reduced, the suction in the subslab cavity should be measured. Low pressure may indicate high air flow or poor fan performance; high pressure indicates poor subslab permeability or low air flow. The air flow in the pipe may have to be measured to determine whether the fan is operating properly. The pressure field extension can be measured at various distances from the suction hole(s) to determine the coverage of the SSD system.

5.3.7 Improving System Performance

Some causes of insufficient subslab pressure field development include: poor subslab permeability, the presence of subslab barriers, competing pressures from subslab return-air ductwork, and air leaks into the system (either air-supply ductwork or from cracks or openings). If the performance of an SSD system is not adequate, a number of different steps can be attempted to improve system effectiveness. These include:

- Additional suction points can be installed to increase coverage area. (This approach is most suitable when communication is poor or pressure and flow are low.)

- Larger pipe diameters, larger fans, and larger subslab cavities have been shown to improve SSD system performance in some cases. (A larger fan and pipe diameter are most appropriate when the pressure is low and the flow is high.)

- Sealing of cracks and holes can also improve the negative pressure field extension and, consequently, radon reduction. Sealing will also help to reduce the energy penalty associated with the increased exhaust of indoor air into the SSD system.

- Reductions in room depressurization (if applicable) may also improve radon mitigation.

- Finally, it is possible that the suction point has been located in a spot with such poor permeability that major improvements can only be made by abandoning the current hole and drilling a new hole in an area with better permeability.

5.3.8 System Maintenance and Monitoring

One of the chief advantages of SSD systems is that there is relatively little maintenance required for their operation, and the fans have long lives. Periodic system inspection and annual retesting of the radon levels may be sufficient if fans with an expected service life of 10-20 years are installed.

The SSD system pressure levels could be checked and all measurements recorded routinely, as is done with the inspection of fire extinguishers. A pressure gauge is the most common type of monitoring device that is used to evaluate the continued performance of a SSD system. Typically a dial pressure gauge (about $50) is used to monitor the subslab cavity or suction pipe pressure. The gauge is usually mounted on or near the suction pipe where it can be checked to determine if the suction pressure is adequate. Other devices that contain pressure switches to turn on a light or sound an alarm if the pressure falls below a given value are also available and are the preferred method.

Each SSD system should be labeled with its installation date, nominal subslab cavity or pipe pressure depending on monitoring system, and the name and telephone number of the persons to contact in case of failure. Once the final system is installed, post-mitigation radon levels should be monitored annually (during cold weather) to ensure that the system is operating effectively.

6. OTHER APPROACHES TO RADON REDUCTION

Other mitigation approaches, in addition to SSD, have been used in some schools. These approaches may be implemented either as a temporary solution prior to installation of a permanent SSD system, or they be considered as the first phase of a more extensive mitigation plan. In some cases, implementation of these approaches alone may adequately reduce radon levels in the school. After confirming adequate reductions with short-term tests, follow up with long-term measurements to ensure that the system continues to maintain an adequate level of radon reduction.

Classroom pressurization, increasing ventilation, and crawl space depressurization are discussed below. It should be emphasized that these approaches have not yet been thoroughly researched by the EPA in school applications, and more definitive guidance will be published following additional research. Other mitigation techniques, such as extensive sealing and submembrane depressurization (SMD) in a crawl space will also require extensive testing. For technical details on how these techniques have been used in house mitigation, refer to the manuals on radon reduction listed in Section 1.2.

6.1 CLASSROOM PRESSURIZATION

Maintaining a positive pressure in the building (relative to the subslab area) through HVAC system operation has been used successfully for temporary mitigation in a limited number of schools. Whether pressurization is a feasible long-term mitigation solution depends upon factors such as the proper operation of the HVAC system by maintenance personnel, performance with changing climatic conditions, and any additional maintenance costs and energy penalties associated with the changes in operation of the HVAC system. Any HVAC modifications should be made in cooperation with a qualified HVAC system specialist.

Since central HVAC systems are normally designed to operate in a forced supply mode, the occupied spaces may be maintained under a slight positive pressure (relative to the outdoors) depending on the balance between the supply and the exhaust in the building. These systems should be checked periodically for proper operation to ensure that a positive pressure is maintained, and adjustments should be made as necessary. HVAC modifications that reduce fresh air intake, reduce supply air, or increase return air in a given area, and improper system maintenance can lead to pressure imbalances, and, consequently increase radon entry.

If positive pressures are not being achieved in a 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 and operating the fans for a sufficient time prior to occupancy and continuously while the school is occupied will help to reduce radon levels that accumulate during night or weekend setback periods. This approach will maintain low levels during occupied hours by maintaining a positive pressure to prevent radon entry and providing fresh (dilution) air.

In dual-fan systems, the return-air fan can be set back or restricted so that all the rooms are under a positive pressure with only the supply fan operating. The fresh-air intake to the supply fan can also be increased up to the design limit of the system. Another option might be to consult with a HVAC engineer to redesign a fresh-air intake or to add one to a system. Diagnostic measurements made with continuous radon monitoring equipment <u>in each classroom with elevated radon levels</u> can help to determine the necessary fan operation schedule in such situations.

In schools with unit ventilators, increasing the fresh-air intake to the design limit and operating the fans continuously while the school is occupied will help to maintain a positive pressure in the building. A central exhaust-only ventilation system used in conjunction with unit ventilators or fan coil heaters might need to be modified or replaced with a system that operates under a slight positive pressure. For schools with no active ventilation systems or exhaust-only fan systems, positive pressurization will probably require major modifications, such as addition of a fresh-air supply, as part of a HVAC strategy. For more detail on classroom pressurization and how it would apply to a specific type of HVAC system refer to Section 4.2.

If these modifications to HVAC system operation are to be feasible long-term mitigation approaches in a given school, then proper operation and maintenance of the system is critical. Performance during various climatic conditions and any additional maintenance costs and energy penalties associated with the changes in operation of the HVAC system must also be carefully considered. In addition, there may be potential moisture and condensation problems if pressurization is implemented in very cold climates. The applicability of this approach will need to be determined by qualified personnel on a case-by-case basis. Changes made in HVAC system design and/or operation should not reduce the ventilation rate below the minimum standards in ASHRAE guidelines. In addition, any changes in HVAC controls should be documented, labeled, and checked regularly.

6.2 INCREASING VENTILATION

Increasing ventilation by simply opening windows, doors, or vents may be effective, but weather, security problems, the lack of operable windows, and increased energy costs often make this impractical as a permanent approach in most schools. If the windows cannot be opened at night, it may be desirable to use a fan to blow fresh air into the building to lower the radon levels in the morning when the school is opened. Although this approach has been shown to reduce radon levels in some houses, its applicability to schools has not yet been studied. Therefore, ventilation should only be considered as a temporary approach to radon reduction until further research identifies its limitations.

If an increase in ventilation is attempted, crawl spaces and unoccupied basements can sometimes be sealed off from the rest of the building and treated separately. By treating these spaces separately, ventilation reductions can be achieved in adjacent classrooms with smaller fresh air requirements and reduced energy penalty. However, the practicality of this approach in most climates will be limited due to increased heating and/or cooling costs.

For reducing the energy costs associated with an increase in ventilation, a heat recovery ventilator (HRV) may be cost-effective. HRVs allow fresh air to be delivered indoors with reduced heating or cooling costs (depending on season) as compared to natural ventilation. Through a heat exchanger core, heat is transferred between exhaust and fresh air streams, without mixing the two airstreams. However, for an HRV to be a reasonable mitigation option, the savings resulting from the reduced energy penalty should more than offset the initial cost of the HRV.

6.3 CRAWL SPACE DEPRESSURIZATION

In a variation of crawl space ventilation, an exhaust fan is installed in a crawl space vent and all other vents are closed. This is referred to as crawl space depressurization or forced-air exhaust of the crawl space and can prevent radon entry into the building interior by creating a pressure barrier across the floor. In houses, this approach has been more effective in reducing radon levels than passive crawl space ventilation. Experience with crawl space depressurization in schools is limited.

A diagnostic fan door test will indicate the suitability of a crawl space for this mitigation technique. A fan-door (e.g., blower door) will measure the leakiness of the space and will help to indicate the size of fan needed to adequately depressurize the crawl space. If radon measurements show that the crawl space is the primary source of the problem, and if asbestos is not present in the crawl space, then this technique may be feasible for reducing indoor radon levels. More detailed guidance on this approach for schools will be available following further research.

7. SPECIAL CONSIDERATIONS

7.1. BUILDING CODES

Building codes are typically written to reflect minimum design and construction techniques that must be adhered to by the construction industry. They are developed to ensure the public safety, health, and welfare. Building codes are not only directed toward new construction but also apply to renovation of existing structures. They can be developed by the national model code organizations or by local jurisdictions. In general, the model codes published by such organizations as Building Officials and Code Administrators International (BOCA), International Conference of Building Officials (ICBO), and the Southern Building Code Congress International (SBCCI) are adopted by state or local jurisdictions or serve as the basis for locally amended building codes.

