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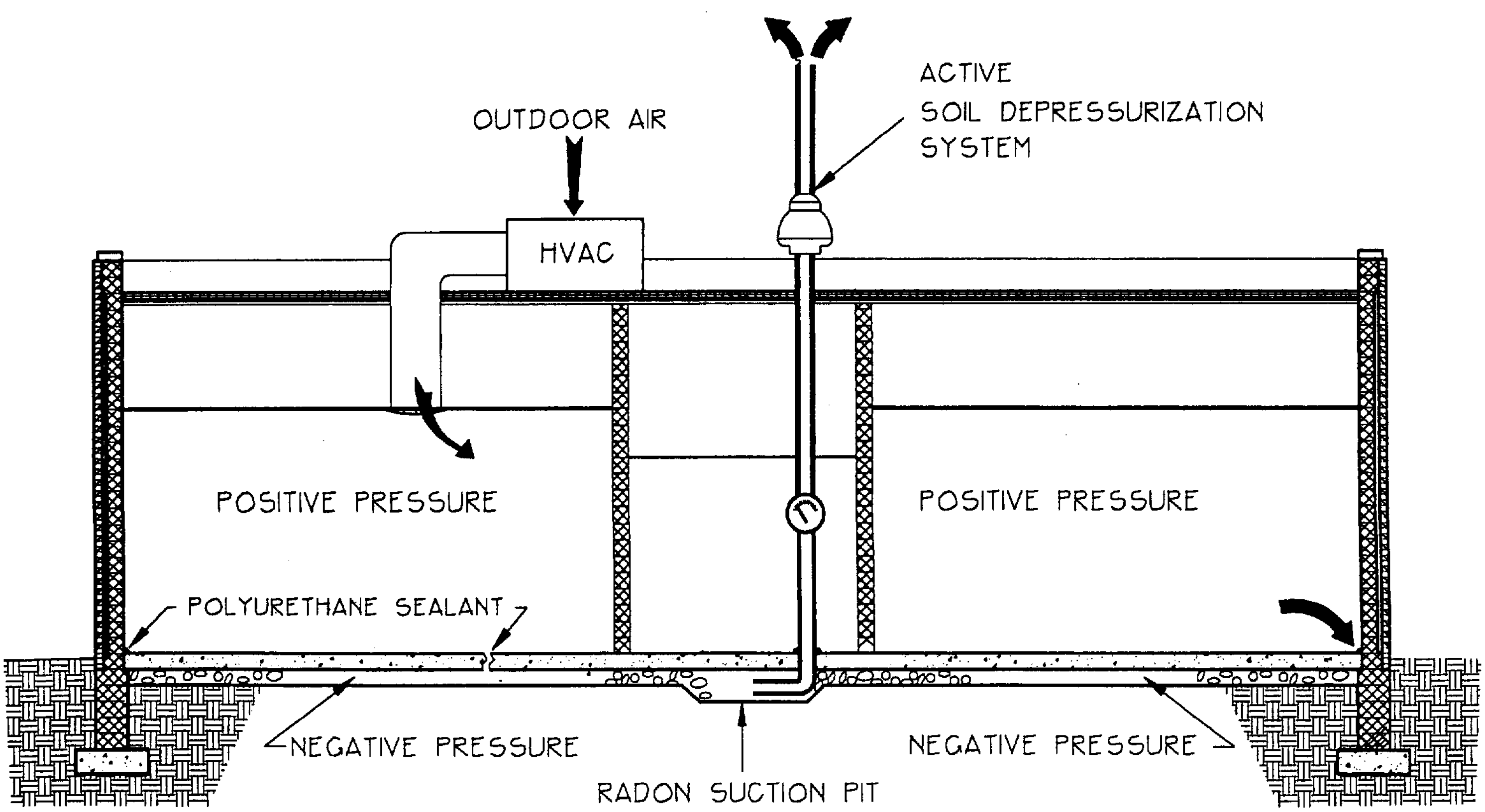
Radon Prevention in the Design and Construction of Schools and Other Large Buildings

Third Printing with Addendum, June 1994



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Radon Prevention in the Design and Construction of Schools and Other Large Buildings

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Abstract

It is typically easier and much less expensive to design and construct a new building with radon-resistant and/or easy-to-mitigate features, than to add these features after the building is completed and occupied. Therefore, when building in an area with the potential for elevated radon levels, architects and engineers should use a combination of radon prevention construction techniques. To determine if your building site is located in a radon-prone area, consult your EPA Regional Office or state or local radiation office.

We recommend the following three radon prevention techniques for construction of schools and other large buildings in radon-prone areas: (1) install an active soil depressurization (ASD) system, (2) pressurize the building using the heating, ventilating, and air-conditioning (HVAC) system, and (3) seal major radon entry routes. Specific guidelines on how to incorporate these radon prevention features in the design and construction of schools and other large buildings are detailed in this manual.

Chapter 1 of this manual is a general introduction for those who need background information on the indoor radon problem and the techniques currently being studied and applied for radon prevention. The level of detail is aimed at developing the reader's understanding of underlying principles and might best be used by school officials or by architects and engineers who need a basic introduction.

Chapter 2 of this manual provides comprehensive information, instructions, and guidelines about the topics and construction techniques discussed in Chapter 1. The sections in Chapter 2 contain much more technical detail and may be best used by the architects, engineers, and builders responsible for the specific construction details.

Metric Conversion Factors

Although it is EPA policy to use metric units in its documents, non-metric units have been used in this report to be consistent with common practice in the radon mitigation field. Readers may refer to the following conversion factors as needed.

Non-Metric	*Times*	*Yields Metric*
cubic foot (ft^3)	28.3	liters (L)
cubic foot per minute (ft^3/m)	0.47	liter per second (L/s)
foot (ft)	0.305	meter (m)
gallon (gal.)	3.79	liters (L)
horsepower (hp)	746	watts (W)
inch (in.)	2.54	centimeters (cm)
inch of water column (in. WC)	248.9	pascals (Pa)
mil (0.001 in.)	25.4	micrometers (µm)
picocurie per liter (pCi/L)	37	becquerels per cubic meter (Bq/m^3)
pound per square inch (psi)	6894.8	pascals (Pa)
square foot (ft^2)	0.093	square meter (m^2)

Acknowledgments

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Drafts of this document have been reviewed by a large number of individuals in the government and in the private and academic sectors. Comments from these reviewers in addition to those from the individuals listed above have helped significantly to improve the completeness, accuracy, and clarity of the document. The following reviewers offered input: William Angell of Midwest Universities Radon Consortium; Timothy M. Dyess and D. Bruce Henschel of EPA's AEERL; Deane E. Evans of AIA/ACSA Joint Council on Architectural Research; Kenneth Gadsby of Princeton University; Patrick Holmes of the Kentucky Division of Community Safety; Norman Grant of Quoin Architects and Engineers; Gene Fisher, Jed Harrison, Dave Murane, Dave Price, and Brian Ligman of EPA's Office of Radiation Programs; Clifford Phillips of Fairfax County Pubic Schools; Steve Sanders of Auburn University; Dave Saum of INFILTEC; Arthur E. Wheeler of Wheeler Engineering Co.; Larraine Kohler of EPA Region 2; Bill Bellanger of EPA Region 3; Steve Chambers of EPA Region 7; Phil Nyberg of EPA Region 8; Michael Bandrowski of EPA Region 9; Kevin Teichman of EPA's Office of Technology Transfer and Regulatory Support; Ruth Robenolt of EPA's Office of Communications; Jerry L. Clement of Educational Facilities in Houston, TX; and Thomas E. Toricelli of T.E. Toricelli AIA Architects.

Chapter 1

Introduction and Overview

1.1 Purpose

Radon is a naturally occurring radioactive gas in ambient air. It can also accumulate in varying amounts in enclosed buildings. Radon is estimated to cause many thousands of lung cancer deaths each year. In fact, the Surgeon General has warned that radon is the second leading cause of lung cancer in the U.S. today. Only smoking causes more lung cancer deaths (1).

Our increased understanding of the risks posed by indoor radon has underscored the need for construction techniques that prevent exposure to radon in residential and non-residential buildings. The Indoor Radon Abatement Act of 1988 states, "The national long-term goal of the United States with respect to radon levels in buildings is that the air within buildings should be as free of radon as the ambient air outside the building." This manual is intended to address this goal in the new construction of schools and other large buildings.

The U.S. Environmental Protection Agency (EPA) has developed construction techniques that are being used to reduce radon levels in new buildings. This manual provides architects, engineers, designers, builders, and school officials with an understanding of operating principles and installation instructions for these radon prevention techniques. Research indicates that many radon prevention features can be installed relatively easily and inexpensively during building construction. Installing these features during construction increases their effectiveness and involves less labor, disruption, and cost than when these same features are installed after the building is completed and occupied. Thus, the primary purpose of this manual is to provide information and guidelines about radon prevention techniques so that they can be cost-effectively incorporated into a building during the design and construction stages.

1.2 Scope and Content

This manual is divided into two parts:

Chapter 1—Introduction and Overview: Chapter 1 of this manual is a general introduction for those who need background information on the indoor radon problem and the techniques currently being studied and applied for radon prevention. The level of detail is aimed at developing the reader's understanding of underlying principles and might best be used by school officials or by architects and engineers who need a basic introduction to radon and radon reduction techniques. Those who are already familiar with the problems of constructing radon-resistant buildings should go on to Chapter 2. Chapter 1 contains the following sections:

1.3 Radon and Its Sources—an introduction to the problem of indoor radon.

1.4 Radon Prevention Techniques—an overview of current construction methods for radon prevention.

1.5 Why Radon Prevention Should Be Considered in Building Design.

Chapter 2—Technical Construction Information: Chapter 2 of this manual provides comprehensive information, instructions, and guidelines about the topics and construction techniques discussed in Chapter 1. The sections in Chapter 2 contain much more technical detail than Chapter 1, and may be best used by the architects, engineers, and builders responsible for the specific construction details. From the information presented in this manual, readers should be able to select radon prevention techniques that are appropriate to their particular situation.

Chapter 2 also briefly covers sources of information on measuring radon in schools and other large buildings. Appendix A contains a case study of a step-by-step installation of radon prevention techniques in a recently constructed large building. Radon levels and associated costs of the radon prevention features are included. References are in Appendix B, and Appendix C lists the EPA Regional Offices.

The recommendations in this manual are based on the best available information gathered from numerous research projects in existing and new construction, and in current field practice. Most new schools and other large buildings use slab-on-grade construction; therefore, this manual focuses on radon prevention techniques that can be applied to slab-on-grade buildings. But because radon can enter a building regardless of its foundation type, it also presents techniques applicable to buildings with basement and crawl space foundations.

As research continues and experience in the application of radon-resistant construction techniques grows, a variety of techniques might also prove effective in reaching radon reduction goals. These goals are to keep radon levels in new construction well below the currently recommended EPA action level of 4 pCi/L and as close to the long-term national goal of ambient radon levels (0.4 pCi/L) as possible. Many of these radon prevention techniques will eventually prove to be transferable to the architect's and engineer's common practices and, it is hoped, will be adopted in national building codes by the model building code organizations. EPA is currently working with the American Society of Testing and Materials (ASTM) to develop a standard for radon prevention in the construction of large buildings.

1.3 Radon and its Sources

The following subsections answer three basic questions that many people have about radon:

1) Why is radon a problem?

2) How does radon enter a building?

3) How should one evaluate a construction site?

1.3.1 Why is Radon a Problem?

Radon is a colorless, odorless, radioactive gas produced by the radioactive decay of radium-226, an element found in varying concentrations in many soils and bedrock. Figure 1-1 shows the series of elements that begin with uranium-238 and eventually decay to lead-210. Of all the elements and isotopes in the decay chain, radon is the only gas. Because radon is a gas, it can easily move through small spaces between particles of soil and thus enter a building. Radon can enter a building as a component of the soil gas and reach levels many times higher than outdoor levels.

While many of the isotopes in the uranium-238 decay series exist for a long time before they decay, radon has a half-life of only 3.8 days. Radon decay products have even shorter half-lives than radon and decay within an hour to relatively stable lead-210. At each level of this decay process, energy is released in the form of radiation. This radiation constitutes the health hazard to humans.

When radon and radon decay products are present in the air, some will be inhaled. Because the decay products are not gases, they will stick to lung tissue or larger airborne particles that later lodge in the lungs. The radiation released by the decay of these isotopes can damage lung tissue and can increase one's risk of developing lung cancer. The health risk depends on how long and at what levels a person is exposed to radon decay products. Radon and radon decay products cause thousands of deaths per year in the United States (1).

Like other environmental pollutants, there is some uncertainty about the magnitude of radon health risks. However, we know more about radon risks than the risks from most other cancer-causing substances. This is because estimates of radon risks are based on the studies of cancer in humans (underground miners). Additional studies of more typical populations are underway. Smoking combined with exposure to elevated levels of radon is an especially serious health risk.

Children have been reported to have greater risk than adults of certain types of cancer from radiation, but there are currently no conclusive data on whether children are at greater risk than adults from radon.

Radon levels are usually measured in picocuries per liter of air (pCi/L). Currently, it is recommended that indoor radon levels be reduced to less than 4 pCi/L. But the lower the radon level, the lower the health risk; therefore, radon levels should be reduced to as close to ambient levels as feasible (0.4 pCi/L). For additional information on the estimated health risks from exposure to various levels of radon, refer to EPA's *A Citizen's Guide to Radon, Second Edition* (1).