It is important that the installer take into account all applicable codes and laws regarding qualifications for design and type of equipment used when designing and installing radon mitigation systems in any building. Typically, this may include electrical, mechanical, fire protection, plumbing, and building codes. However, since these codes can vary between different areas, the applicable codes for a given locality should be referred to when retrofitting a school with a radon mitigation system. It is anticipated that specific additions or amendments to these codes will be made in the future to address both retrofit of school buildings for radon reduction and radon preventative new construction.

7.2 WORKER PROTECTION

Worker protection during radon mitigation system installation is a legal, safety, and ethical consideration for all school administrators. Normal safety precautions must be observed when performing any type of construction or remodeling work. Exposure to radon gas and its decay products creates an additional health risk. Therefore, it is important to reduce that exposure as much as possible. Specifically, this may mean increasing ventilation in the work area and/or utilizing respirators in areas where the radon concentration is elevated. Attention should also be given to other potential hazards, such as organic solvents in sealants and coatings and potential biological hazards growing in crawl spaces or HVAC systems.

Before drilling into the slab, utility pipes and conduits should be noted from the plans and confirmed to avoid drilling through them. (However, it should be mentioned that subslab plumbing and conduit are sometimes located where the installer finds it convenient and do not always conform to the plans.) One suggestion for avoiding an electrical shock in this situation is to ground the case of the drill. If the tool itself is properly grounded, it will prevent the tool from becoming "hot" and should cause the breaker to disconnect the conduit that was hit. Shutting off the supply to the drill will stop the drill but will not shut off the subslab conduit that was hit unless they happen to be on the same breaker.

7.3 ASBESTOS

Any potential airborne asbestos fibers identified in a basement, crawl space, utility tunnel, boiler room, or any other part of the school that may be entered as part of radon diagnostics or mitigation should be removed or encapsulated according to AHERA before attempting any radon reduction activities.

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APPENDIX A: TECHNICAL INFORMATION

A.1 USING CONSTRUCTION DOCUMENTS

The term "construction documents" refers to the formally agreed upon construction drawings and specifications (project manual), as well as all subsequent addenda and change orders. The documents are a complete pictorial depiction of the project and consist of the architectural, structural, mechanical, and electrical drawings. The specifications include the bidding documents, the conditions of the contract, and the technical information that outlines materials and workmanship for the entire project.

Both the specifications manual and the drawings should be obtained to aid in the understanding of the building's radon problem. Each of these will provide useful information. Table A.1 summarizes the information provided in these documents.

A.1.1 Specifications

The specifications will primarily aid the mitigator in identifying subslab aggregate composition and soil compaction requirements. Both of these are usually found in the section detailing concrete work and/or fill (typically Division 3 - Concrete). The mechanical section (Division 15) summarizes the heating, ventilating, and air-conditioning (HVAC) systems applicable to the building. This section will give details on the mechanical equipment and offer design information that may or may not be found on the drawings. The electrical section (Division 16) summarizes the electrical system.

> Note: The specifications have precedence over the drawings if there are contradictions. For instance, it is unlikely that aggregate was provided if

Table A.1 Radon Mitigation Information In Construction Documents

Document	Information
Specifications:	
Concrete (Division 3)	Subslab composition; aggregate identification
Mechanical (Division 15)	HVAC system summary; equipment identification
Electrical (Division 16)	Electrical system summary; equipment identification
Drawings:	
Architectural	Typical wall sections
Structural	Foundation plan; footing locations and communication barriers, subslab fill and material thickness
Mechanical	HVAC system design; including duct system design, duct run length; supply/return flow design; fresh-air introduction; exhaust systems
Electrical	Electrical equipment design and location; conduit location

the specifications do not call for it, even if the drawings show aggregate under the slab.

A.1.2 Drawings

The drawings provide a wealth of information that may be useful for radon mitigation. The architectural drawings usually show a typical wall section. Subslab fill information is usually shown and labeled on this section. The structural drawings include a foundation plan which locates footings of load-bearing walls and columns. This is useful when identifying potential barriers to subslab. The mechanical drawings should include all plumbing and HVAC drawings. Supply and return duct runs show the amount of supply and return air flow serving a room or area. By simply adding together all of the flows, it can be determined if the room was designed to be under positive or negative pressure. Most sophisticated HVAC systems are designed to be balanced or pressurized in most, if not all, rooms. The drawings should note whether or not fresh air is introduced into the mechanical system and if room air is removed by exhaust fans.

The electrical drawings should be consulted to ensure that no unusual conduit routes (e.g., under the slab) are present in areas where the slab may be drilled (either for placement of suction points or for communication testing).

A.2 FAN AND PIPE SELECTION

SSD systems in houses and schools require fans that are quiet, long-lived, energy efficient, resistant to moisture, and that have good air flow at pressures around 1 inch WC. A number of centrifugal duct fans manufactured by various companies have the performance characteristics required for most radon mitigation with an expected service life of 10 to 20 years. Fans that utilize the vane-axial fan blade which surrounds the motor can be mounted in a variety of enclosures. Specifications of some typical in-line and pedestal fans used in radon mitigation are shown in Table A.2.

The in-line fans are designed to be mounted between two sections of pipe. The fan and pipe are usually coupled with the black rubber pipe couplings fitted with stainless steel hose clamps that are used for plumbing pipe connections. These couplings are available in a wide variety of sizes so that pipes and fans of various sizes can be coupled. Pedestal fans are designed to be mounted on a square base that can be constructed of pressure-treated wood. This base is attached over a pipe penetration on a roof or a wall, and the fan is screwed onto and sealed to the base.

In houses, mitigators often attempt to install the smallest, quietest, least obtrusive, lowest power SSD system possible. Pipes are generally 4 inches in diameter or smaller; fans are rated generally less than 100 watts power consumption and move less than 150 cfm air at 0.75-inch WC pressure. In schools, however, the considerations of noise, energy loss, and size are not as important. Larger fans and pipes should be considered if they produce simpler and more effective mitigation. It is recommended that fire-rated PVC piping, Schedule 40 PVC as a minimum, be used.

Mitigation experience in schools, although limited, has shown that it is advisable to use fans that are at least twice as large (200 W and 300 cfm at 1-inch WC pressure) and pipes that are 6-inches in diameter. The higher air flow requires larger pipe diameters so that the increased fan capacity is not lost in pipe resistance. For example, these larger pipes can be used to provide a low restriction manifold to the fan that is connected to two vertical 4-inch pipes penetrating the slab. The 6-inch pipe can carry 300 cfm to the fan while each of the two 4-inch pipes carries about 150 cfm. If the larger fans are attached directly to 4-inch pipes, then a large part of the increased fan performance will be lost to flow resistance of the pipe. In summary, the larger slab areas found in schools normally require larger fans and pipes for the most effective SSD installations.

Table A.3 shows the flow resistance for 100-feet of pipe with diameters from 2- to 6-inches. The length of pipe that would produce the equivalent resistance of a system that contains pipe, pipe fittings, and subslab flow resistance is assumed to be about 100-feet, although typical

Table A.2 Typical Fans Used for Radon Mitigation

Fan Type	Elec. Power (W)	Noise Level (sones)	Flow* (cfm)	Press. Max @No Flow (in. WC)	Width Max. (in.)	Pipe Diam. (in.)	Pipe Length (in.)
In-line	40	2.1	25	0.8	8.00	4.0	8.50
In-line	40	2.1	45	0.7	8.00	5.0	8.60
In-line	40	2.1	45	1.0	8.00	5.0	7.50
In-line	90	2.8	140	1.7	11.50	6.0	9.05
In-line	80	2.8	140	2.0	11.50	6.0	7.50
In-line	110	3.2	180	2.0	13.25	8.0	8.25
In-line	110	3.2	180	2.0	13.25	8.0	9.37
In-line	160	4.5	310	2.0	13.25	8.0	9.37
In-line	160	4.5	310	2.0	13.25	8.0	8.25
In-line	200	4.5	456	2.0	16.00	12.0	12.60
In-line	280	5.6	470	2.0	16.00	12.5	10.25
In-line	250	5.6	470	2.5	13.25	10.0	9.64
Pedestal	90	2.7	75	0.7	na	na	na
Pedestal	90	na	90	1.4	12.50	na	8.00
Pedestal	90	na	110	1.4	14.00	na	10.00
Pedestal	120	na	200	1.6	16.00	na	12.50
Pedestal	150	na	200	2.4**	12.50	na	8.00
Pedestal	150	na	300	2.8**	16.00	na	12.50
Pedestal	175	na	530	1.5	16.50	na	13.00

* flow measured at 0.75 inch WC pressure
** INFILTEC measured value

Table A.3 Air Flow Resistance in 100 Feet of Round Pipe

Flow (cfm)	2-in. Pipe (in. WC)	3 in. Pipe (in. WC)	4 in. Pipe (in. WC)	6 in. Pipe (in. WC)
10	0.34	0.04	0.01	0.001
15	0.72*	0.08	0.02	0.002
25	1.80	0.24	0.06	0.007
50	6.30	0.83*	0.20	0.030
100	22.00	2.90	0.69*	0.090
200	78.00	10.30	2.40	0.300
300	164.00	21.60	5.10	0.670*
400	276.00	36.40	8.60	1.100
500	414.00	55.40	13.00	1.700

* These values show the approximate flows for each pipe for which the resistance is closest to 0.75-inch WC.

mitigation systems usually do not have pipe runs of more than 40-feet. For example, if a particular fan draws 310 cfm at 0.75-inch WC and 100 feet of 4-inch pipe has a resistance close to 5.1-inches WC at a flow of 300 cfm, it would be advisable to use 6-inch pipe to avoid wasting most of the fan power on pipe resistance. However, large pipe is unnecessary if little or no subslab air flow due to low subslab permeability. Pressure drops caused by bends (e.g., elbows) in the pipes should also be considered when designing the SSD piping system.