Architects and engineers should consider the health risks of radon prior to constructing new buildings or renovating existing buildings in radon-prone areas. Including radon pre-

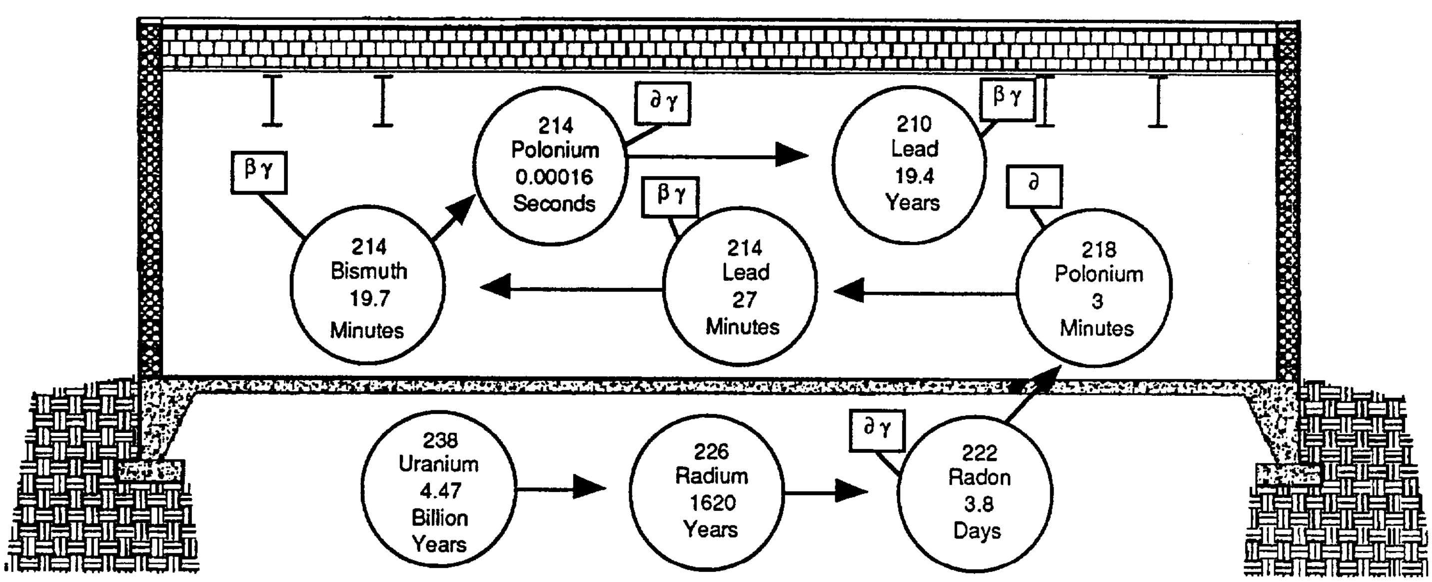

Figure 1-1. Radon decay chart. Time shown in half-life.

vention techniques during building design and construction will reduce the chance that a building will have a radon problem and also reduce the cost of reducing radon levels, if needed.

1.3.2 How Radon Enters a Building

The most common way for radon to enter a building is from the soil gas through pressure-driven transport. Radon can also enter a building through diffusion, well water, and construction materials. These modes of radon entry are briefly explained below.

Pressure-Driven Transport

Radon can enter a building through pressure-driven transport only if all of the following four conditions exist:

1) a source of radium to produce radon

2) a pathway from the source to the building

3) an opening in the building to permit radon to enter the building

4) a driving force to move radon from the source into the building through the opening

Pressure-driven transport is the most common way radon enters a building. Pressure-driven transport occurs when a lower indoor air pressure draws air from the soil or bedrock into the building. This transport happens in many schools and other large buildings because these buildings usually operate at an inside air pressure lower than that of the surrounding soil. Negative pressure inside buildings is due in part to building shell effects. For example, indoor/outdoor temperature differences, wind, and air leaks in the shell of the building can contribute to negative pressures in the building. The design and operation of mechanical ventilation systems that depressurize the building can also greatly influence radon entry. Sources of negative pressure in a typical building are shown in Figure 1-2.

Other Ways Radon Enters a Building

Radon also can enter buildings when there are no pressure differences. This type of radon movement is called diffusion-driven transport. Diffusion is the same mechanism that causes a drop of food coloring placed in a glass of water to spread through the entire glass. Diffusion-driven transport is rarely the cause of elevated radon levels in existing buildings. It is also highly unlikely that diffusion contributes significantly to elevated radon levels in schools and other large buildings.

Another way radon can enter a building is through well water. In certain areas of the country, well water that is supplied directly to a building and that is in contact with radium-bearing formations can be a source of radon in a building. At this writing, the only known health risk associated with exposure to radon in water is the airborne radon that is released from the water when it is used. A general rule for houses is that 10,000 pCi/L of radon in water contributes approximately 1 pCi/L to airborne radon levels. It is unlikely that municipal water supplied from a surface reservoir would contain elevated levels of radon and, thus, buildings using this source of water should not need to conduct radon testing of the water.

Radon can also emanate from building materials. However, this has rarely been found to be the cause of elevated levels in existing schools and other large buildings. The extent of the use of radium-contaminated building materials is unknown but is generally believed to be very small.

Because pressure-driven transport is by far the most common way radon enters a building, this manual does not address the other ways that radon can enter a building.

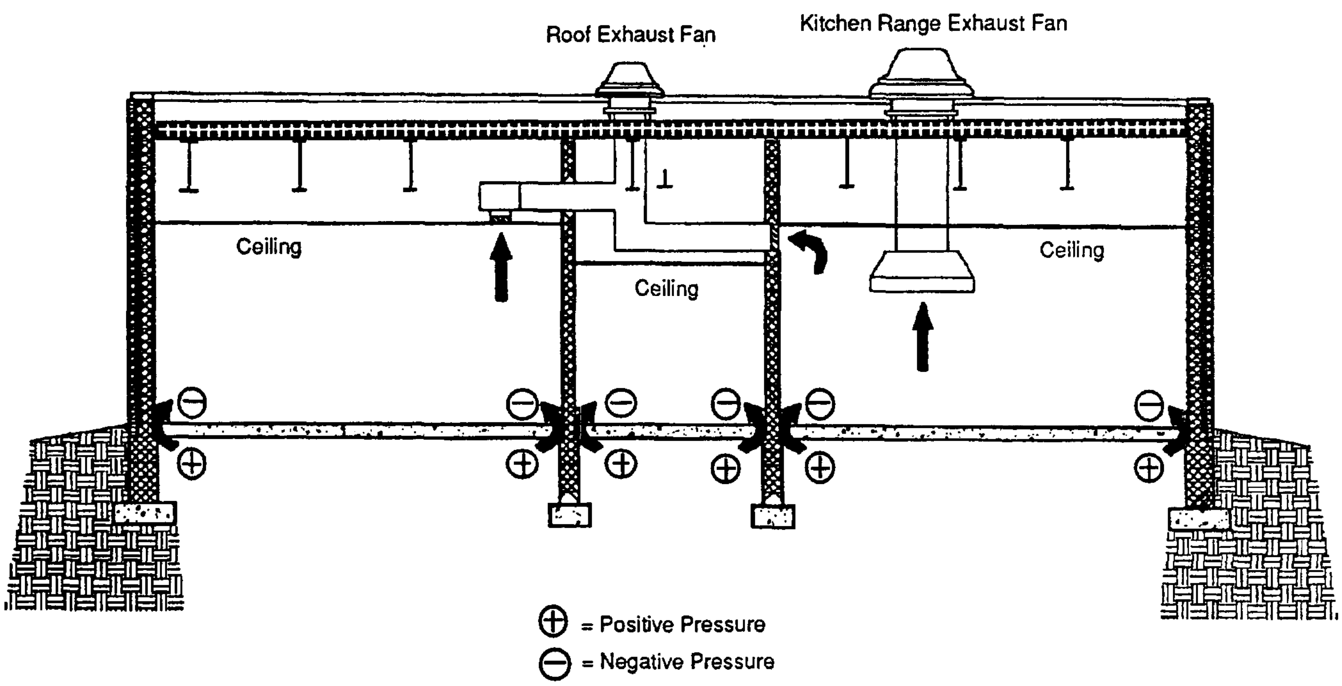

Figure 1-2. Examples of negative pressure sources in a typical building.

Radon Entry and Substructure Type

Elevated levels of radon can occur in any building regardless of foundation type. Figures 1-3, 1-4, and 1-5 show common radon entry routes for buildings constructed on slab-on-grade, basement, and crawl space foundations, respectively. Because a large majority of the new buildings constructed today are slab-on-grade substructures, Section 2.1 of this manual emphasizes radon prevention for slab-on-grade buildings. However, many of the radon prevention techniques used for slab-on-grade substructures are also applicable to basements and crawl spaces.

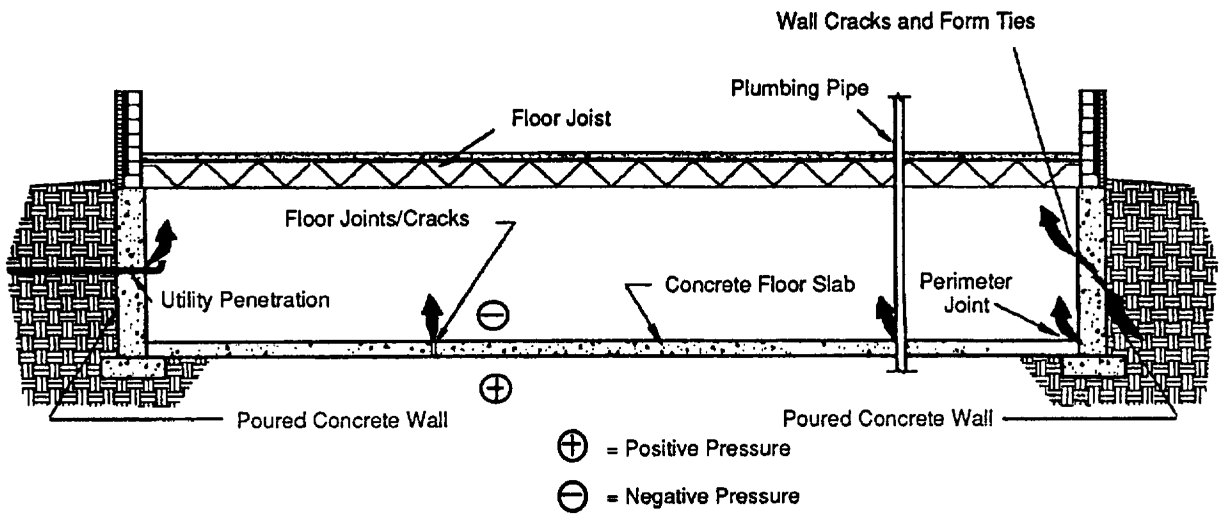

Figure 1-3. Typical radon entry routes in slab-on-grade construction.

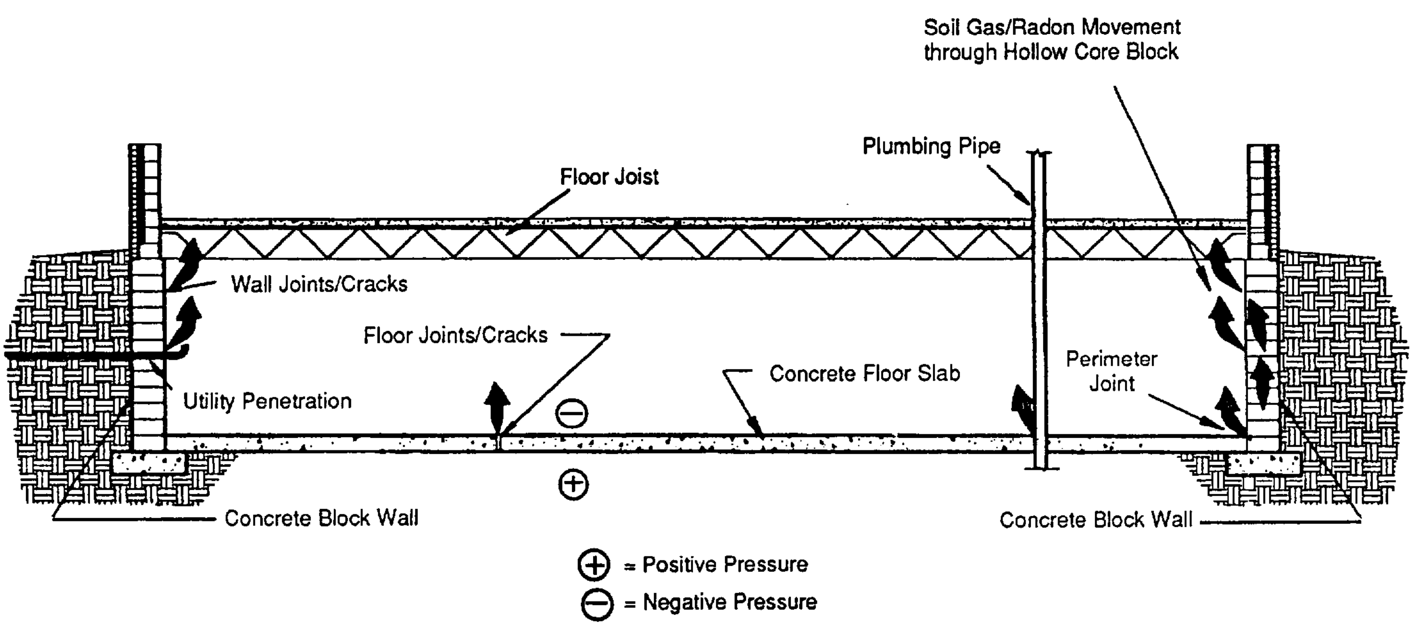

Figure 1-4a. Typical radon entry routes in concrete block basement walls.

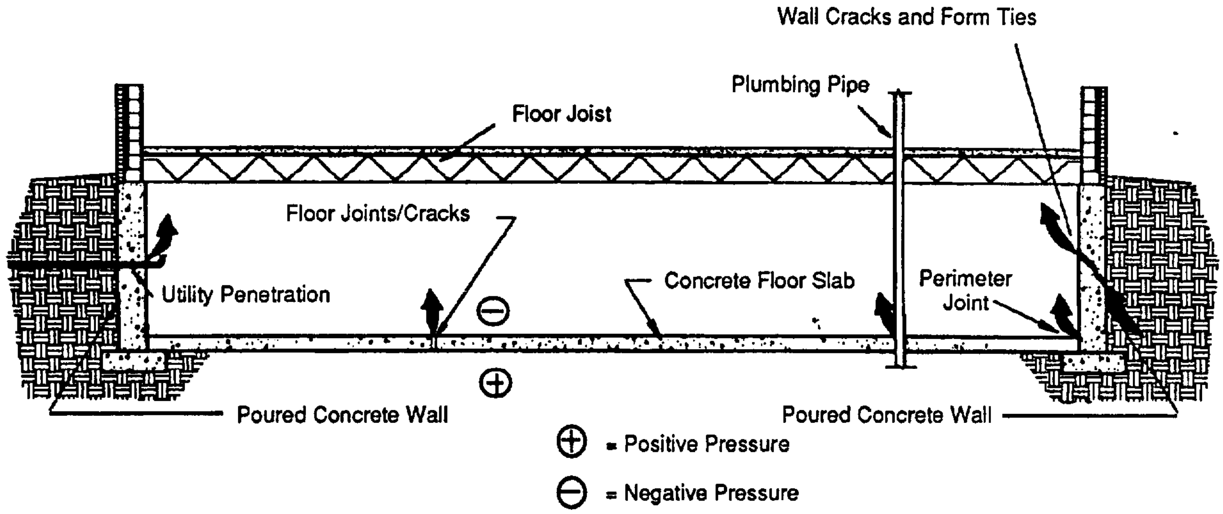

Figure 1-4b. Typical radon entry routes in poured concrete basement walls.

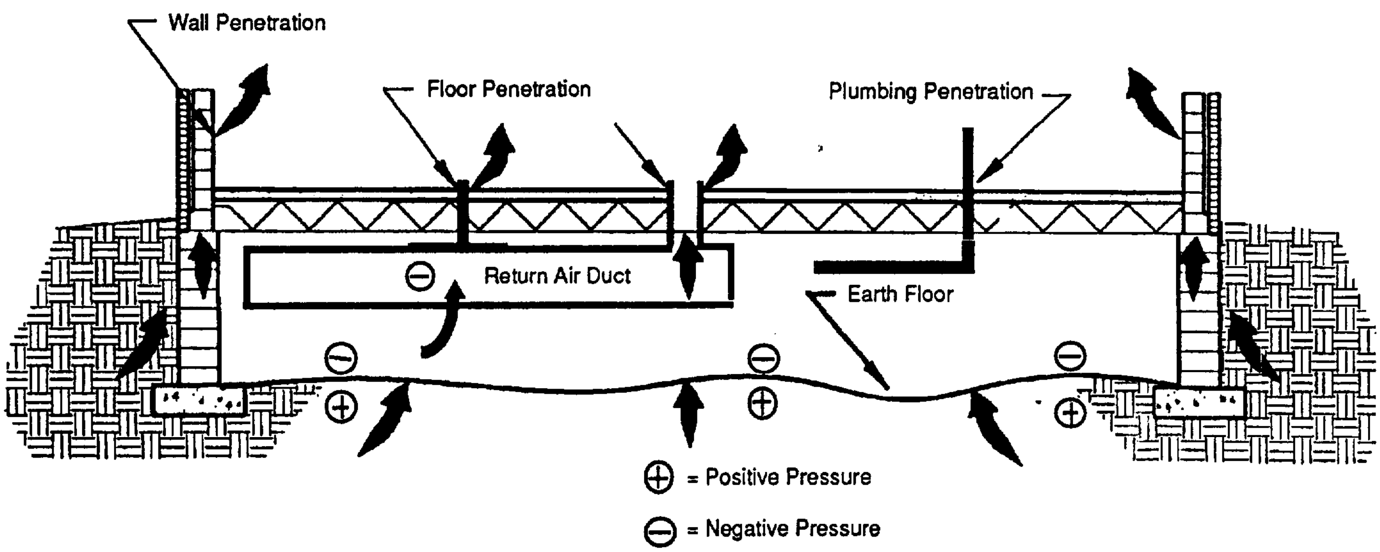

Figure 1-5. Typical crawl space foundation entry routes.

The specific additional requirements for basement substructures (such as sealing of basement walls) are discussed in Section 2.1.3. The additional recommended requirements for crawl spaces are discussed in Section 2.1.4 (submembrane depressurization).

1.3.3 How to Determine if Radon Prevention is Needed

An often-asked question is "Can one determine if radon-resistant construction techniques are necessary for a given site?" A simple and inexpensive standardized test that could conclusively identify problem sites would be very helpful. At present there are no reliable, easily applied, and inexpensive methods for correlating the results of radon evaluation tests of soils at a building site with subsequent indoor radon levels contained in a building built on that site. Bedrock and soils interact in complex ways with dynamic building behavior and environmental factors. There are too many combinations of factors that cause elevated indoor radon concentrations for simple correlations to exist.

In the absence of a simple test to determine when radon prevention techniques are needed, the discussion below covers various sources of information to assist architects and engineers with site assessment.

EPA National Radon Potential Map

One source of guidance is the growing body of radon data available at local, state, and regional levels. With these data, EPA is compiling a National Radon Potential Map. The map integrates five factors to produce estimates of radon potential. These factors are indoor radon screening measurements, geology, soil permeability, aerial radioactivity, and substructure type. All relevant data were collected and carefully evaluated so that the five factors could be quantitatively ranked for their respective "contribution" to the radon potential of a given area. The map assigns every county of the U.S. to one of three radon zones. Zone 1 areas have the highest potential for elevated levels, Zone 2 areas also have potential for elevated indoor radon levels but the occurrence is more variable, and Zone 3 areas have the least potential for elevated levels.

The radon potential estimates assigned on the map are stated in terms of predicted average screening levels. They are not intended to predict annual average measurements, but rather to assess the relative severity of the potential for elevated indoor radon levels. We recommend you use this map when it becomes available to help determine when radon prevention construction techniques might be needed.

Radon Levels in Nearby Buildings

Radon levels in a sample of existing U.S. school buildings were recently surveyed by EPA. Measurements to date indicate that many schools and other large buildings throughout the country have rooms or classrooms with radon levels above 4 pCi/L. Many have been measured at levels in excess of 20 pCi/L. It is expected that the geographic distribution of the radon problem in schools and other large buildings will be similar to that for homes. You can contact regional, state, or local officials for information about radon levels in nearby buildings and use this information, together with the National Radon Potential Map, to help decide if you are in a radon-prone area.

Soil

Several studies have attempted to make simple correlations between radon or radium concentrations in the soil and indoor radon concentrations. No direct correlations have been found.

Building Materials

An extremely small percentage of U.S. buildings with indoor radon concentrations greater than 4 pCi/L can be attributed to building materials. Most of the building material problems have arisen from the use of known radium-rich wastes such as aggregate in block or in fill around and under houses, or in areas of buildings with no ventilation. None of the existing large buildings studied in EPA's Air and Energy Engineering Research Laboratory's research program have had any identifiable problem associated with radon from building materials. However, be aware that building materials are a potential problem. But unless building materials have been identified as radium-rich in that region of the country, the chance of obtaining significant radon levels from building materials is very small.

Summary

Based on current research and the additional cost of radon resistant construction features, the expected impact on the building budget will probably be much less than $1.00 per ft^2 of earth contact floor area in most parts of the country. In most cases (buildings that are already designed to have subslab aggregate and plastic vapor retarder), sealing major radon entry routes and installing an ASD system will add less than $0.10 - $0.20 per ft^2 of earth contact floor area to total costs. Therefore, it is often more cost-effective to build using radon prevention techniques, rather than waiting until the building is completed and then having to add a radon mitigation system.

1.4 Radon Prevention Techniques

Like most other indoor air contaminants, radon can best be controlled by keeping it out of the building in the first place, rather than removing it once it has entered. The following subsections briefly describe the recommended radon prevention techniques discussed in Chapter 2 of this manual:

1.4.1 **Soil Depressurization.** A suction fan is used to produce a low-pressure field under the slab. This low-pressure field prevents radon entry by causing air to flow from the building into the soil.

1.4.2 **Building Pressurization.** Indoor/subslab pressure relationships are controlled to prevent radon entry. More outdoor air is supplied than exhausted so that the building is slightly pressurized compared to both the exterior of the building and the subslab area.

1.4.3 **Sealing Radon Entry Routes.** Seal major radon entry routes to block or minimize radon entry.

These radon prevention techniques are relatively inexpensive and easy to install. We recommend that all three of these techniques be used in new construction to ensure maximum radon control.

1.4.1 Soil Depressurization

The most effective and frequently used radon-reduction technique in existing buildings is active soil depressurization (ASD).

How an ASD System Works

An ASD system creates a low-pressure zone beneath the slab by using a powered fan to create a negative pressure beneath the slab and foundation. This low-pressure field prevents soil gas from entering the building because it reverses the normal direction of airflow where the slab and foundation meet. If the low pressure zone is extended throughout the entire subslab area, air will flow from the building into the soil, effectively sealing slab and foundation cracks and holes (2). For a simplified view of the operating principle of an ASD, refer to Figure 1-6. A similar system without a fan for "activation" is referred to as a "Rough-in" of an ASD system, and is briefly discussed at the end of this section.

The following are essential instructions for the design and construction of a soil depressurization system:

- Place a clean layer of coarse aggregate of narrow particle size distribution (naturally occurring gravel or crushed bedrock) beneath the slab.

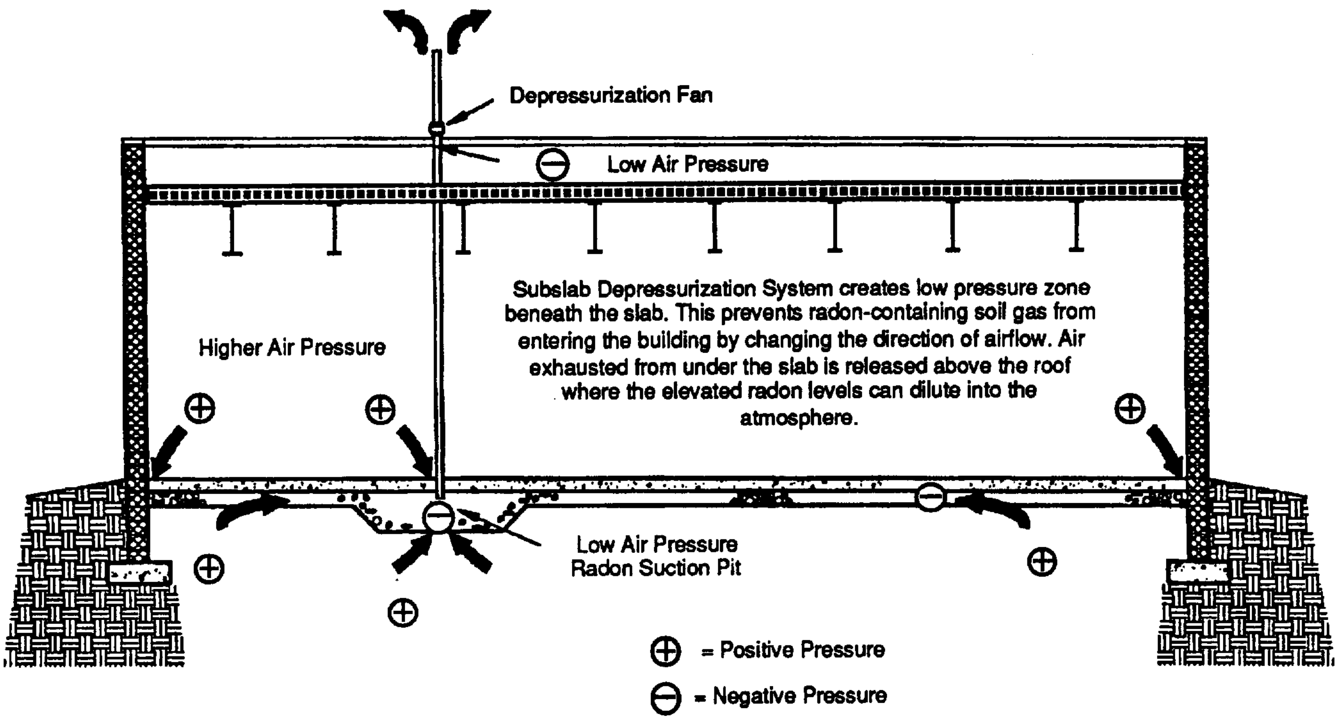

Figure 1-6. Subslab depressurization theory.

- Eliminate all major barriers to extension of the subslab low pressure zone, such as interior subslab walls.
- Install radon suction pit(s) beneath the slab in the aggregate (one radon suction pit for each area separated by subslab walls).
- Install a vent stack from the radon suction pit(s) under the slab to the roof.
- Install a suction fan on the vent stack. (The fan should be operated continuously, and the system should be equipped with a warning device to indicate loss of negative pressure through fan failure or other causes.)
- Seal all major slab and foundation penetrations.

Rough-in for an ASD System

A rough-in for an ASD system is the same as an ASD system except there is no fan. For new construction where radon levels are elevated even marginally, the installation of a rough-in system is a prudent investment and is recommended. If a building is found to have a radon problem, then a rough-in can easily be converted into an ASD system by installing a fan.