A.3 DIAGNOSTIC MEASUREMENT TOOLS

Several types of tools* are useful in gathering diagnostic data in schools. They include an electric-pneumatic hammer drill, a large shop vacuum, a continuous or grab-sample radon monitor, a sensitive pressure measurement device, an air-flow indicator, and an air-flow meter.

Depending on the number of schools to be mitigated in a given district, it may be cost-effective to purchase some of this equipment or it may be more practical to employ the services of an experienced radon mitigator. It may be possible to purchase some of this equipment from experienced mitigators in the area or they may be able to recommend a local source for purchase or rental of radon mitigation supplies.

A.3.1 Small Hammer Drill

Drills capable of drilling holes through concrete slabs of at least 3/8- to 1-inch in diameter are useful for subslab pressure, communication, and radon measurements. The suction hole should be 1-inch or larger in diameter, and the communication test holes are usually 1/4- to 3/8-inch in diameter. The inexpensive hammer drills sold in hardware stores are often incapable of drilling through concrete which has hard aggregate embedded in it. Professional quality, lightweight hammer drills with spline bits are recommended. This type of drill costs approximately $250.

A.3.2 Vacuum

Most of the shop-type vacuum systems can draw a vacuum of 60- to 120-inches WC and have a maximum air flow of about 100 cfm. This is quite adequate for inducing flow through drilled holes approximately 1 1/2-inches in diameter for communication tests. These vacuums are available for $40 to $250.

A.3.3 Continuous Radon Monitor

Continuous radon monitoring (typically averaging at 1-hour intervals) is very useful in evaluating the effects of HVAC interactions on school radon levels. Pylon, Femto Tech, and At Ease are types of continuous monitors commonly used. A number of school systems have purchased continuous radon monitors to aid in their school mitigation work. A continuous monitor allows each stage to be evaluated quickly when mitigation is performed in stages or a number of rooms need to be measured.

A.3.4 Grab-Sample Radon Monitor

In order to map sub-slab radon, a radon monitor is needed that can pump a sample into its measurement chamber and hold it long enough for a measurement. It is very convenient to use a Pylon AB-5 monitor which has a built-in pump and scintillation counter although a separate pump, Lucas cell, and scintillation counter can be used. This instrument can be used to take grab samples from holes for subsequent counting, or it can be used for continuously "sniffing" from a series of holes. The Pylon system costs about $4500.

A.3.5 Pressure Gauge

A sensitive pressure gauge is necessary to measure the pressure fields generated by SSD systems. Pressure differentials as low as 0.001-inch WC are common. The most sensitive Dwyer Magnahelic pressure gauge, which costs about $50, is sensitive only to about 0.01-inch WC. The slant-tube manometer is difficult to read, to set up, and to transport. It costs about $100 and has a sensitivity of about 0.001-inch WC. The best type of pressure gauge for these measurements is the electronic digital micromanometer which can read from 0.001- to 20-inches WC. These micromanometers cost about $1500.

A.3.6 Air-Flow Indicators

The direction of pressure or air flow in a test hole can provide an indication of system performance even if it cannot be measured. Smoke pencils or guns are most commonly used as flow or pressure indicators. The smoke is generated by a chemical reaction with the moisture in the air and has an acrid odor because of its high acid content. Chemical smoke is used because it is not associated with heat; therefore, it will respond more accurately to minimal air flows. The smoke pencils cost about $3 to $4 each and can last a couple of hours if they are used carefully. A refillable smoke gun is also available for about $70.

A.3.7 Air-Flow Meters

Measuring air flow through HVAC registers requires a "flow hood" which costs from $1500 to $4000. These devices are most commonly used to balance air flows in large buildings. For air flow measurements in ducts or pipes, a Pitot tube (about $20) can be used in conjunction with a sensitive pressure gauge. Alternatively, a hot wire or hot film anemometer, costing about $700 to $1,500, can be used. Pinwheel anemometers, vortex shedders, and mass flow sensors are examples of other air-flow meters that can also be used.

A.4 INSTALLATION TOOLS

Most of the tools used for installing radon mitigation systems are conventional tools used by home improvement contractors. The only specialized tool that may be required is a drill to cut 4- to 6-inch holes through the concrete floor slab. The following options are available:

- Use a large rotary hammer drill, costing about $400, which has a chisel action and regular drill bits. Experience shows that in about 20 minutes this drill can make a large hole by drilling a circular pattern of smaller holes and punching the core out with the chisel.

- Use a hammer drill with a carbide core bit. The carbide core bits are expensive (as much as $800) and may not be available for your drill in larger size diameters. They can drill a neat hole in about 10 minutes.

- Use a core drill with diamond bits and water cooling. This equipment costs as much as $2000 and is very heavy and bulky. However, it is the fastest way to drill precise holes in concrete.

All of these tools can usually be rented from tool rental shops. It may be economical to hire a core drilling company to come to your location with a diamond core drill if you have a number of holes to drill.

A.5 SCHOOL SSD INSTALLATION VARIATIONS

All SSD installations should have the exhaust pipe exiting the building shell. The fan should be mounted on the pipe outside the building shell to avoid leakage of the radon-laden air from cracks in the fan or from the exhaust end pipe which is under positive pressure. EPA recommends that the system exhaust point be installed above roof level and be situated to avoid any possible human exposure to high radon levels from the SSD vented soil gas. For any type of fan mount, extreme care should be taken to prevent high concentrations of radon from re-entering the building through HVAC fresh-air intakes, windows, doors, or any other openings to the building interior. Following are the types of installations, and their advantages and disadvantages, which have been used in schools.

A.5.1 Pedestal Fan on Roof

In this type of installation the pipe penetrates the roof and connects to a pedestal fan. Disadvantages of this type of installation are the need to construct and seal a pedestal on the roof for the fan to be mounted on and the need to cut a hole in the roof. (This may lead to roof leaks or may invalidate warranties on the roof.) Advantages are a vertical pipe run without high resistance bends, and the low visibility (aesthetics) of the installation.

A.5.2 In-Line Fan on Side Wall

In this type of installation the pipe penetrates the side wall and an in-line fan is mounted vertically on the pipe. Disadvantages of this type of installation are the necessity of securing the fan and the pipe and the potential for damage or injury if someone climbs the pipe. Advantages are the ease in venting above the roof line and the fact that the roof is not penetrated.

A.5.3 Pedestal Fan on Side Wall

In this type of installation the pipe penetrates the side wall and discharges horizontally with a pedestal fan mounted on the wall. A significant disadvantage of this type of installation is the possibility of someone coming into contact with the discharge if the fan is not mounted high enough or radon from the discharge leaking back into the building through HVAC fresh-air intakes, windows, doors, or any other openings to the building interior. An advantage is the lack of roof penetration.

A.5.4 In-Line Fan Above Suspended Ceiling

In this type of installation the pipe penetrates the roof and connects to a fan which is mounted inside the building above the suspended ceiling. This is generally not acceptable because of possible leakage from the fan or exit pipe inside the building. Any radon leakage could be distributed throughout the building if the area above the suspended ceiling is a return plenum for the HVAC system.

APPENDIX B: SCHOOL MITIGATION CASE STUDIES

These case studies illustrate the staged approach that characterizes many radon mitigation projects in large buildings and complex houses. Instead of trying to solve the radon problem in an initial step, most of these projects consisted of multiple stages where one solution was attempted and then the results were evaluated before initiating the next stage. The case studies show examples of the step-by-step procedure for radon reduction in schools. Some of these projects (Schools A, B, C, D, E, F, G, and H) were previously documented in the technical paper "Radon Reduction Systems in Schools" (Saum, Craig, and Leovic).

School A: Prince George's County, MD

This school had a sophisticated dual-fan HVAC system that produced unbalanced flow and exacerbated a radon problem in several rooms. Sealing of cracks and replacement of the HVAC fan were tried without much effect on the radon levels. SSD systems will be installed in the rooms with the highest radon levels since the problem of room depressurization could not be readily eliminated.

A.1 School Description

The school building, which was built in 1969, is two-story, slab-on-grade construction. It uses a large dual-fan air handling system for HVAC. Each room has separate supply and return louvered vents in the suspended ceiling. The HVAC system is designed to operate continuously during occupied hours and to provide positive pressurization in all rooms.

A.2 Initial Radon Tests

Radon levels in this school were initially measured in February 1988. 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.

A.3 Building Plan Inspection

The foundation drawings call for a 4-inch gravel bed and a 6-mil plastic vapor barrier under a 4-inch slab. A ½-inch expansion joint runs across the entire building. The footings run below virtually all interior and exterior walls. Square footings support columns.

The HVAC system fans have a rated capacity of 51,000 cfm of air supply and 34,000 cfm of return air. This would result in positive pressure in all rooms if the system were properly balanced.

A.4 Walk-Through Building Inspection

Examination of the air-handling system showed that the air supply fan had been damaged and part of the housing cut away; this resulted in a great loss of capacity. It was determined that the distribution fan was actually supplying less air than the return air fan was removing; this resulted in a negative pressure in many rooms.

The room with the highest radon level had the greatest negative pressure and also had a very large floor-to-wall crack along one wall. This particular floor-to-wall crack was an expansion joint where two parts of the building were joined. The expansion joint had disintegrated and the two building sections appeared to have separated an additional ½-inch, leaving a full 1-inch gap between the floor and wall. This gap was concealed by an aluminum angle iron installed when the building was built. The expansion joint and the angle iron continued vertically up both corners so that they were serving as an expansion/contraction joint between the two parts of the building.

A.5 Pre-Mitigation Diagnostics

Pressure measurements indicated that many of the rooms were under negative pressure when both the supply and return fans were in operation. The room with the highest radon level measured 0.060-inch WC negative pressure (relative to the subslab). There was a good correlation between negative pressure and radon levels in all rooms, with the highest radon levels in the rooms with the highest negative pressures. All rooms in the school with any amount of positive pressure had low radon levels. Subslab radon levels were about 500 pCi/L in all rooms. When the return air fan was turned off, the pressure in all rooms became positive and radon levels decreased to less than 2 pCi/L.

A.6 Temporary Mitigation

As a temporary solution to reduce radon levels, the return air fan was left off and the HVAC system operated with only the air distribution fan. Under these conditions all rooms showed positive pressure and had radon levels below 2 pCi/L.

A.7 First-Stage Mitigation

The floor-to-wall building expansion crack was sealed with a backer rod and polyurethane caulking. This sealing decreased radon levels only slightly when both fans were off, which indicated that there were other soil gas entry points in the room. This poor result from sealing a major crack was surprising because this crack was about 1-inch wide and soil gas with 500 pCi/L flowed out of it when the pressure was negative.

A.8 Second-Stage Mitigation

Little effect was seen on the negative pressures in the problem rooms although the damaged supply fan was replaced. Building personnel have attempted to identify the cause of the flow imbalance to these rooms. This will be further investigated.

A.9 Third-Stage Mitigation

A decision was made to install SSD systems in the two rooms with the highest radon levels since an HVAC modification was not found to solve the negative pressure problem in the rooms. Installation of SSD systems would also reduce radon entry when the air handlers are not operating during night or weekend setbacks. T3B fans were installed on 6-inch pipes in the two rooms with the highest radon levels. The return air grill was permanently disconnected from the return air duct in the teacher's lounge to alleviate the problem there. Since the lounge is used for smoking, it is probably not a good idea to recirculate the air. The return grill is now directly vented to the outdoors.
Post-mitigation tests from this stage are not yet available.

A.10 Conclusions

Although mitigation of this school is not yet complete, SSD in this case appeared to be a more reliable solution to the radon problem than crack sealing or HVAC modifications. SSD should solve the radon problem both during the day while the HVAC system is turned on and during the night when it is turned off.

School B: Washington County, MD

This is an example of a school with a complex radon problem that was mitigated in multiple steps. A large number of SSD suction points had to be used because of the school's complex footing structure and poor aggregate. The mitigation performance was evaluated by retesting as each suction system was installed or improved with a larger fan, larger pipe, or larger subslab cavity. With hindsight it is clear that some of these steps could have been consolidated; radon mitigation is not an exact science and it is often beneficial to try a simple solution and evaluate the results before continuing. In this case, the simplest solution was installing a single suction point in the center of the basement slab near the highest concentrations of subslab radon. Although this single suction point did provide considerable radon reduction in the basement, it was necessary to install several other suction points around the edges of the slabs to bring the levels well below 4 pCi/L.

B.1 School Description

This is a small school, 80 by 150 feet, built on the side of a hill. The school has a 21 by 150 foot walk-out basement along its 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 constructed of concrete blocks. The interior walls of the basement support the end of the bar joists and the slab. This wall is not painted or waterproofed on either side. Separate single-fan, roof-mounted HVAC systems with ceiling-mounted duct work are provided for the basement and upstairs.

B.2 Initial Radon Tests

Charcoal canister measurements taken over a weekend in March 1988 averaged 10.5 pCi/L in the basement and 4.3 pCi/L on the first floor. It is unknown how the air handlers were operating during the test. All rooms were retested over a weekend in May 1988 with air handlers turned off. Measurements ranged from 78 to 82 pCi/L in the basement and from 18 to 33 pCi/L on the first floor.

B.3 Building Plan Inspection

The building plans indicate that the first floor and unfinished basement were constructed in 1971. In 1976 the basement was converted into classrooms and a slab-on-grade greenhouse was added. The foundation plans show a complex footing structure upstairs that would limit the extent of pressure fields from SSD systems. There are, however, basement footings at the periphery of the slab which would allow any basement SSD pressure fields to be limited only by the aggregate porosity. One specification notes that "completed fill, prior to laying of floor slabs, shall have density and compressive value of not less than 95% of the normal undisturbed soil value....The fill directly under concrete slabs on grade shall be clean crushed limestone; 1/2 in. minimum, 1 in. maximum size leveled, compacted to 4 in. minimum thickness or as shown on drawings." No soil test results are provided.

B.4 Walk-Through Building Inspection

The upstairs and downstairs are mostly open areas subdivided by movable low partitions. The HVAC supply and return grills are positioned so that there are only a few offices and storage areas where the HVAC system could cause depressurization. No major radon entry routes were noted other than typical small (1/8-inch) cracks between the walls and the floor slabs and expansion joints.

B.5 Pre-Mitigation Diagnostics

Radon mapping was conducted by drilling small holes in the floor and walls and "sniffing" with a continuous radon monitor. These tests resulted in measurements of about 1500 pCi/L in the floor and block walls around the central stair well. Other floor and wall samples were below 500 pCi/L.

Hourly continuous radon monitoring over several weeks showed that radon levels were low when the HVAC systems were operating. During nights and weekends when the system was in a "setback" mode, radon levels rose quite rapidly to as high as 150 pCi/L downstairs and 80 pCi/L upstairs. Pressure measurements through holes in the slab showed that the HVAC systems resulted in small positive pressures within the building that provided complete remediation as long as they were operating. However, the HVAC fans only operated when heating or cooling was demanded; during mild weather they seldom operated. The March charcoal measurements were made during cold weather that probably required more HVAC operation than the May tests which showed much higher radon levels. Communication tests showed that a trace of suction could be measured across 20-feet of the center of the basement floor and in the nearby walls. This suction confirmed that some aggregate was present, that the permeability was marginal, and that an SSD system might be able to produce significant mitigation.

B.6 Temporary Mitigation

When the radon problem was discovered in March, the students were moved out of the basement classrooms where the levels were the highest. Tests in May showed the levels increasing upstairs, probably because of the diminished cycling of the HVAC system in mild weather. For temporary mitigation, until the school recessed for the summer, the HVAC fans were turned on continuously both upstairs and downstairs when the building was occupied. Although this provided complete mitigation under spring conditions, it was not considered an acceptable permanent solution because of the increased wear on the HVAC fans and the unknown level of performance in the winter. Even with closed fresh-air dampers, a very slight positive pressure which produced complete remediation was generated in the building. If HVAC mitigation had not been possible, one option might have been to install a large portable fan which would have been used to blow air in through an open door while classes were in session, or the school might have been closed early for the summer.

B.7 First-Stage Mitigation

A 4-inch diameter suction hole was drilled through the slab in a centrally located basement closet near the highest subslab radon measurements. The aggregate exposed by this hole was about 4-inches deep; it contained fine material which limited its permeability. A 1-foot diameter cavity was excavated in the aggregate and a 4-inch diameter suction pipe was installed across a dropped ceiling, out a back wall on the downhill side, and vented up above the roof line. Larger 6-inch diameter pipe would have been installed to allow more air flow and a bigger fan, but the clearance above the suspended ceiling was too low. A Kanalflakt T2 in-line fan was coupled to the pipe to provide about 1-inch WC of suction in the subslab cavity. After several days of operation, a continuous radon monitor showed a drop in the basement radon to about 40 pCi/L. These tests had to be made during the weekend when the temporary mitigation scheme involving the HVAC system could be discontinued without exposing the students to high radon levels. The upstairs levels dropped to about 20 pCi/L. (All air-handlers were off.) These results suggested that the SSD system had a significant effect on the major radon source in the building, but other sources remained to be mitigated and/or the main source was not completely mitigated.