Passive Soil Depressurization

Architects and engineers may ask, "Is it possible to install a soil depressurization system that works passively (that is, without a fan)?" Although research has shown that passive systems are sometimes effective in home construction, they are not recommended for use in schools and other large buildings. Many competing negative pressures in large buildings can easily overcome a passive system. Also, the large number of radon suction pits and vent pipes needed for passive systems to be effective in a large building would make installation more expensive than an ASD system. Therefore, in radon-prone areas we recommend you do not use passive soil depressurization systems. We do recommend, as a minimum, that the design features for an ASD system be roughed-in for later activation if needed.

ASD Costs

Several factors affect the cost of an active soil depressurization system. Incremental installation costs for a system designed into a new large building range from as low as $0.10 per ft^2 of earth contact area to more than $0.75 per ft^2, depending on the availability of aggregate and sealing costs (3, 4, 5, 6, 7, 8). If aggregate is already part of the design, the costs will be at the low end. Incorporation of the aggregate and vapor retarder is considered good architectural practice and is required by code in most areas of the U.S., and, therefore would not be considered a radon-prevention cost.

For comparison, a recent EPA survey showed that the average cost for installing ASD in an existing school is about $0.50 per ft^2 (9). These costs could range from about $0.10 up to $3.00 per ft^2 of earth contact floor area depending on the structure and subslab materials.

1.4.2 Building Pressurization

Building pressurization involves bringing in more air to the building than is exhausted, causing a slightly positive pressure inside the building relative to the subslab area. The positive pressure in the building causes air to flow from inside the building to the outdoors through openings in the substructure and building shell; this effectively seals radon entry routes. Building pressurization is similar to ASD in that both methods block radon entry routes using air pressure barriers; but the systems are different in that, with building pressurization, air is pushed out of the building from inside rather than being drawn out from under the slab, as in ASD. The following section explains the principles of building pressurization using the heating, ventilating, and air-conditioning (HVAC) systems.

How Buildings Typically Operate

Many buildings (both leaky and tight buildings) tend to maintain an indoor air pressure lower than outdoors. It is often difficult to continuously operate a building to obtain slightly positive pressure conditions unless the building shell is tight and the building HVAC system supplies more outdoor air to each room than is exhausted. This difficulty is due to a complex interaction between the building shell, the mechanical systems, the building occupants, and the climate.

Modern buildings generally are constructed with fan-powered HVAC systems to provide outdoor air to the occupants. Many buildings also have exhaust fans to remove internally generated pollutants from the building. If the systems place the earth contact area under a slightly positive pressure with respect to the subslab, they will prevent radon entry and will dilute radon under the slab for as long as the systems are operating. However, if these fan systems (by design, installation, maintenance, or adjustment) place any earth contact area of the building under a negative pressure with respect to the soil, radon can enter through any openings in the slab.

Important Features of HVAC Systems to Prevent Radon Entry

The following HVAC system features and operating guidelines should be followed for radon prevention:

- In radon-prone areas, eliminate air supply and return ductwork located beneath a slab, in a basement, or in a crawl space in accordance with ASHRAE Standard 62-1989 (10).
- Supply outdoor air in accordance with guidelines in ASHRAE Standard 62-1989 (10).
- Construct a "tight" building shell to facilitate achieving a slightly positive pressure in the building.
- Seal slab, wall, and foundation entry points as noted in Section 1.4.3, especially in areas of the building planned to be under negative pressure by design (such as restrooms, janitor's closets, laboratories, storage closets, gymnasiums, shops, kitchen areas).
- Ensure proper training and retraining of the HVAC system operators, together with an adequate budget, so that the system is properly operated and maintained. (This appears to be a major area of neglect in existing school buildings.)
- In areas with large exhaust fans, supply more outdoor air than air exhausted if possible.

Once radon has entered a building, another way to reduce radon levels is by diluting them with ventilation air (outdoor air). Dilution air should be supplied from outdoors in accordance with ASHRAE Standard 62-1989 (10). To reduce highly elevated radon levels it may be necessary to supply higher quantities of outdoor air than those recommended by ASHRAE. (Note that neither pressurization nor dilution is effective when the HVAC system is not operating, such as in night and week end setback.) Additionally, dilution is not an effective stand-alone radon reduction technique if radon levels are substantially elevated. Dilution is a less reliable and frequently more costly approach than the other radon prevention techniques.

In summary, building pressurization with the HVAC system can reduce radon levels; however, because of the difficulty of properly operating the system in a way that continuously prevents radon entry, building pressurization is not recommended for use as a stand-alone radon-control system in new buildings. When building pressurization is used with the other methods of radon prevention (ASD and sealing of major radon entry routes), building pressurization contributes to low radon levels.

Costs and savings for HVAC systems and a tight building shell are not presented because they are considered good architectural and engineering practice, and moreover, are mandated by many building and energy codes.

1.4.3 Sealing Radon Entry Routes

Because the greatest source of indoor radon is almost always radon-containing soil gas that enters the building through cracks and openings in the slab and substructure, a good place to begin when building a radon-resistant building is to make the slab and substructure as radon-resistant as economically feasible.

However, it is difficult, if not impossible, to seal every crack and penetration. Therefore, sealing radon entry routes and constructing physical barriers as a stand-alone approach for radon control in schools and other large buildings, is not currently recommended. On the other hand, sealing of major radon entry routes will help reduce radon levels and will also greatly increase the effectiveness of other radon prevention techniques. For example, sealing increases the effectiveness of ASD by improving the pressure field extension beneath the slab. Sealing also helps to achieve building pressurization by ensuring that the building is a "tight box" without air leakage. Many of these sealing techniques are standard good construction practices.

Sealing Recommendations

Radon entry routes that should be sealed are:

- Floor/wall crack and other expansion joints. Where code permits, replace expansion joints with pour joints and/or control saw joints because they are more easily and effectively sealed.
- Areas around all piping systems that penetrate the slab or foundation walls below grade (utility trenches, electrical conduits, plumbing penetrations, etc.).
- Masonry basement walls.

Limitations of Sealing

Many construction materials are effective air and water barriers and also retard the transfer of radon-containing soil gas. In practice however, the difficulties that arise when using sealing and physical barrier techniques as the only means of control are virtually insurmountable. Physical barriers have proven to be frequently damaged during installation; moreover, failure to seal a single opening can negate the entire effort, especially when radon concentrations are high. Nevertheless, you should seal major radon entry routes; not only will sealing retard radon transfer but sealing will also increase the effectiveness of ASD and building pressurization.

The cost of sealing major radon entry routes is dependent on the building design and local construction practices. For one example, refer to the case study in Appendix A.

1.5 Why Radon Prevention Should be Considered in Building Design

Most of the radon prevention techniques covered in this manual can be applied to existing buildings, but installation will cost more than if these techniques were installed during initial construction. For example, factors that increase the difficulty and cost to install an ASD system in an existing building include:

- Poor communication below the floor slab (i.e., no aggregate or aggregate with many fines or with wide particle size distribution range).
- Barriers to subslab communication (internal subslab walls).
- Radon entry points at expansion and control joints.
- Ease of running the radon vent pipe and power source through and/or out onto the building's roof.
- Building depressurization caused by the HVAC system (or other fans) exhausting more air than is supplied.

All of the above factors can be controlled in new construction. As further research is conducted, additional information on the radon prevention features, or better guidance on when they are not needed, should become more clear and will be documented in future updates of this manual.

Again, we emphasize that it is important to include radon prevention features during design. Including these features during building construction makes their application *easier and costs much less* than adding them after the building is completed.

Chapter 2

Technical Construction Information

As outlined in Chapter 1, there are three practical and cost-effective approaches to preventing elevated radon levels in new buildings.

- Active Soil Depressurization (Section 2.1)
- Building Pressurization (Section 2.2)
- Sealing Radon Entry Routes (Section 2.3)

EPA recommends using all three of these methods to ensure effective and reliable radon control.

The following three sections present detailed technical information for implementing the above approaches. These sections might best be used by the architects and engineers who are developing the specifications and construction drawings for the building, and by the contractor who is building the structure. Guidelines for conducting radon measurements in schools and other large buildings are briefly discussed in Section 2.4.

2.1 Active Soil Depressurization (ASD)

This section describes how to design, install, and maintain an ASD system. The discussion pertains to slab-on-grade substructures since most new schools and other large buildings are constructed slab-on-grade. Guidelines for basement substructures are similar to slab-on-grade buildings, except that basement walls add another potential radon entry point that must be sealed. The application of ASD to basements is briefly covered in Section 2.1.3. Radon control in buildings with crawl space substructures is addressed in Section 2.1.4.

In most parts of the U.S., design and construction of new buildings with ASD systems is relatively easy and cost effective. Incorporating an ASD system into a new building is highly recommended in radon-prone areas, since effective operation of an ASD system is dependent on building design factors. Although it is possible to add an ASD system after the building is complete, the cost and effectiveness of the system will be directly influenced by building design parameters that can be easily controlled during building design and construction. Certain parameters, such as aggregate selection and subslab walls, cannot be practically modified in an existing building.

Principles of Operation

An ASD system prevents radon entry by creating a negative-pressure zone beneath the slab. If the negative-pressure zone is extended throughout the entire subslab area, air will flow from the building into the soil, effectively sealing slab and foundation cracks and holes, and thus preventing the entry of radon-containing soil gas. Figure 2-1 illustrates a typical ASD system.

To create this negative-pressure zone, a radon suction pit is installed in the aggregate under the slab. This subslab pit is then connected to a vent pipe that runs from the pit to the outdoors. A suction fan is connected to the pipe outside of the building to produce the negative-pressure zone beneath the slab, hence the system is "active." A lower air pressure in a building relative to the surrounding soil is what draws radon-containing soil gas into a building. The ASD system reverses the pressure difference — and thus the airflow direction at the slab — causing the subslab pressure to be lower than the indoor pressure. This air pressure differential keeps radon-containing soil gas from entering the building.

This manual describes the design and installation of a complete ASD system. A soil depressurization system could also be "roughed-in" and activated with a fan later, if needed. For new construction, where radon levels may be even marginally elevated, the installation of a rough-in system is a prudent investment and is recommended. If the completed building has a radon problem, then the roughed-in soil depressurization system can easily be made active at a low cost by adding a fan.

Architects and engineers may ask, "Is it possible to install a soil depressurization system that works passively (that is, without a fan)?" Although research has shown that passive systems are sometimes effective in home construction, they are not recommended for use in schools and other large buildings. Many competing negative pressures in large buildings can easily overcome a passive system. Also, the large number of radon suction pits and vent pipes needed for passive systems to be effective in a large building would make installation more expensive than an ASD system. Therefore, in radon-prone areas we recommend you do not use passive soil depressurization systems. We do recommend, as a minimum, that the design features for an ASD system should be roughed-in for later activation if needed.

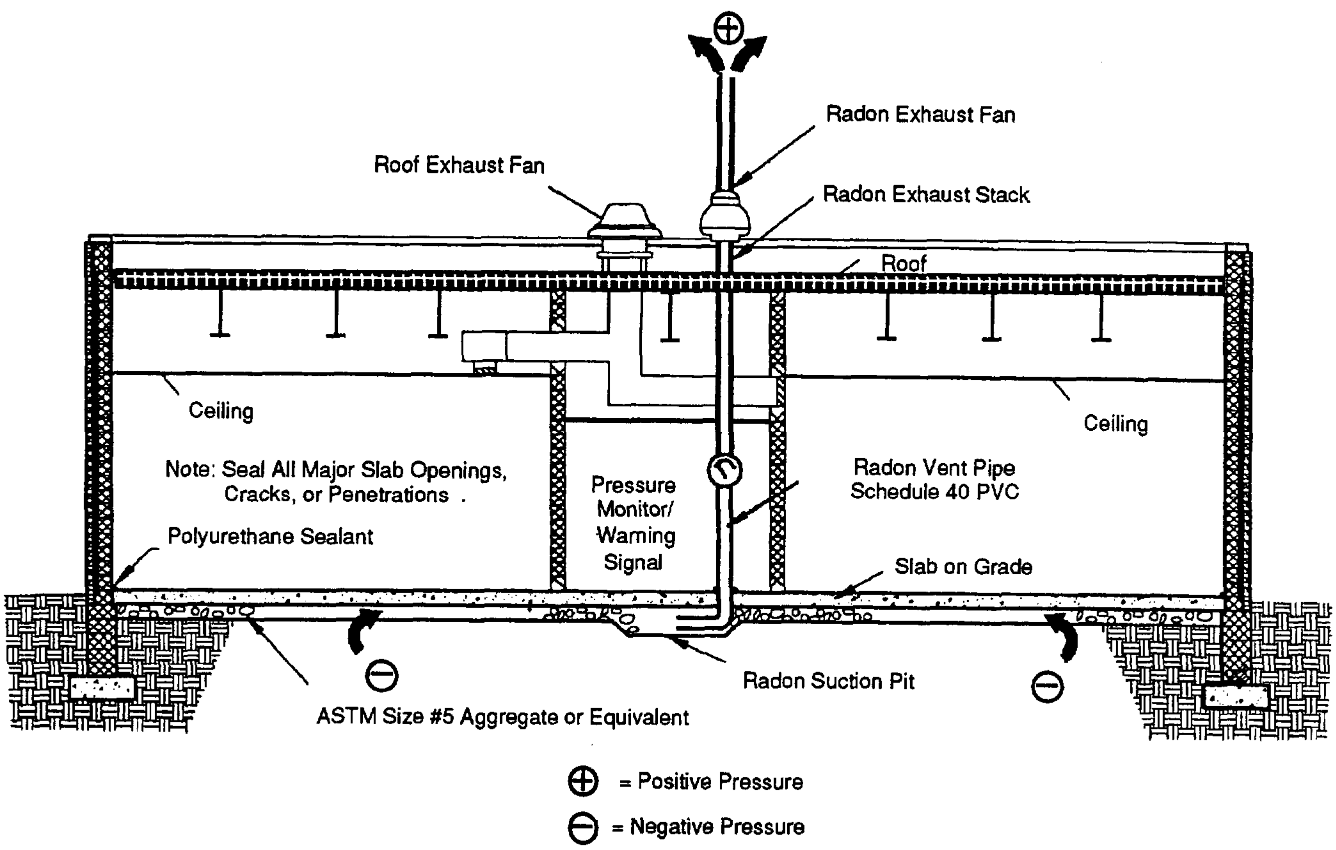

Figure 2-1. Typical subslab depressurization system. Not to scale.