B.8 Second-Stage Mitigation

In order to improve the performance of the single suction-point system, the subslab cavity was expanded from about 1-foot in diameter to about 2 by 3 feet. This significantly increased the air flow as indicated by a drop in cavity pressure from about 1- to 0.5-inch WC. It also doubled the pressure field under the slab as indicated by the fact that the pressures in a hole 13-feet from the suction point increased from 0.012- to 0.025-inch WC. Radon levels upstairs and downstairs also decreased slightly.

B.9 Third-Stage Mitigation

In the next attempt to increase the performance of the single point SSD system in the basement, the fan was increased from a Kanalflakt T2 to a T3B. This increased the suction in the cavity from 0.5- to 0.7-inch WC which was not as large as might be expected since the T3B is capable of moving more than twice the air flow of the T2 at the same pressure. The increase that was smaller than expected in subslab pressure is probably due to the flow restriction and pressure loss in the 4-inch diameter pipe. A slight decrease in radon levels was noted, but the levels downstairs and upstairs were still about 20 and 15 pCi/L, respectively, after the HVAC fans were off for 24 hours.

B.10 Fourth-Stage Mitigation

Since some radon was thought to be coming from under the first floor slab, a suction system was installed near the woodworking shop where the highest upstairs subslab air measurements had been taken. A T2 fan and 4-inch pipe were installed and a "T" fitting was coupled to the pipe and sealed so that a second suction point could be added to this system. The subslab aggregate was found to be only 2 inches deep and full of fine material, limiting its permeability. Continuous radon measurements showed very little change after the system was turned on.

B.11 Fifth-Stage Mitigation

To improve the performance of the upstairs system, a second suction point was installed about 20 feet away from the first. In addition, the fan was replaced with a T3B and the pipe near the fan was replaced with 6-inch diameter pipe to handle the increased flow from the two suction pipes. The initial suction point cavity beneath the slab was increased from 1-foot in diameter to 3 by 2 feet to increase the subslab air flow. A slight decrease in the upstairs radon levels was observed.

B.12 Sixth-Stage Mitigation

In order to complete the mitigation system downstairs, two more suction systems were installed at the ends of the basement. These systems used 4-inch pipe and T2 fans, with about 1-foot cavities in the aggregate beneath the slab. In addition, all three downstairs systems had "T" fittings installed in the pipe about 6-feet above the floor; horizontal 4-inch pipes penetrated the hollow concrete block walls. Unfortunately, the wall suction created so much air flow in the pipes that the subslab cavity pressures in all the systems fell to about 0.2-inch WC, and the continuous radon monitor in the basement showed that the net result was a significant increase in basement radon.

B.13 Seventh-Stage Mitigation

When the wall suction pipes were cut and sealed, the subslab cavity pressures in all the systems rose to about 0.7-inch WC and the basement continuous radon monitor showed levels below 2 pCi/L. Pressure field measurements in the basement showed measurable depressurization under all of the slab.

B.14 Eighth-Stage Mitigation

The upstairs radon levels were still observed to range from 4 to 10 pCi/L, so three more subslab suction points were installed along the uphill side of the upstairs slab. These systems were separated by about 30 feet and consisted of 6-inch pipe with two points manifolded to a T2 fan and a third connected to a GV9 wall-mounted fan that discharged horizontally about 10 feet off the ground.

B.15 Ninth-Stage Mitigation

Continuous radon measurements showed that some peaks above 4 pCi/L were associated with the greenhouse area which had two of the three new suction points. After the fan on these points was increased to a T4, the radon levels remained below 2 pCi/L.

B.16 Cost Estimates

The cost estimates given below are higher than the actual expenses because of the research nature of this project, but the following breakdown may be useful:

1. Labor for SSD installations:

   6 SSD Systems @ 2 person days per system = 12 person days.

2. Parts cost for SSD installations (fans, pipe, electrical):

   6 SSD Systems @ $500 per system = $3,000.

3. Labor for post-mitigation testing:

   9 stages @ 0.5 person day for distribution and pickup = 4.5 person days

4. Charcoal canisters for post-mitigation testing at each stage:

   9 stages with 10 canisters each @ $10 per canister = $900

5. Pre-mitigation diagnostic work by experienced home mitigator:

   2 days @ $500 per day = $1000

6. Continuous radon monitoring by consultant to monitor progress:

   30 days @ $100/ per day = $3000

The total is 16.5 person days of labor and $7,900 in parts and consultant fees. Since continuous radon monitors are available for about $3000, it may be cost effective for school systems with extensive radon problems to purchase their own monitors.

B.17 Conclusion

Houses with marginal subslab porosity can often be mitigated with SSD if enough suction points can be installed. This school required a similar mitigation system. Winter testing with long term alpha-track monitors measured below 4 pCi/L with most of the rooms measuring below 2 pCi/L. Pressure gauges were placed on most of the suction pipes so that the fan performance can be quickly checked.

School C: Washington County, MD

This successful school mitigation project is an example where large SSD fans can be used to mitigate large slab areas with 6-inch diameter pipe used as a manifold to connect the fan to several 4-inch diameter pipes that penetrate the slab.

C.1 School Description

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 were used in each room. No part of the building is air-conditioned.

C.2 Initial Radon Tests

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. The April 1988 screening tests with charcoal canisters showed that 21 of 72 tests were above 4 pCi/L: 7 were above 8 pCi/L, and 1 was above 20 pCi/L (26.7). The highest levels were in the new classroom wing.

C.3 Pre-Mitigation Diagnostics

Although the locker rooms and gymnasium are on the same air handler, the gymnasium measured 1.8 pCi/L whereas the girls' locker room measured 4.9 to 6.3 pCi/L and the boys' locker room measured 5.3 to 19 pCi/L. Further examination indicated that each locker room area had a large exhaust fan 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 gym pressure was slightly positive, the girls' locker room area slightly negative, and the boys' locker room area significantly negative.

In April 1988 weekend charcoal canister measurements were made in the new classroom wing with the unit ventilators turned off. All rooms but one were above 4 pCi/L; a room in the northeast corner of the building measured 26.7 pCi/L. Radon levels decreased from north to south in this wing as did subslab radon levels. A continuous radon monitor 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 operating continuously. Pressure measurements made with a micromanometer confirmed that the unit ventilator was pressurizing the room slightly.

C.4 First-Stage Mitigation

Construction plans showed that each locker room area was a continuous slab with aggregate beneath it. As a result, a 6-inch subslab suction point was placed in each of the two locker room areas with a 1-foot diameter subslab hole and a Kanalflakt GV-9 fan (rated at 200 cfm at 0.75 inch static pressure). Both locker room areas measured less than 4 pCi/L with the exhaust fans and the subslab depressurization systems operating.

In the new wing, the unit ventilators are turned off at night except in extremely cold weather when they are cycled. It was decided to install two subslab depressurization points in this wing to provide mitigation when the unit ventilators were not operated. The two 4-inch pipes were installed in the hall and manifolded with an above-ceiling 6-inch pipe running to a Kanalflakt GV-12 fan (rated at 510 cfm at 0.75 inch static pressure) at the north end of the building. One suction point was installed with a 3-foot diameter subslab hole about 20 feet from the east end of the hall. The other suction point was installed with a 1-foot diameter subslab hole about 60 feet from the end of the hall. Pressure field extension measurements indicated that the two fields overlapped; all slab areas of the wing, except the most southern classrooms, were depressurized to the outside walls.

C.5 Second-Stage Mitigation

Since the new wing pressure field extension around the 1-foot diameter suction hole was not as great as around the 3-foot suction hole, the 1-foot subslab suction hole was increased to 3 feet in diameter. This extended the measurable depressurization area by 10 feet to the south, which was sufficient to reach the last two classrooms. The amount of depressurization in the test holes in all directions around the suction point was doubled. With the subslab depressurization system operating, radon levels were below 4 pCi/L in all classrooms with the unit ventilator fans off.

C.6 Conclusion

This school was relatively simple to mitigate and, although the subslab communication was not very good due to low quality aggregate, the three SSD systems performed adequately because of large fans, large diameter pipe, and large subslab suction pits.

School D: Washington County, MD

This successful school mitigation showed that schools with radiant heating coils in the slab can be mitigated with SSD if a deep layer of aggregate is under the slab. The project was expected to be difficult because of the limited number of places where the slab could be penetrated without the danger of drilling through a hot water pipe. A newer section of the school, heated with unit ventilators, was mitigated with two multi-point SSD systems.

D.1 School Description

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 in an off set to the original building, and a separate building (Building B) was built which contains 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 can be used to exhaust air in plenums over the hall ceiling. Each room has a ceiling vent which connects to these hall plenums. However, the exhaust fans are never used. Consequently, the building has no active ventilation system.

D.2 Initial Radon Tests

All rooms in both buildings were tested with charcoal canisters over a weekend in mid-April. Of 24 tests, 21 were over 4 pCi/L, 16 were over 8 pCi/L, and 3 were over 20 pCi/L. 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.

D.3 Building Plan Inspection

Plans showed that the initial building and kindergarten addition had 6 inches of aggregate under a 6-inch thick slab containing hot water pipes for heating. Building B had 4 inches of aggregate under a 4-inch slab.