2.1.1 ASD Design and Installation

The six essential guidelines for designing and installing ASD systems in schools and other large buildings are listed below. The design and construction procedures for each are discussed in detail in the sections that follow.

1) Place a continuous 4- to 6-in. layer of clean, coarse aggregate under the slab. (Aggregate, Section 2.1.1.1)

2) Eliminate barriers to subslab airflow such as subslab walls. (Subslab Walls, Section 2.1.1.2)

3) Install a 4- by 4-ft area by 8-in. deep radon suction pit (or equivalent) under the slab. (Suction Pits, Section 2.1.1.3)

4) Run a 6-in. diameter PVC radon vent pipe from the radon suction pit to the outdoors. (Radon Vent Pipe, Section 2.1.1.4)

5) Install a suction fan designed for use in ASD systems. (Suction Fan, Section 2.1.1.5)

6) Seal major radon entry routes including slab and foundation joints and cracks and utility and pipe penetrations. (Sealing Radon Entry Routes, Section 2.3)

2.1.1.1 Aggregate

Figure 2-1 illustrates how the creation and extension of a negative pressure field beneath the slab will cause air to flow from the building into the subslab area. This direction of airflow will prevent entry of soil gas into the building. The radon-containing soil gas is drawn up the vent pipe and exhausted outdoors where it will be quickly diluted to ambient levels.

To extend this negative pressure field effectively, highly permeable material, such as aggregate, should be placed under the slab. If the subslab material has low permeability (such as tightly packed sand or clay), or is interrupted by interior subslab walls (as discussed in Section 2.1.1.2), the pressure field might not extend to all areas of the soil under the slab. The building should be designed so that the pressure field extends under the entire building. To ensure the proper extension of the pressure field, install a 4- to 6-in. layer of clean, coarse aggregate beneath the slab prior to the pour.

Aggregate Specifications

In most areas of the U.S., subslab aggregate is routinely installed (and frequently required by code) to provide a drainage bed for moisture and a stable, level surface for pouring the slab. The preferred aggregate for ASD systems is crushed aggregate meeting Size #5 specifications as defined in ASTM C-33-90, "Standard Specification for Concrete Aggregates"

(11). This aggregate is in the range of 1/2 to 1 in. diameter with less than 10 percent passing through a 1/2-in. sieve and has a free void space of approximately 50 percent.

In September 1992, the average cost for a ton of crushed stone was $6.86. This cost represents an average for 20 U.S. cities, with a range from $4.50 to $11.32 per ton (12). For a layer of crushed stone 4 in. deep, this would be about $0.10 to $0.25 per ft².

Aggregate Placement

Place a minimum of 4 to 6 in. of aggregate evenly under the entire slab, taking care not to introduce any fine material. If the aggregate is placed on top of a material with a lot of fines and compaction of the aggregate is required for structural or code reasons, a geotextile fabric or an additional reinforced vapor retarder beneath the aggregate can be used so that fine particles from the natural soil do not mix with the aggregate. A vapor retarder should also be placed over the aggregate prior to pouring the slab. Although the vapor retarder probably will not serve as a stand-alone radon barrier (due to inevitable holes and tears in the plastic), it will keep the wet concrete from filling in spaces in the aggregate layer.

Drainage Mats

In areas where crushed aggregate is not readily available or is very expensive, some residential builders have used drainage mats designed for soil stabilization. Drainage mats cost $0.60 to $0.72 per ft² and are normally placed under only part of the slab. The use of drainage mats has not been demonstrated by EPA in any schools or other large buildings.

2.1.1.2 Subslab Walls

Because every subslab area isolated by subslab walls will normally need a radon suction pit and radon vent pipe, limiting subslab barriers to airflow will reduce ASD installation and operating costs. Figure 2-2a shows how an interior subslab wall can interrupt the aggregate layer and, hence, the subslab pressure field. Figure 2-2b, on the other hand, shows how a continuous aggregate layer under a thickened slab footing does not interrupt the subslab pressure field.

Figures 2-3a through 2-3d illustrate examples of four subslab wall layouts that have been observed in existing school buildings. The discussion below explains the effects that these example configurations have on ASD system design.

The Figure 2-3a design is preferred for radon control because internal subslab barriers are completely eliminated, thus maximizing subslab communication and ASD system performance. This design is referred to as post-and-beam construction and is very common in modern construction of large buildings. With this type of building design and the other ASD design features discussed in this section, one radon suction pit should provide adequate pressure field coverage over 100,000 ft² of ground contact area or larger. The building in the Appendix A case study has this type of subslab layout. In another recently constructed building with post-and-beam construction, one radon suction point depressurized an area of 480,000 ft².

Figure 2-3b illustrates the use of subslab walls that are perpendicular to the corridor but do not cross the corridor. In this example, the subslab walls would not interrupt the negative pressure field under the slab unless the subslab wall extended across the corridor (not shown in Figure 2-3b). As a result, only one radon suction pit would be needed.

Figure 2-3c shows two subslab walls each parallel to the corridor. In this case, the subslab area is divided into three compartments. For this design, two radon suction pits would probably be required, or three if one is installed in the corridor area.

Figure 2-3d shows the worst case example for a cost-effective ASD system design. Subslab walls run both parallel and perpendicular to the corridor, dividing the subslab area into many compartments. For an ASD system to be effective with such a design, one radon suction pit would normally be required for each subslab compartment.

Figures 2-4a and 2-4b illustrate the side view of the effect of subslab walls on the design of the ASD system. Figure 2-4a corresponds to a possible ASD system design for the subslab wall layouts shown in Figures 2-3a and 2-3b. Figure 2-4b corresponds to the ASD system design required for the layouts in Figures 2-3c and 2-3d. For the "worst case" scenario shown in Figure 2-3d, this sideview of the suction points would be required for each area surrounded by subslab walls. (Note that the radon suction pit shown in the corridor in Figure 2-4b may not be necessary.)

It is important that the issue of subslab walls be addressed early in the planning stages so that the building can be designed with limited subslab barriers. Designing subslab walls as illustrated in Figure 2-3a will significantly reduce the cost of radon prevention as evidenced by the case study (Appendix A).

In buildings where subslab walls must be used, the designer should consider "connecting" subslab areas by eliminating subslab walls (Figures 2-4a and 2-4b) under interior doors. This "connecting or bridging" should allow the negative pressure field to extend from a centrally located radon suction pit to areas that would have otherwise been isolated. This approach has had only limited field testing, but it is theoretically sound and is undergoing further field testing. Subslab communication could also be facilitated by using subslab "pipe sleeves" to connect areas separated by subslab walls. Again, using "pipe sleeves" is theoretically sound, but has not yet been field-demonstrated by EPA.

2.1.1.3 Radon Suction Pits

Purpose and Specifications

Radon suction pits facilitate communication throughout the subslab aggregate layer. Figure 2-5 presents an example of a radon suction pit that has been successfully field-demonstrated by EPA in ASD systems in new construction. The most important feature of the pit is that the end of the vent pipe terminates in a large void (or its equivalent exposed aggregate surface area). We recommend that for a 6-in. diameter vertical stack, you construct a radon suction pit with a 4 ft by 4-ft void area and 8 in. deep. These dimensions provide a pit void to aggregate interface of about 7 ft².

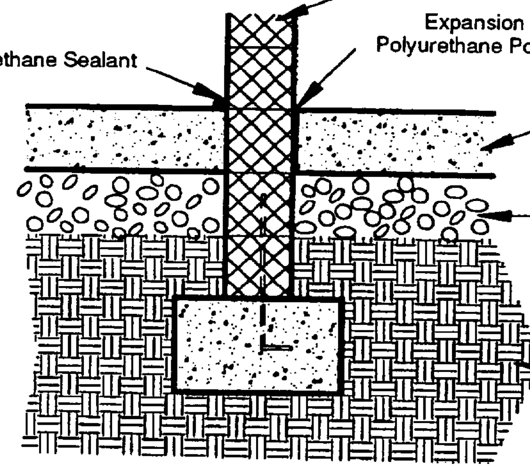

Figure 2-2a. Interior footing/foundation wall. Not to scale.

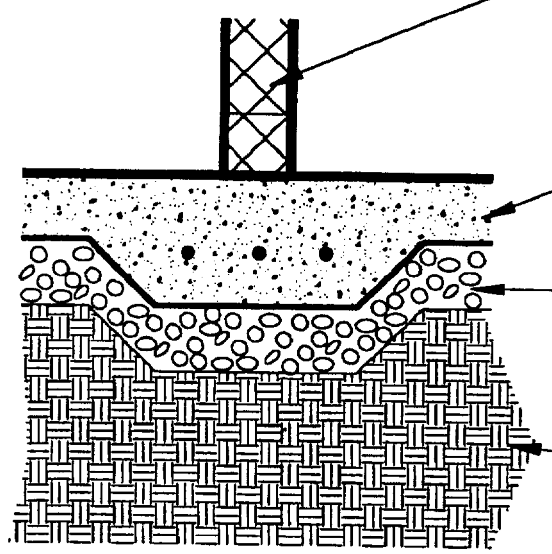

Figure 2-2b. Thickened slab footing. Not to scale.

A suction pit with a minimum exposed aggregate surface area about 30 times the cross sectional area of the vent pipe entrance is very effective. A concrete drainage distribution box or other structure that meets the 30-1 ratio should also be effective. However, only the construction detailed in Figure 2-5 has been field-tested by EPA. As shown in Figure 2-5, the vent pipe should enter the radon suction pit horizontally so that the suction pit may be located in a central location and the vertical vent pipe may be located wherever is most convenient rather than simply at the pit location.

Alternatively, the vent pipe can exit the radon suction pit vertically. The vertical approach is normally used for ASD systems in existing buildings because of the ease of installation. However, new construction provides the designer with the flexibility for selecting the most convenient and effective location for the radon suction pit and vent stack. When the slab is poured over the radon suction pit as shown in Figure 2-5, be sure to follow appropriate structural guidelines for reinforced concrete.

Location of Radon Suction Pits

The radon suction pit should be centrally located. A centrally located pit will provide even pressure field extension in all directions. Do not locate the pit near subslab barriers

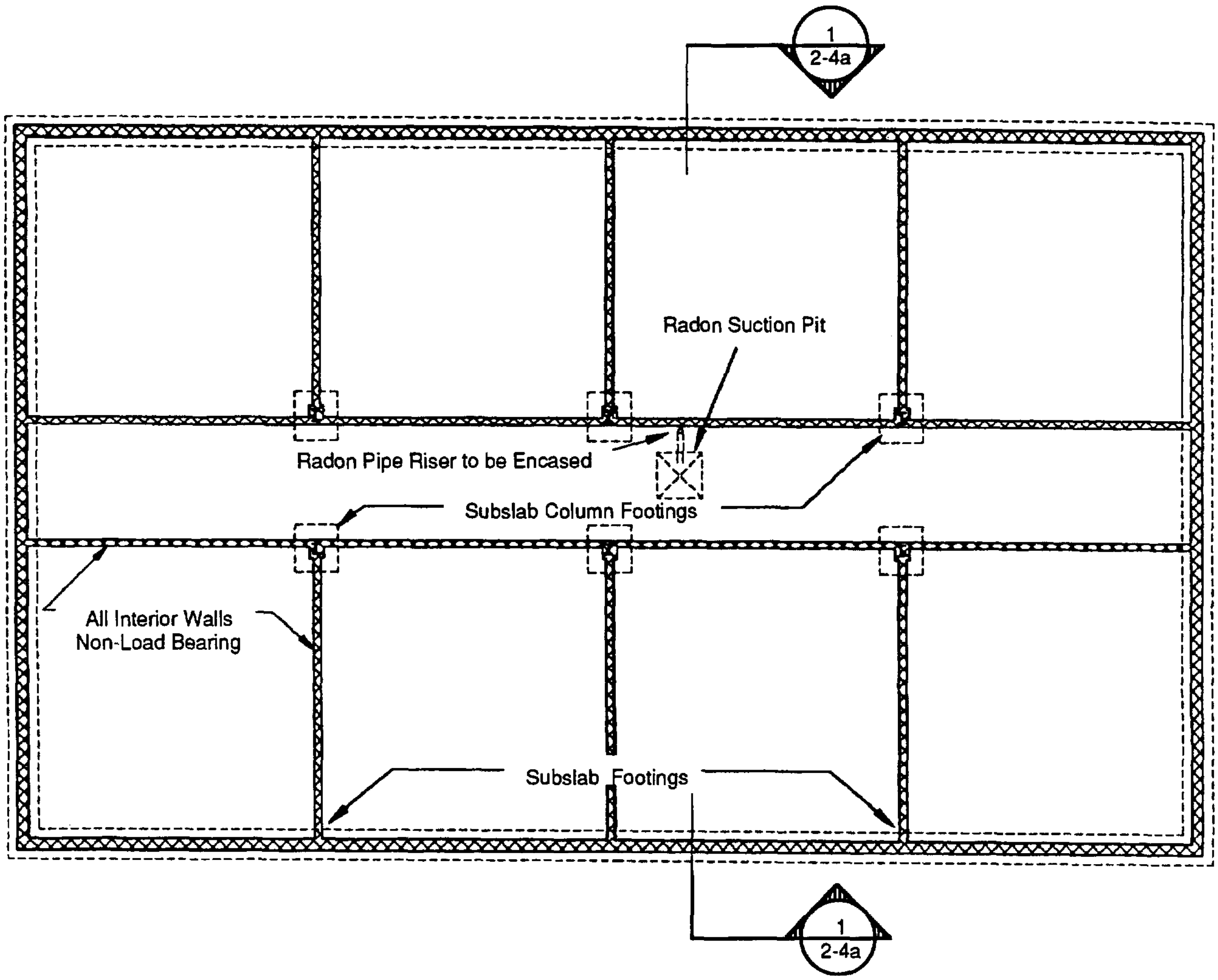

Figure 2-3a. Outside walls and post load bearing. Not to scale.

(such as footings) or near unsealed openings through the slab. As shown in Figure 2-5, the vent pipe should enter the radon suction pit horizontally. The vent pipe is then run under the slab, exiting the subslab in a convenient location.

Number of Radon Suction Pits

With the use of a properly designed radon suction pit, ASTM Size #5 aggregate, the elimination of subslab barriers, and sealing of major radon entry routes, one radon suction pit per 100,000 ft^2 of slab area should result in a very effective ASD system. This Figure 2-5 approach was recently successfully demonstrated by EPA in two large buildings: one building is 60,000 ft^2 in area, and the other is 480,000 ft^2. The 60,000 ft^2 building is discussed in detail in Appendix A.

Subslab Perforated Pipe

Instead of a radon suction pit, some designers prefer laying perforated polyvinyl chloride (PVC) drainage pipe under the slab and connecting the perforated pipe to the vent pipe. Horizontal perforated pipe is not necessary in ASD systems if the system is designed as recommended in this manual. This is because for a subslab horizontal pipe system to provide the equivalent exposed surface area to aggregate as a 4-ft by 4-ft by 8-in. deep radon suction pit, it is necessary to have approximately 240 linear ft of 4-in. pipe (with ten 3/4-in. holes per ft).

One recently constructed school with 50,000 ft^2 of ground contact used 11 suction points with 120 linear ft of perforated pipe extending from each suction point, totaling over 1300 linear ft. Field testing by EPA demonstrated that only one of the 11 suction points was needed and that the perforated pipe was not necessary for an effective ASD system (7).

Although some designers use systems with perforated pipe instead of a radon suction pit (7), this type of system can significantly increase construction costs due to both the quantity of pipe needed and the cost of placement. Therefore, EPA prefers the radon suction pit approach to installing subslab perforated pipe. If perforated pipe is used, size it so as not to significantly reduce the air flow which could normally be achieved through the connecting 6-in. vent pipe.

Interaction With Interior Drainage

Designers and builders of houses also have tried connecting the ASD system into interior footing drainage systems. Although this connection might facilitate the functioning of a

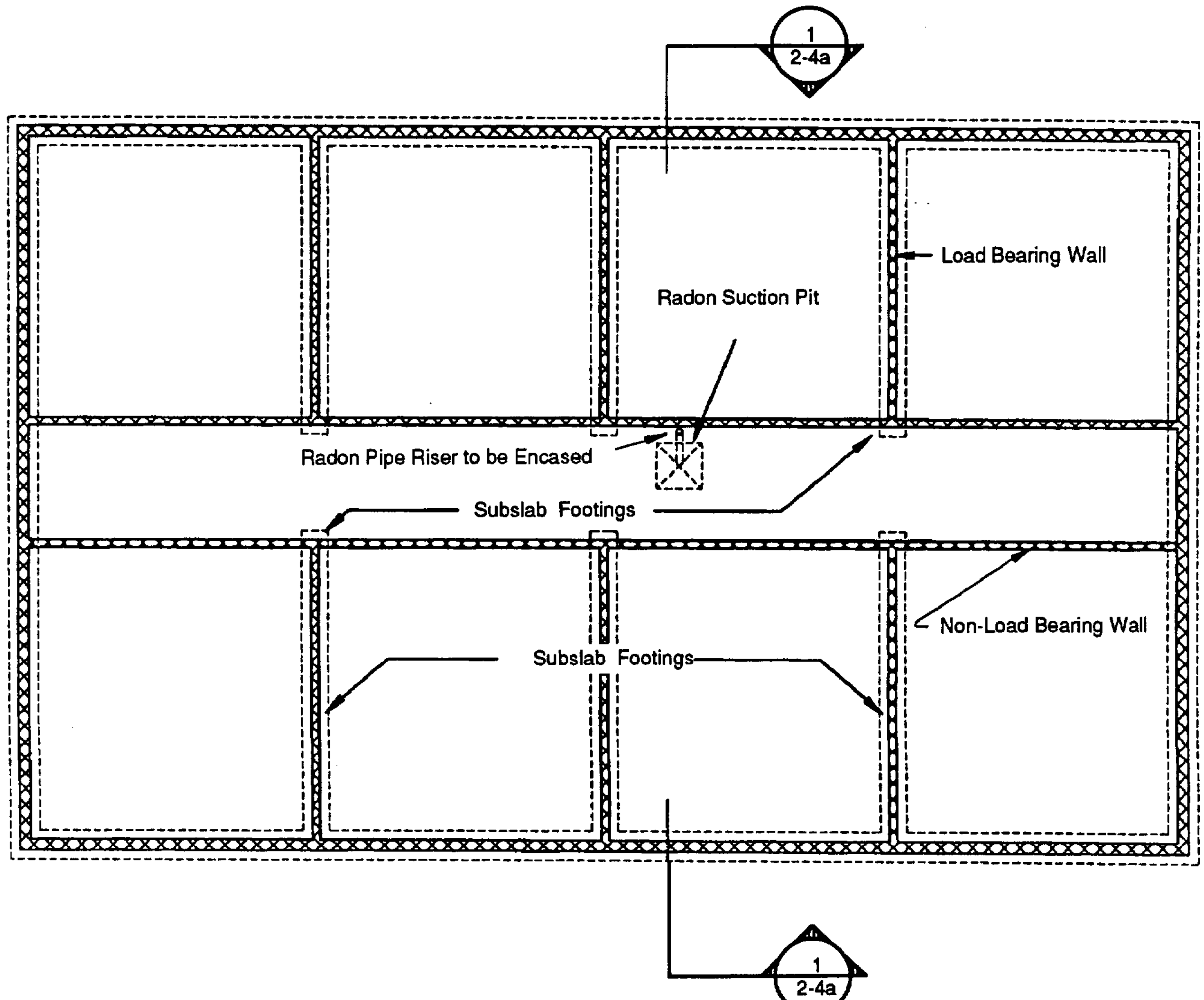

Figure 2-3b. Interior walls between rooms and outside walls load bearing. Not to scale.

passive system if the system is airtight, this approach has not been evaluated by EPA in schools or other large buildings.

Similarly, the use of interior footing drains for water control can affect the pressure field extension of an ASD system. Interior footing drains sometimes terminate in a sump hole. If this is the case, the builder must seal the sump hole airtight; if the sump hole is not sealed airtight, building air will be drawn into the sump by the subslab system, and the pressure field will be weakened, and pressure field extension will be decreased. It is also possible to use the sealed sump hole as a radon suction pit; this approach is common in houses (5), but its applicability in schools and other large buildings has not been demonstrated.

If interior footing drains are used and extend out beneath the footing to daylight or to a sewer, the drain must be airtight while still allowing water to drain in order for the system to work. Water traps have been used in houses, but this approach has yet to be demonstrated or evaluated in schools or other large buildings.

2.1.1.4 Radon Vent Pipe

Specifications

For new construction of schools and other large buildings, EPA recommends 6-in. diameter solid PVC pipe. Other sizes are available; 4-in. pipe is normally used for drainage systems and plumbing stacks and is easy to route vertically. However, if you are not planning on sealing expansion joints, we recommend you use vertical piping at least 6 in. in diameter. This size pipe is necessary since greater airflow will be needed to produce the same level of subslab suction and pressure field extension as a system with sealed expansion joints.

Building Codes

PVC radon vent pipes are typically used in existing buildings because of their ease of handling and cost; however, building codes in some areas of the country might prevent the use of PVC piping in some sections of buildings. For example, special restrictions sometimes apply to pipe used in firewall penetrations and plenums above dropped ceilings.

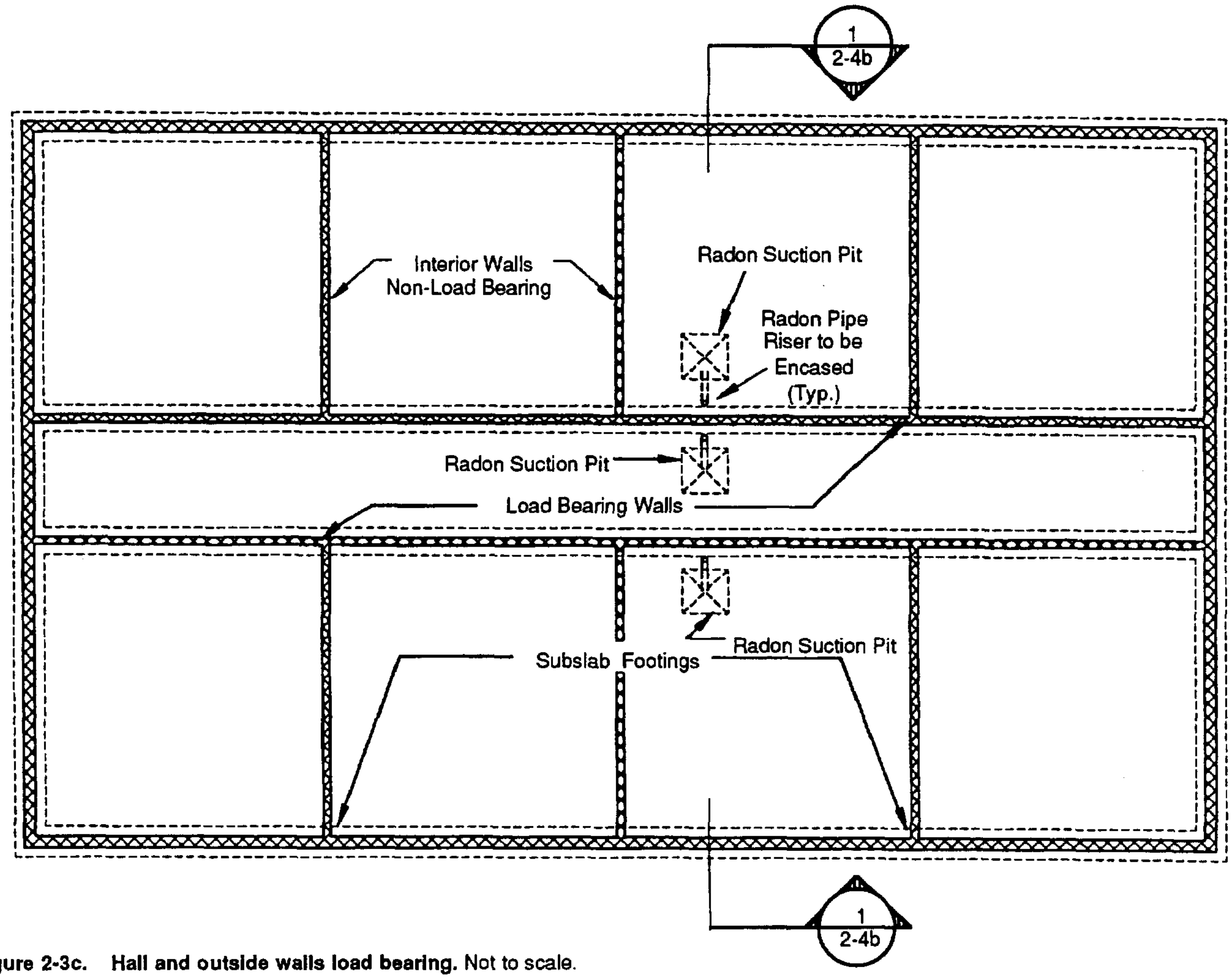

Figure 2-3c. Hall and outside walls load bearing. Not to scale.

Also, building codes in some areas require steel pipe; in most areas, code requires suitable fire stop details at any location where the exhaust piping penetrates a fire rated wall, a ceiling deck, or a floor deck. Generally, PVC pipe can penetrate a firewall if a material to block fire is used. When installing the radon vent pipe, make sure you do not violate applicable codes. For example, the building in the Appendix A case study used Schedule 40 PVC pipe beneath the slab and steel pipe above the slab in order to meet state codes.

Piping Installation

Attention to detail while installing the vertical risers will help ensure the proper operation and long life of the system. Starting at the floor slab, seal any openings between the pipe and the floor slab with a high adhesive sealant (polyurethane is currently preferred). Also, seal all piping joints. An illustration of sealing pipe penetrations through the roof is shown in Figure 2-6. Additional details on sealants and sealing are provided in Section 2.3.

It is important that all horizontal pipe runs are pitched a minimum of 1/8 in. per ft so that accumulating condensation drains back to the radon suction pit. Accordingly, it is also important to avoid any low areas in the horizontal pipe that could block airflow if condensation were to accumulate in the pipe. One architect has noted that, when piping is installed in dropped ceilings that may have a drop in temperature, insulation of the piping helps to avoid condensation problems.

Labeling of System Components

Label the exposed radon vent pipe to identify the pipe as a component of a radon vent system that may contain hazardous levels of radon. Labels should be placed at regular intervals (at least every 10 ft) along the entire pipe run. Clearly mark all components of radon reduction systems as radon reduction devices to ensure that future owners of the building do not remove or defeat the system. At the roof exit, attach a permanent label to the vent with a warning such as "Soil gas vent stack may contain high levels of radon; do not place air intake within 25 ft." Refer to local codes to determine the specific minimum distance for air intakes. The suction fan discharge location is covered in greater detail in the following section.