D.4 Pre-Mitigation Diagnostics

A continuous radon monitor was placed in one of the classrooms in Building B to measure the effect of unit ventilator operation on radon entry. It was found that radon levels would rise overnight to above 20 pCi/L with the ventilator off but would remain below 2 pCi/L with the ventilators operating. Again, this shows that a unit ventilator can reduce radon levels by pressurizing the room slightly. When run continuously this type of unit ventilator can prevent radon entry.

D.5 First-Stage Mitigation

Since the Building B ventilators are off during night setback, a four-point, two-fan subslab depressurization system was installed to reduce radon entry. The risers are 4-inch pipes connected to two 6-inch manifold pipes above the dropped ceiling. (Two risers are manifolded to each pipe.) A Kanalflakt GV-9 fan (rated at 200 cfm at 0.75-inch static pressure) is used to exhaust each system. Pressure field extension measurements indicated that subslab depressurization extended 50 feet, the minimum distance necessary to reach all parts of the slab.

With the Building B 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 of marginal value 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. A ½-inch expansion joint around all of the slabs in the building is deteriorating, leaving significant openings to the subslab. This probably leads to some short-circuiting of the subslab depressurization system.

D.6 Second-Stage Mitigation

Subslab suction on this original building (the intra-slab radiant-heat building) was a challenge since construction plans showed that the hot water pipes in the slab were separated by no more than 15 inches over the entire building. As a result, it was difficult to locate an area where a 6-inch subslab suction point could be put through the slab without running the risk of damaging a hot water pipe. Building plans identified a 3-foot square area without water pipes in each room. A hole was successfully cut through one of these areas. The plans indicated that the aggregate was a minimum of 6 inches deep, much deeper than at any other school examined. A 6-inch suction point was installed with a 3-foot diameter hole with a Kanalflakt KTR150-8 fan (rated at 510 cfm at 0.75-inch static pressure). Pressure field extension was far greater than expected; depressurization could be measured as far as 90 feet 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 enhanced pressure field extension; this will be studied further. It appears that this one suction point will solve the problem in the original building. If this one suction point is not sufficient to treat the entire building, it may take a second point, operated on a separate fan, to completely mitigate the building.

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 inches apart to clear the commode's sewer line. A Kanalflakt T-2 fan (rated at 140 cfm at 0.75 inch static pressure) installed on this point lowered radon levels to below 2 pCi/L. No pressure field extension measurements were made for fear of damaging a heating water pipe.

This school has been retested over the winter to determine if the SSD systems continue to mitigate during cold weather conditions; results should be available soon.

D.7 Conclusion

The ease of mitigating several thousand square feet with one SSD suction point in the older section of this school was an encouraging result. Building B was a standard installation with two suction points on each of two SSD systems.

School E: Fairfax County, VA

This successful school mitigation project showed that radon problems can be aggravated by exhaust-only ventilation systems that produce continuous negative pressures in all rooms (relative to the subslab area). However, it was also shown that, with sufficient subslab permeability, SSD systems can achieve successful radon mitigation under these adverse conditions of negative pressure.

E.1 School Description

This slab-on-grade building is "L-shaped," and each wing has a central hall with classrooms on each side. The rooms are heated by hot water fin heaters along the outside walls. Each room had ceiling exhaust vents into a plenum over the rooms and halls. Since there was no supply air fan, the roof-mounted exhaust fans in this plenum caused severe depressurization (0.060 inch WC negative pressure) of the entire building, and any make-up air entered the building only through infiltration induced by the depressurization.

The building was designed so that each classroom would be ventilated adequately only if one of the windows was left open. Unfortunately, the severe depressurization was also drawing subslab soil gas containing radon into the building.

E.2 Initial Radon Tests

Tests during the fall of 1987 in this school were the first to suggest that radon levels in classrooms varied widely from room to room, and that the test results were difficult to predict from room location and construction. Initially, charcoal screening tests were conducted in a few classrooms with the highest test showing approximately 6 pCi/L. Subsequent tests in all classrooms by the PTA showed several classrooms over 20 pCi/L. The two end classrooms of the southwest wing had levels of 22 and 17 pCi/L with three other rooms above 4 pCi/L. The southeast wing had three rooms with moderately elevated levels of 5, 6, and 7 pCi/L.

E.3 Building Plan Inspection

The building plans and specifications called for 4 inches of aggregate under the slab. The foundation plans showed that the slab was thicker along the hall between the classrooms.

E.4 Temporary Mitigation

The students were moved out of the rooms with the highest radon levels until the problem could be corrected. Since there was little experience with school radon mitigation in Fairfax County at this time, it was not known how long it would take to fix the problem.

E.5 Pre-Mitigation Diagnostics

Subslab communication tests and radon tests were performed to locate the radon sources and to determine whether SSD was a possibility. Radon levels from 25 to 2000 pCi/L were found under the slab and were consistent with the location of rooms with highest screening measurements. The subslab communication was found to be good, except in the thickened area of the slab. Separate suction points would have to be placed on each side of the hall. There was good communication under the interior walls that are perpendicular to the hall. This was consistent with the foundation plans that showed that these walls were non-load-bearing.

E.6 First-Stage Mitigation

A number of mitigation strategies were considered, including reversal of the exhaust fans to create pressurization, drilling ventilation holes through the walls behind the radiators to provide more fresh air, and replacing the entire HVAC system with a positive pressurization system. Before these expensive solutions were attempted, it was decided to try the simple techniques recommended by the EPA for house mitigation: eliminating depressurization, sealing cracks, and SSD. For eliminating depressurization, the HVAC exhaust fans were turned off and the rooms were retested to determine if the building could be mitigated by simply removing the negative pressure. Surprisingly, some of the rooms were still above 10 pCi/L under these conditions. It seems that the lower pressure probably reduced radon entry rates, but it also reduced the entry of fresh air that was diluting the radon.

E.7 Second-Stage Mitigation

The rooms with the highest radon levels were found to have cracks between the floor and wall that varied from to ¼ inch wide. These cracks were carefully sealed and re-testing of the room indicated a reduction of radon levels from 0 to 50 percent.

It is not unusual to get marginal mitigation results from crack sealing in houses. This is thought to be due to the difficulty in sealing all the radon entry routes such as porous hollow block walls. In addition, the radon levels often build up behind effective sealants, so that any unsealed leaks may provide more radon.

E.8 Third-Stage Mitigation

Subslab suction points were put in the two end rooms of the southwest wing. The subslab suction points were manifolded overhead and connected to one Kanalflakt GD-9 fan (rated at 310 cfm at 0.75-inch static pressure). Subslab excavation revealed that the aggregate was present and that it did not have significant fine material that would impede air flow. With this SSD system in operation there was good pressure field extension to at least three rooms on each side of the hall. In addition, all of the floor-to-wall joints were carefully sealed in all of the rooms of both wings. Following sealing and installation of the two suction points, all of the rooms in both wings tested below 4 pCi/L.

E.9 Fourth-Stage Mitigation

During December 1988, short-term tests revealed that radon levels were again above 4 pCi/L (despite the previous sealing work) in the southeast wing that did not have an SSD installed. Although longer term tests indicated that the long-term averages were below 4 pCi/L, school personnel decided to install an SSD system in this wing. This work has been completed, and all classrooms are below 4 pCi/L.

E.10 Conclusion

Mitigation of this school showed that, since subslab permeability was good, SSD was applicable despite the large size and complex ventilation system. Sealing and the reduction of depressurization were marginally effective, but SSD was very effective despite the depressurization of the building by the HVAC exhaust fans.

School F: Washington County, MD

This ongoing, initially unsuccessful school mitigation project shows that mistakes can be made easily in selecting an appropriate radon mitigation method. In this case, an attempt to use SSD to overcome subslab return air duct leakage was a failure; a more expensive solution will probably be necessary.

F.1 Initial Radon Tests

In April 1988, 39 charcoal canister radon tests showed that 28 were above 4 pCi/L, 8 were above 8 pCi/L, and none were above 20 pCi/L. All of the screening and confirmation tests were made when the building was unoccupied and the HVAC system was turned off.

F.2 Building Plan Inspection

The original school was built in 1954, and additions were made in 1964. Both are slab-on-grade construction. The additions have an HVAC system with return air ducts that are underneath the slab. The foundation plans and specifications call for 4 inches of aggregate under the slabs.

F.3 Pre-Mitigation Diagnostics

Radon grab samples showed about 20 pCi/L in the HVAC supply air when the system was turned on. This indicated that the return air ducts under the slab were drawing in soil gas and recirculating it through the school. Subslab pressure measurements indicated a pressure field that ranged from 0.1- to 0.001-inch WC of negative pressure. The largest pressures were nearest the return air exhaust vent that went up to the roof mounted fan system. These measurements suggested that if a SSD system were installed which would produce a larger competing pressure under the slab, the soil gas could not enter the cracks in the return air pipes.

F.4 First-Stage Mitigation

A Kanalflakt GV9 fan was mounted on the roof, connected by a 6-inch manifold pipe to two 4-inch diameter pipes. Suction points for these smaller pipes were drilled though the slab near the return exhaust stack in order to maximize the suction where diagnostics had indicated that the return air subslab suction was the highest. These slab penetrations uncovered good aggregate without excessive fine material.