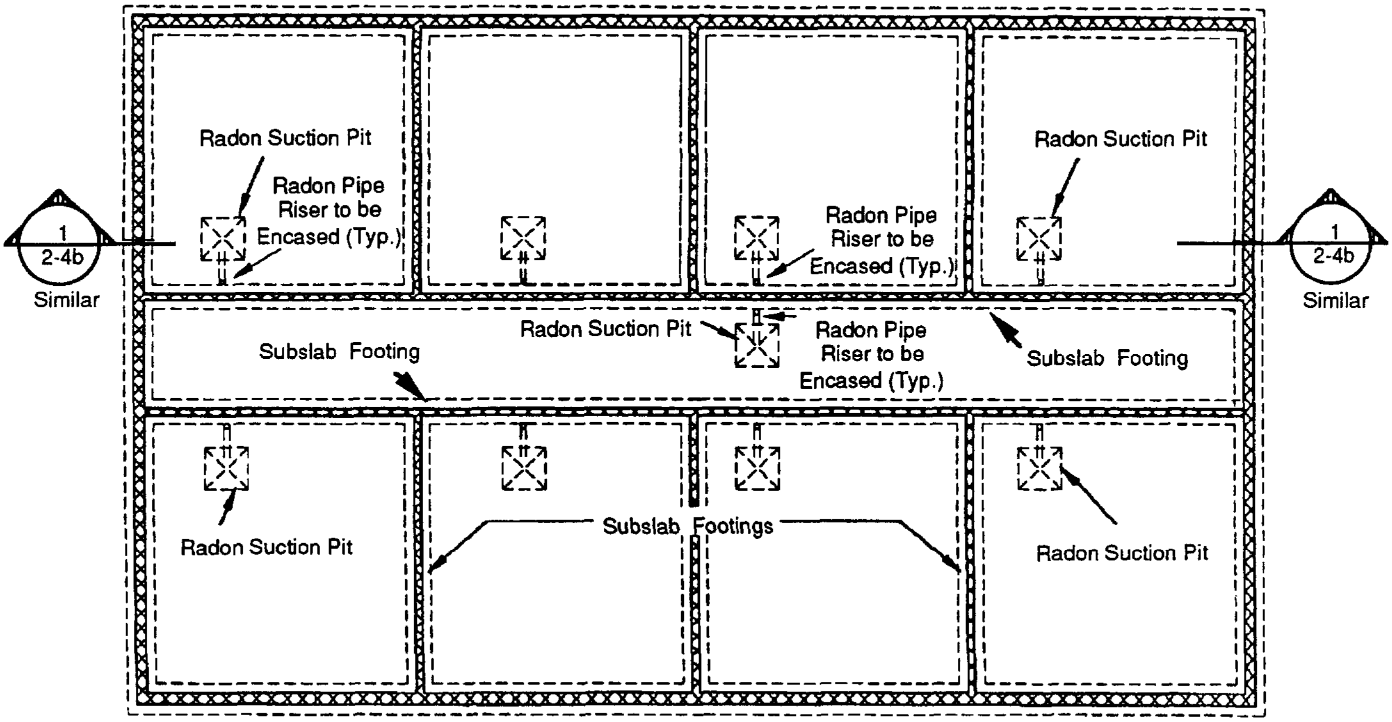

Figure 2-3d. All interior walls load bearing. Not to scale.

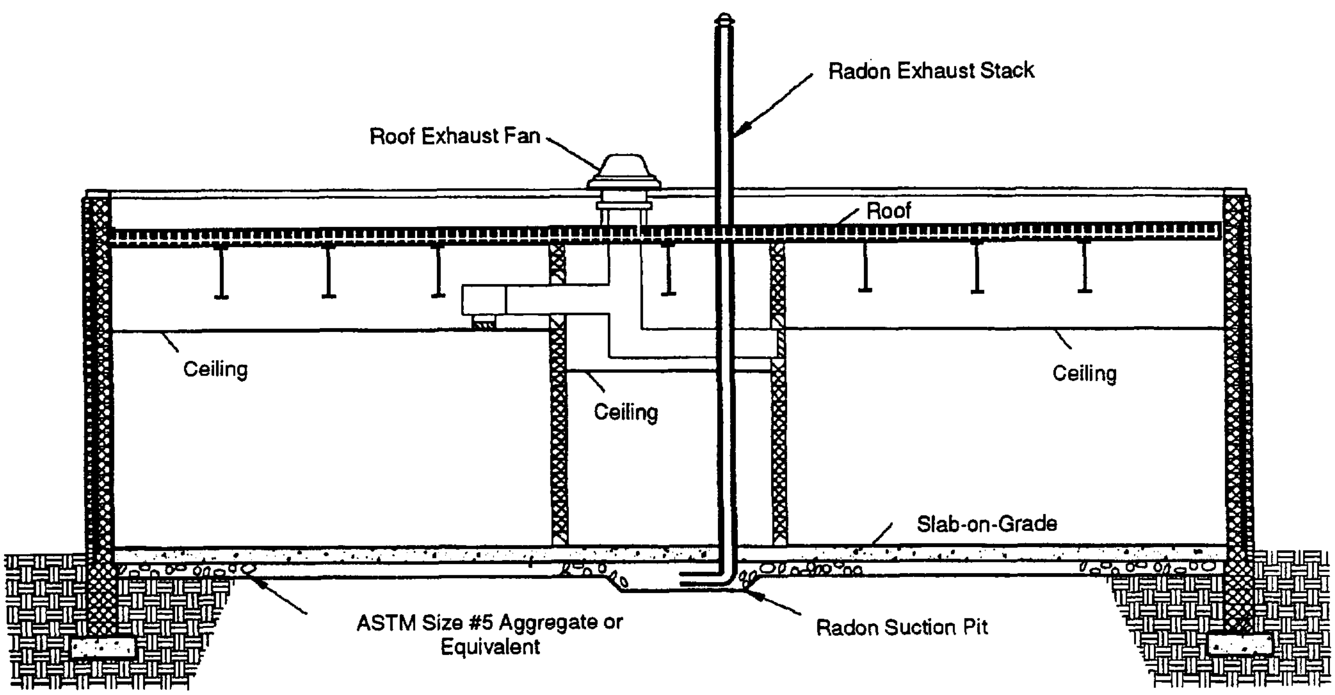

Figure 2-4a. Section 1 (corresponds to Figures 2-3a and b). Not to scale.

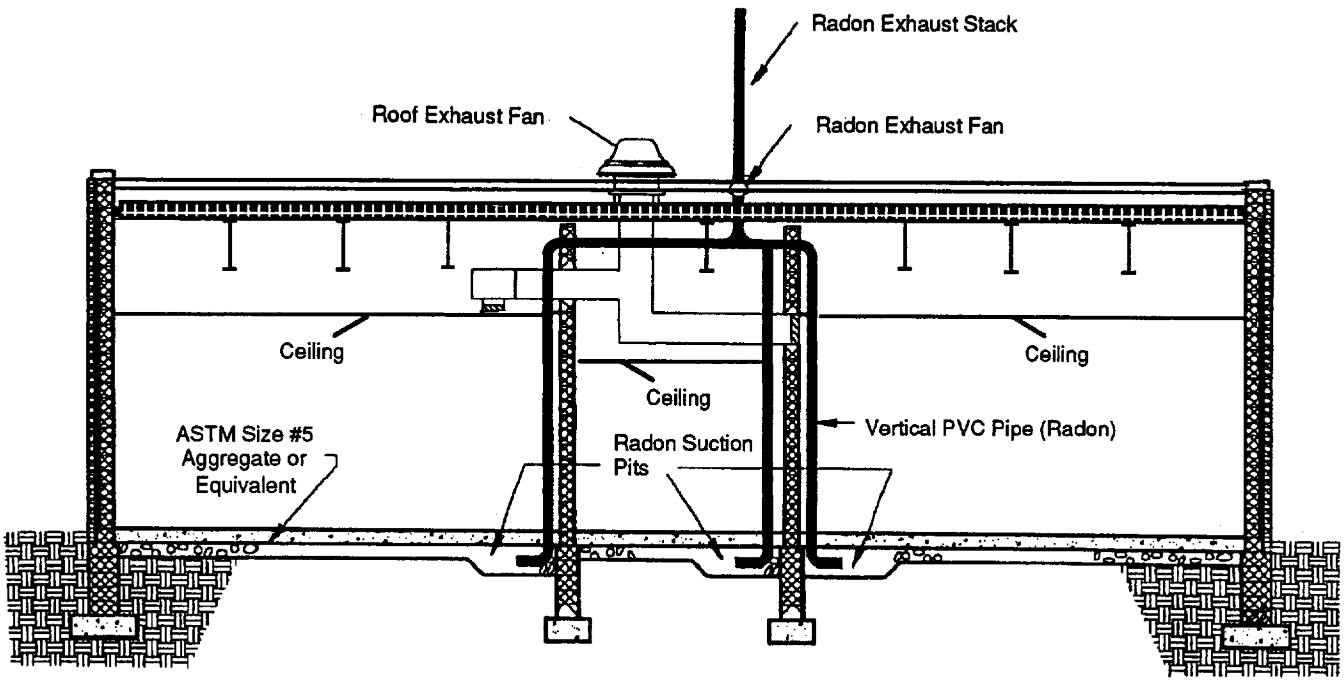

Figure 2-4b. Section 1 (corresponds to Figures 2-3c and d). Not to scale.

2.1.1.5 Suction Fan

When to Install

A suction fan can be installed during building construction or the piping can be terminated and capped at roof level and the fan installed later. As discussed previously, passive systems (without a fan) are not recommended for radon control in schools and other large buildings. ASD system fans should be operated continuously; otherwise elevated levels of radon may accumulate. The cost of operating the fan continuously is comparable to the cost of operating any other exhaust fan in the building (such as a restroom exhaust fan).

Fan Selection and Installation

Use fans manufactured specifically for outdoor use in radon control systems. These are available from many vendors in a variety of sizes. Fans normally used for schools and other large buildings are in-line duct fans rated from 500 to 600 cfm at zero inches static pressure. Because piping on the exhaust side of the fan is under positive pressure and might be subject to leaks, the fan always should be mounted outside the building. Designers should be aware that leakage inside the envelope of the building is not acceptable.

Most installers connect the fans to the pipe system with rubber sewage pipe connectors. This connection allows for a tight seal, quiet operation, and easy replacement of the fan (if needed). Additional materials and components are normally included in a system to satisfy safety needs, system performance indications, and noise reduction. Typically code requirements dictate that waterproof electrical service switches be placed within view of the fan to ensure that the system will not be activated during maintenance. If the ASD system is being roughed-in, with the fan to be installed later if needed, installation of the waterproof electrical connection above the roof during construction will facilitate addition of the fan.

Suction Fan Discharge

The exhaust discharge configuration of an ASD system should be treated similarly to the discharge of a laboratory fume hood or other rooftop exhaust that vents toxic fumes. Some building codes, for example, specify that any discharge of pollutants must be located at least 25 ft from any outdoor air intakes. Examples of suitable discharge configurations are presented in the *Industrial Ventilation Manual of Recommended Practices, 19th Edition* (13), and the *1989 ASHRAE Fundamentals Handbook* (14).

We recommend that the vent pipe terminate in a vertical position above the roof with sufficient height that the discharge does not re-enter the building. The discharge can contain extremely high levels of radon. If this configuration is not possible, we recommend that you choose a configuration that provides at least a 1,000 to 1 dilution ratio to the nearest air intake or operable window. This dilution ratio is calculated from the *ASHRAE Fundamentals Handbook* Chapter 14 equations (14).