However, it soon became obvious that this SSD system could not overcome radon entry into the return air ducts. The diagnostic measurements of the return air pressure field had been made through holes drilled through the slab and not through holes drilled through the actual return air pipe under the slab. When this pipe was exposed through the holes drilled for the 4-inch pipe, pressure measurements showed 0.8-inch WC inside the pipe. The diagnostics had confused the small subslab negative pressure that was caused by duct leakage with the much larger negative pressure in the pipe. It is very unlikely that a SSD system could realistically depressurize all areas of the slab to a level (approximately 0.8-inch WC in this case) that would be required to prevent soil gas from entering any cracks in the pipe. Subsequent radon tests indicated that the installed system had a negligible effect on the radon levels in the school.

F.5 Conclusion

Schools with subslab HVAC ductwork create a major problem that may require an alternative mitigation approach to SSD. Although it is generally a good idea to try a simple, inexpensive mitigation technique before trying the more complex and expensive techniques, there should be some experience or theory that provides some confidence that the technique will work.

A new overhead air-return system is now being installed in this school, and follow up diagnostic measurements are planned.

School G: Arlington County, VA

This successful school mitigation project showed that schools with minor radon problems in a few rooms may be mitigated by crack sealing or correction of HVAC imbalances. However, it is unlikely that these measures would be effective for radon levels significantly over 8 pCi/L since reductions from these approaches are usually about 50 percent.

G.1 School Description

Half of this older school building is one-story slab-on-grade; the other half is two-story with a walk-out basement. The walls are constructed of hollow blocks and the exterior of the school is brick veneer. The HVAC system combines unit ventilators with a single-fan air handling system with overhead duct work.

G.2 Initial Radon Tests

Initial and follow-up charcoal canister tests showed only two basement rooms between 4 and 8 pCi/L. All other rooms were below 4 pCi/L. The measurements were made during unoccupied periods.

G.3 Walk-Through Building Inspection

The HVAC supply vent in one of the problem rooms was found to be inoperative and the other room was found to have a 1/2-inch wide building expansion crack that was loosely covered by baseboard molding.

G.4 Pre-Mitigation Diagnostics

Subslab radon levels of 500 to 1000 pCi/L were measured in the basement area. A negative pressure in the room with the inoperative supply vent could be detected by air movement into the room when the HVAC fan was operating.

G.5 First-Stage Mitigation

An HVAC contractor was called in to correct the HVAC supply duct problem, and the building separation crack was sealed with a pourable polyurethane caulk. After these mitigation efforts were complete, continuous radon monitoring and short-term charcoal tests showed that the room with supply vent problems was below 2 pCi/L, but the room with the building separation crack still had daily peaks above 4 pCi/L. Further examination of the slab in this room showed an additional ¼ inch wide and 30-foot long crack between the floor and the wall underneath a unit ventilator system along one wall.

G.6 Second-Stage Mitigation

The unit ventilator covers in the remaining problem room were removed to gain access to the crack and pourable polyurethane caulk was used to seal it. Continuous monitoring and charcoal canister tests showed that the radon levels were now consistently below 4 pCi/L. Both problem rooms will be retested over the winter to determine if the mitigation continues to be effective.

G.7 Conclusion

When radon levels are slightly elevated (less than 8 pCi/L), then mitigation solutions such as crack sealing and elimination of gross HVAC depressurization may be effective. However, in many cases these techniques fail to reduce radon levels by as much as 50 percent, and the problem may recur during the winter. Sealing may not be very effective because many entry routes such as porous hollow block walls are hard to seal. Effective sealing causes a higher concentration of radon to build up behind the seal so that the few remaining entry routes may leak soil gas with higher radon concentrations. When HVAC depressurization is eliminated, there is still a slight depressurization of the upper surface of the slab due to the buoyancy of warmer air in the building (natural stack effect). The more effective and dependable mitigation techniques rely on positive pressurization above the slab, or negative pressurization beneath the slab.

School H: Washington County, MD

This ongoing school mitigation project is attempting to mitigate a combination crawl-space/slab-on-grade school. A large exhaust fan has been installed in the crawl space and the radon levels in the crawl space and the building have been slightly reduced. Future plans call for increased air sealing of the crawl space, retesting of the pressure and radon levels, evaluation of the mitigation effects of the HVAC system, and installation of a subslab suction system under the slab-on-grade section of the school.

H.1 School Description

Half of this single story building is over a crawl space and the other half is slab-on-grade. The HVAC system is a single-fan system with overhead duct work. The exterior of the school is brick veneer. All exterior entrances to the crawl space appear to be sealed.

H.2 Initial Radon Tests

In April 1988, 35 charcoal canister radon tests showed that 34 were above 4 pCi/L, 15 were above 8 pCi/L, and 1 was above 20 pCi/L (23.5 pCi/L). The radon levels were generally higher in the rooms over the crawl space. All of the screening and confirmation tests were made when the building was unoccupied and the HVAC system was turned off.

H.3 Building Plan Inspection

The original school, which is approximately 150,000 square feet in area, was built in 1936 over a crawl space. In 1967 a slab-on-grade addition was built onto two sides of the old building. The crawl space has a dirt floor and the wooden floor joists rest on a maze of masonry walls. The foundation plans and specifications for the slab call for 4 inches of aggregate under the slabs. The addition was constructed so that its floor would be at the same level as the crawl space floor. Retaining walls were built and shale fill was used to raise the level.

H.4 Walk-Through Building Inspection

The crawl space is accessible through hatches in the floor, but the crawl space size and maze of support walls do not appear to offer good access for laying down a ground cover for submembrane depressurization (SMD), as is often done in houses built over crawl spaces. Some plumbing pipes are in the crawl space and all exterior vents appear to have been sealed for security and to prevent the pipes from freezing.

H.5 Pre-Mitigation Diagnostics

Since there is little experience with radon mitigation of large crawl spaces, there are no guidelines for diagnostic analysis. Blower door testing of the crawl space was considered, but the installation of a 500 cfm exhaust fan was simpler to evaluate. Radon grab samples taken before the fan installation showed about 30 pCi/L in the crawl space.

H.6 First-Stage Mitigation

A Kanalflakt GV9 fan was mounted on one of the wooden panels that covered the crawl space vents. This fan can move 510 cfm at 0.0 pressure. It was mounted so that it would exhaust air from the crawl space. No crawl space sealing was done before evaluation of the system's performance.

The fans were turned off over the Christmas holiday weekend, and continuous radon monitors were placed in the crawl space and the main office to determine if the crawl space exhaust fan was reducing the radon. The monitoring showed that the crawl space levels dropped slightly when the fan was running. In addition, the office radon seemed to be well below 4 pCi/L when school was in session and the HVAC fans were operating. Pressure differentials in the crawl space did not change measurably (less than 0.001 inch WC) due to crawl space exhaust fan operation. Calculations of these results estimate that there is at least 10 square feet of leakage in the crawl space envelope.

H.7 Second-Stage Mitigation

The school will be retested with the HVAC system operating to determine the mitigation effect. If the HVAC system induces a positive pressure in all parts of the building, then the radon problems may be mitigated while the HVAC fans are operating. Further investigation will be required to determine if the HVAC mitigation can be relied on under all operating conditions, and whether there is a remaining radon exposure problem to those who use the school outside of normal operating hours when the HVAC fans are off. The crawl space exhaust fan seems to be lowering the radon levels slightly, but it does not seem to be creating much of a pressure barrier to prevent soil gas from moving into the building. To increase the depressurization, several large holes between the crawl space and the boiler room will be sealed.

A SSD system will be installed in the slab-on-grade part of the school. This system will be mounted externally by drilling a 6-inch diameter hole in the retaining wall, just below the slab level. A Kanalflakt T3B in-line fan will be mounted on a 6-inch stack that exhausts above roof level.

H.8 Conclusion

Several more mitigation stages are anticipated in order to obtain an effective radon mitigation system for this complex school. The final mitigation system will probably combine a number of methods due to the school's complex substructure.

APPENDIX C: STATE RADON OFFICES AND EPA REGIONAL RADIATION PROGRAM OFFICES

C.1 STATE RADON OFFICES

Radiological Health Branch
Alabama Department of Public Health
State Office Building
Montgomery, AL 36130
(205) 261-5313

Alaska Dept. of Health and Social Services
P.O. Box H-06F
Juneau, AK 99811-0613
(907) 586-6106

Arizona Radiation Regulatory Agency
4814 South 40th Street
Phoenix, AZ 85040
(602) 255-4845

Div. of Radiation Control and Emergency Management
Arkansas Department of Health
4815 Markham Street
Little Rock, AR 72205-3867
(501) 661-2301

Indoor Quality Program
California Department of Health Services
2151 Berkeley Way
Berkeley, CA 94704
(415) 540-2134

Radiation Control Division
Colorado Department of Health
4210 East 11th Avenue
Denver, CO 80220
(303) 331-4812

Connecticut Department of Health Services
Toxic Hazards Section
150 Washington Street
Hartford, CT 06106
(203) 566-3122

Division of Public Health
Delaware Bureau of Environmental Health
P.O. Box 637
Dover, DE 19903
(302) 736-4731

DC Dept. of Consumer and Regulatory Affairs
614 H Street, NW, Room 1014
Washington, DC 20001
(202) 727-7728

HRS Office of Radiation Control/Radon
1317 Wirewood Boulevard
Tallahassee, FL 32399-0701
(904) 488-1525
(800) 543-8279 (Consumer inquiries only)

Georgia Dept. of Natural Resources
Environmental Protection Division
205 Butler Street, NE
Floyd Towers East, Suite 1166
Atlanta, GA 30334
(404) 656-6905

Environmental Protection and Health Services Division
Hawaii Department of Health
591 Ala Moana Boulevard
Honolulu, HI 96813
(808) 548-4383

Bureau of Preventive Medicine
450 West State Street
Fourth Floor
Boise, ID 83720
(208) 334-5927

Illinois Department of Nuclear Safety
Illinois State Board of Health
1301 Knotts Street
Springfield, IL 62703
(217) 786-6399
(800) 225-1245

Division of Industrial Hygiene and Radiological Health
Indiana State Board of Health
1330 W. Michigan Street
P.O. Box 1964
Indianapolis, IN 46206-1964
(800) 272-9723

Bureau of Environmental Health
Iowa Department of Public Health
Lucas State Office Building
Des Moines, IA 50319-0075
(800 383-5992

Bureau of Air Quality and Radiation Control
Attention: Radon
Forbes Field, Building 740
Topeka, KS 66620-0110
(913) 296-1560

Radiation Control Branch
Cabinet for Human Resources
275 East Main Street
Frankfort, KY 40621
(502) 564-3700

Louisiana Nuclear Energy Division
P.O. Box 14690
Baton Rouge, LA 70898-4690
(504) 925-4518

Division of Health Engineering
Maine Department of Human Services
State House Station 10
Augusta, ME 04333
(207) 289-3826

Division of Radiation Control
Maryland Dept. of Health and Mental Hygiene
201 W. Preston Street
Baltimore, MD 21201
(301) 631-3300
(800) 872-3666

Radiation Control Program
Massachusetts Department of Public Health
23 Service Center
Northhampton, MA 01060
(413) 586-7525
(617) 727-6214 (Boston)

Michigan Department of Public Health
Division of Radiological Health
3500 North Logan
P.O. Box 30035
Lansing, MI 48909
(517) 335-8190

Section of Radiation Control
Minnesota Department of Health
P.O. Box 9441
717 SE Delaware Street
Minneapolis, MN 55440
(612) 623-5348
(800) 652-9747

Division of Radiological Health
Mississippi Department of Health
P.O. Box 1700
Jackson, MS 39125-1700
(601) 354-6657

Bureau of Radiological Health
Missouri Department of Health
1730 E. Elm, P.O. Box 570
Jefferson City, MO 65102
(800) 669-7236 (Missouri only)

Occupational Health Bureau
Montana Dept. of Health and Environmental Sciences
Cogswell Building A113
Helena, MT 59620
(406) 444-3671

Division of Radiological Health
Nebraska Department of Health
301 Centennial Mall South
P.O. Box 95007
Lincoln, NE 68509-5007
(402) 471-2168

Radiological Health Section
Health Division
Nevada Department of Human Resources
505 East King Street, Room 203
Carson City, NV 89710
(702) 885-5394

New Hampshire Radiological Health Program
Health and Welfare Building
6 Hazen Drive
Concord, NH 03001-6527
(603) 271-4588

New Jersey Dept. of Environmental Protection
380 Scotch Road, CN-411
Trenton, NJ 08625
(609) 530-4000/4001 or (800) 648-0394 (in state) or (201) 879-2062 (Northern NJ Radon Field Office)

New Mexico Environmental Improvement Div.
Community Services Bureau
1190 St. Francis Drive
Harold Runnels Building
Santa Fe, NM 87503
(505) 827-2948

Bureau of Environmental Radiation Protection
New York State Health Department
2 University Place
Albany, NY 12203
(800) 342-3722 (NY Energy Research & Development Authority)

Radiation Protection Section
North Carolina Department of Human Resources
701 Barbour Drive
Raleigh, NC 27603-2008
(919) 733-4283

Division of Environmental Engineering
North Dakota Department of Health and Consolidated Laboratory
Missouri Office Building
1200 Missouri Avenue, Room 304
P.O. Box 5520
Bismarck, ND 58502-5520
(701) 224-2348

Radiological Health Program
Ohio Department of Health
1224 Kinnear Road, Suite 120
Columbus, OH 43212
(614) 644-2727 or
(800) 523-4439 (in state only)

Radiation and Special Hazards Service
Oklahoma State Department of Health
P.O. Box 53551
Oklahoma City, OK 73142
(405) 271-5221

Oregon State Health Department
1400 S.W. 5th Avenue
Portland, OR 97201
(503) 229-5797

Bureau of Radiation Protection
Pennsylvania Department of Environmental Resources
P.O. Box 2063
Harrisburg, PA 17120
(717) 787-2480 or
(800) 237-2366 (in state only)

Puerto Rico Radiological Health Division
G.P.O. Call Box 70184
Rio Piedras, PR 00936
(809) 767-3563

Division of Occupational Health and Radiation Control
Rhode Island Department of Health
206 Cannon Building
75 Davis Street
Providence, RI 02908
(401) 277-2438

Bureau of Radiological Health
South Carolina Department of Health and Environmental Control
2600 Bull Street
Columbia, SC 29201
(803) 734-4700/4631

Office of Air Quality and Solid Waste
South Dakota Department of Water and Natural Resources
Joe Foss Building, Room 416
523 E. Capital
Pierre, SD 57501-3181
(605) 773-3153

Division of Air Pollution Control
Custom House
701 Broadway
Nashville, TN 37219-5403
(615) 741-4634

Bureau of Radiation Control
Texas Department of Health
1100 West 49th Street
Austin, TX 78756-3189
(512) 835-7000

Division of Environmental Health
Bureau of Radiation Control
288 North 1460 West
P.O. Box 16690
Salt Lake City, UT 84116-0690
(801) 538-6734

Division of Occupational and Radiological Health
Vermont Department of Health
Administration Building
10 Baldwin Street
Montpelier, VT 05602
(802) 828-2886

Bureau of Radiological Health
Department of Health
109 Governor Street
Richmond, VA 23219
(804) 786-5932 or
(800) 468-0318 (in state)

Environmental Protection Section
Washington Office of Radiation Protection
Thurston Airdustrial Center
Building 5, LE-13
Olympia, WA 98504
(206) 753-5962
Radon Hotline (800) 323-9727

Industrial Hygiene Division
West Virginia Department of Health
151 11th Avenue
South Charleston, WV 25303
(304) 348-3526/3427
(800) 922-1255

Division of Health
Section of Radiation Protection
Wisconsin Department of Health and Social Services
5708 Odana Road
Madison, WI 53719
(608) 273-6421

Radiological Health Services
Wyoming Department of Health and Social Services
Hathway Building, 4th Floor
Cheyenne, WY 82002-0710
(307) 777-7956

C.2 EPA REGIONAL OFFICES

Region	Address/Telephone	States in Region
1	U.S. Environmental Protection Agency APT-2311 John F. Kennedy Federal Building Boston, MA 02003 (617) 565-3234	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont
2	U.S. Environmental Protection Agency 2AWM:RAD 26 Federal Plaza New York, NY 10278 (212) 264-4418	New Jersey, New York, Puerto Rico, Virgin Islands
3	U.S. Environmental Protection Agency 3AM12 841 Chestnut Street Philadelphia, PA 19107 (215) 597-8320	Delaware, District of Columbia, Maryland, Pennsylvania, Virginia, West Virginia
4	U.S. Environmental Protection Agency 345 Courtland Street, N.E. Atlanta, GA 30365 (404)347-3907	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee
5	U.S. Environmental Protection Agency 5AR-26 230 South Dearborn Street Chicago, IL 60604 (800) 572-2515 (Illinois) (800) 621-8431 (other states in region)	Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin

6	U.S. Environmental Protection Agency 6T-AS 1445 Ross Avenue Dallas, TX 75202-2733 (214) 655-7208	Arkansas, Louisiana, New Mexico, Oklahoma, Texas
7	U.S. Environmental Protection Agency 726 Minnesota Avenue Kansas City, KS 66101 (913) 236-2893	Iowa, Kansas, Missouri, Nebraska
8	U.S. Environmental Protection Agency 8HWM-RP 999 18th Street, Suite 500 Denver, CO 80202-2405 (303) 293-1709	Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming
9	U.S. Environmental Protection Agency A-1-1 215 Fremont Street San Francisco, CA 94105 (415) 974-8378	American Samoa, Arizona, California, Guam, Hawaii, Nevada
10	U. S. Environmental Protection Agency AT-082 1200 Sixth Avenue Seattle, WA 98101 (206) 442-7660	Alaska, Idaho, Oregon, Washington