Warning Device

ASD system designers should include a device that warns building owners and occupants if the system is not operating properly. A preferred warning system has an electronic pressure sensing device that activates a warning light or an audible alarm when a system pressure drop occurs. These are readily available from several suppliers. We advise installing a device that warns of a pressure change rather than one that deter-

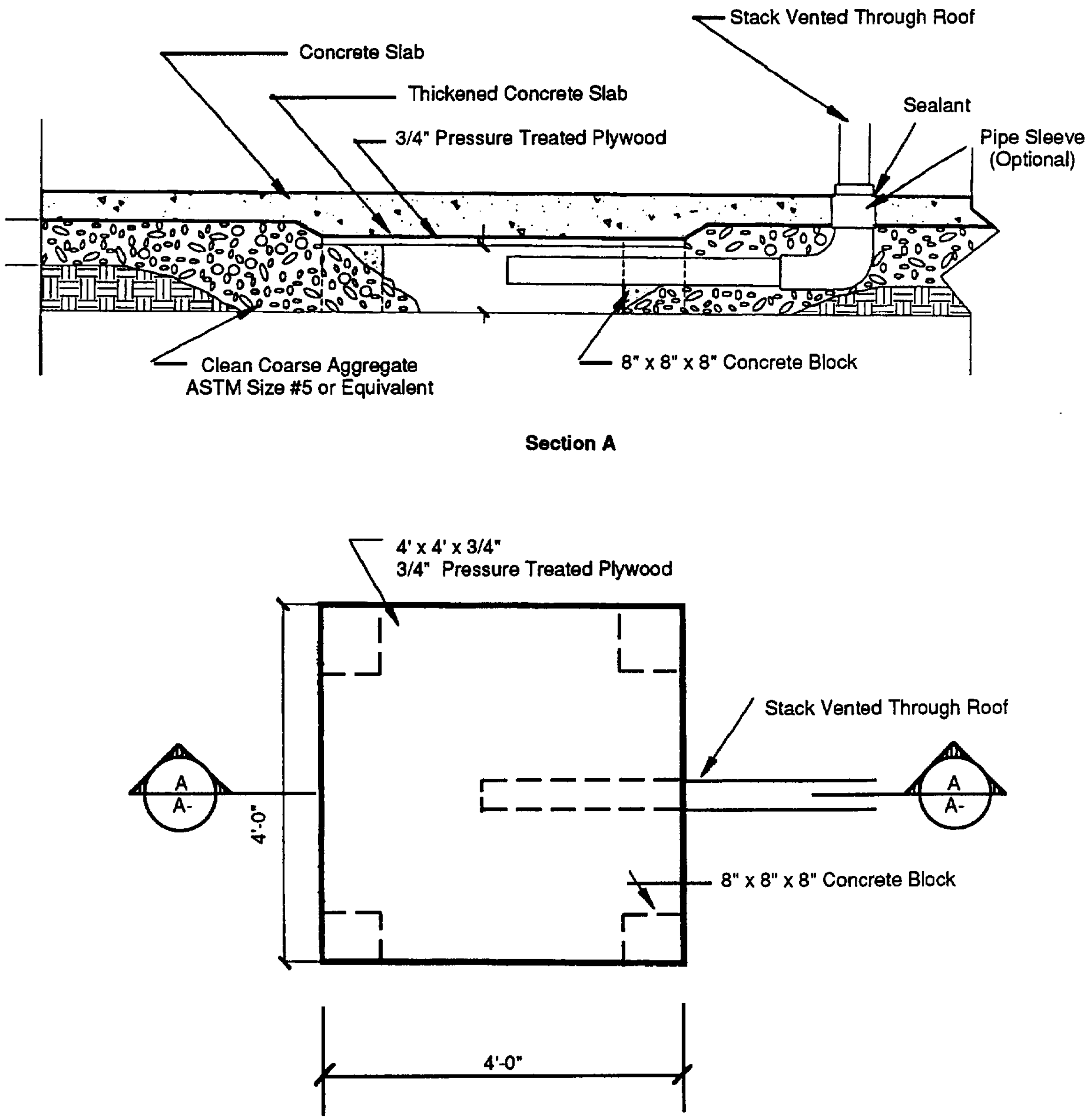

Figure 2-5. Radon suction pit. Not to scale.

mines fan operation. Several things can stop a system from operating effectively besides fan operation. Additionally, the fan may still appear to be operating even though air flow is severely reduced.

Install the warning device in an area frequently visited by a responsible person. In some schools, warning devices have been placed near the HVAC control panels or in the principal's office. Some schools have chosen to connect the signal from a warning device into the energy management system computer for the district.

2.1.1.6 Sealing Major Radon Entry Routes

For an ASD system to be most effective, it is important to seal large openings (such as utility penetrations and expansion joints) that can defeat extension of a low pressure field. Large openings in the slab not only reduce system effectiveness, but also increase operating costs by drawing too much air from inside the building. Section 2.3 provides comprehensive instructions and guidelines for sealing.

2.1.2 Operation and Maintenance

ASD system operation and maintenance concerns fall into three time frames:

- Before Occupancy
- Weekly
- Annually

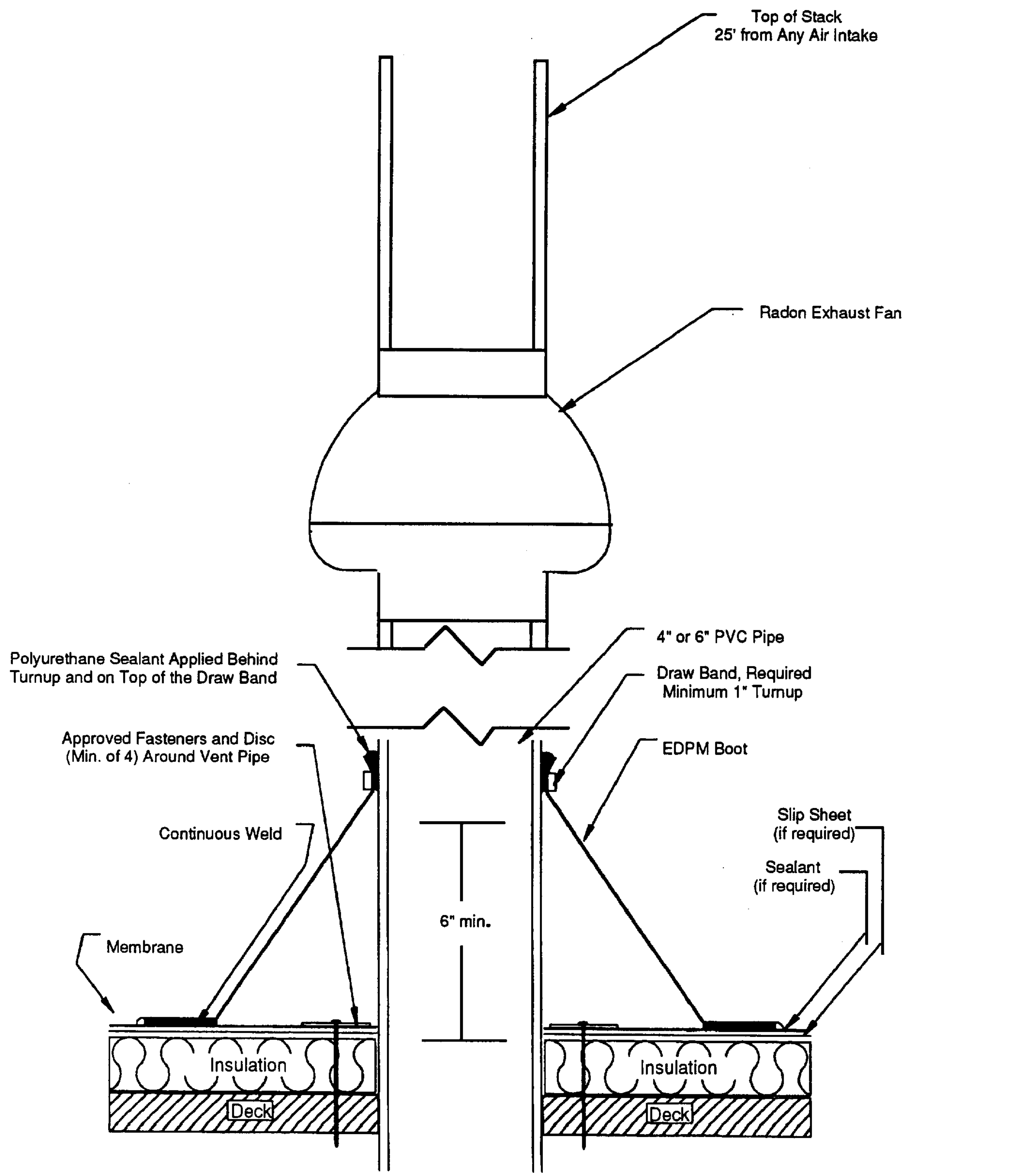

Figure 2-6. Sealing pipe penetrations through roof. Not to scale.

2.1.2.1 Before Occupancy

Measure radon levels in the building at least 24 hours after the ASD fan is turned on. (Guidelines for measuring radon levels are briefly covered in Section 2.4 of this manual.) If you have roughed-in an ASD system without a fan, then these radon measurements will determine if it is necessary to activate your system with a fan. Many building owners continuously operate ASD systems even if radon levels without the system are below 4 pCi/L. Continuous operation of the system will further reduce radon exposure to building occupants.

Measure Subslab Pressures

If the building has elevated radon levels, it is important to confirm that the ASD system is achieving an adequate negative pressure field under all areas of the slab. Measurement of the subslab pressure field is commonly referred to as pressure field extension (PFE) or subslab communication.

To measure PFE, it is necessary to drill about 10 small holes (approximately 1/4 to 1/2 in. diameter) through the slab at various distances and directions from the suction pit. Be sure to carefully determine the locations of all subslab utility lines before drilling through the slab. Then, with the ASD fan off, measure the subslab pressure in each of the holes. This should be done using a sensitive device such as a micromanometer; however, something as simple as a chemical smoke stick could be used to determine if air flows into the slab. These measurements should then be repeated with the ASD fan turned on. Once the PFE tests are complete, the holes should be carefully sealed with concrete patching material.

The purpose of PFE measurements is to confirm that the ASD system maintains an adequate negative pressure under the slab. A minimum subslab pressure of -0.002 in. water column (WC) is required at all test holes for an effective ASD system. If all of the recommendations for ASD discussed in this section are followed, then the pressures at even the farthest test holes should be at least -0.01 in. WC. If measurements indicate that there is inadequate pressure field under the slab, troubleshoot the system by confirming fan operation, sealing major radon entry routes, locating potential subslab barriers, inspecting type of aggregate used, and inspecting the operation of the HVAC system. (See Section 2.2 for information on how an HVAC system can overcome ASD.)

Some builders express concern about drilling holes in a newly constructed building; however, measurement of PFE is the only way to determine if the negative pressure is being extended. Detailed guidelines for measuring PFE are described in numerous EPA publications (2,3,9,15) and are also discussed in the Appendix A case study. The holes do not compromise the structure of the building and are normally covered with finished floor such as carpet or vinyl.

Provide ASD Operating Manual

An operating manual describing the system and its purpose should be provided to building owners. The manual should include a discussion of system components, how to interpret the system failure warning device, and the other important maintenance needs of an ASD system as explained in this section.

2.1.2.2 Weekly

Check the pressure gauge(s) in the radon vent pipes and the system alarm to ensure that the fan is maintaining adequate negative pressure to depressurize the subslab area.

2.1.2.3 Annually

Inspect the fan for bearing failure or signs of other abnormal operation, and repair or replace if required.

Inspect the discharge location of the vent pipe to ensure that no air intake has been located nearby, and that a building usage change has not placed the exhaust near operable windows.

Check the HVAC system to determine if it is being maintained and operated as designed. Even though the ASD system may be functioning as designed, excessively powered exhaust without adequate makeup air might overcome an ASD system.

If building settling is noted, check for slab, floor, or basement wall cracks and perform radon testing (and additional sealing, if needed) to ensure the continued effectiveness of the system. (Refer to Section 2.4 for guidelines on radon measurements.)

2.1.3 Additional Instructions for Basements

Instructions for designing and installing an ASD system in buildings with basement foundations are similar to instructions for slab-on-grade buildings. The primary difference is that basement walls provide additional radon entry routes.

Below-grade walls and stem walls are normally constructed of either poured concrete or masonry blocks. Section 2.3.3 discusses the different types of below-grade walls and the coatings that can be used to seal these walls.

2.1.4 Additional Instructions for Crawl Spaces

This section describes two techniques for radon reduction in crawl space buildings: submembrane depressurization (SMD) and crawl space depressurization. SMD is typically a much more effective approach for maintaining low radon levels; consequently, construction of crawl space buildings in radon prone areas should include provisions for SMD.

Submembrane Depressurization (SMD)

Since ASD cannot be used in crawl spaces with dirt floors, and difficulties are often encountered in isolating a crawl space from the occupied area above, builders must use alternate radon prevention techniques in crawl spaces. SMD is an effective technique for reducing radon levels in crawl spaces. This technique is a variation of the successful ASD method, and is shown in Figure 2-7. Research in schools and houses has shown SMD to be the most effective year-round approach for reducing radon levels in crawl space buildings (15,16).

To install a SMD system in a crawl space, 6 mil (or thicker) polyethylene sheeting is used as a vapor retarder that forms a small-volume plenum above the soil. A suction fan and vent stack are used to pull radon from under the membrane and exhaust it outside the building. Active SMD has been widely applied in houses; limited experience indicates that it is also effective in schools (16). This approach may be expensive in large crawl spaces due to the need for large amounts of polyethylene sheeting; however, because buildings often use polyethylene sheeting as a vapor retarder, the sheeting would not necessarily be considered an additional mitigation cost.

To install a SMD system, place wide polyethylene sheets (with at least 1 ft overlaps between the sheets) directly on the earth. Be sure to remove any large rocks, broken concrete blocks, or other obstructions before placement. After the sheet is placed, we recommend that you seal the seams in the polyethylene in the vicinity of the suction point to increase system effectiveness. Use the special sealants recommended by the manufacturers of the sheeting for gluing polyethylene together. Where the soil surface is exceptionally hard and smooth or the crawl space is very large, use a radon suction pit or perforated piping manifolded under the sheeting to improve the pressure field extension. In large crawl spaces with many support piers it might be more difficult to install SMD. If many support piers exist, or if the radon suction point has to be located close to support piers, seal the polyethylene sheeting to the piers.

The polyethylene sheeting can also be sealed to the foundation walls to reduce air leaks; however, this additional sealing has proved to be unnecessary in some existing buildings. Currently, research is being done to determine exactly how much sealing of the membrane is necessary.

Crawl Space Depressurization

Crawl space depressurization is another method for control of indoor radon. For crawl space depressurization, a fan is used to depressurize the entire crawl space area. The negative pressure in the crawl space relative to the building interior keeps the radon from entering the building. However, the negative pressure in the crawl space will increase radon levels in the crawl space, so this technique should not be used if people need to enter the crawl space frequently. Because of the potential for high radon levels in the crawl space, it is very important that the area between the crawl space and building interior is thoroughly sealed. This sealing is also important to reduce energy loss from air flowing from the building interior into the crawl space.

To achieve a sufficient negative pressure in the crawl space, the vents should be closed. Research has shown that closing the crawl space vents will not create a moisture problem if a vapor retarder is placed over the ground (17).

A forthcoming EPA manual on radon mitigation of existing schools will have a more detailed section on crawl space mitigation. Call your state radon office or EPA Regional Office for more information.

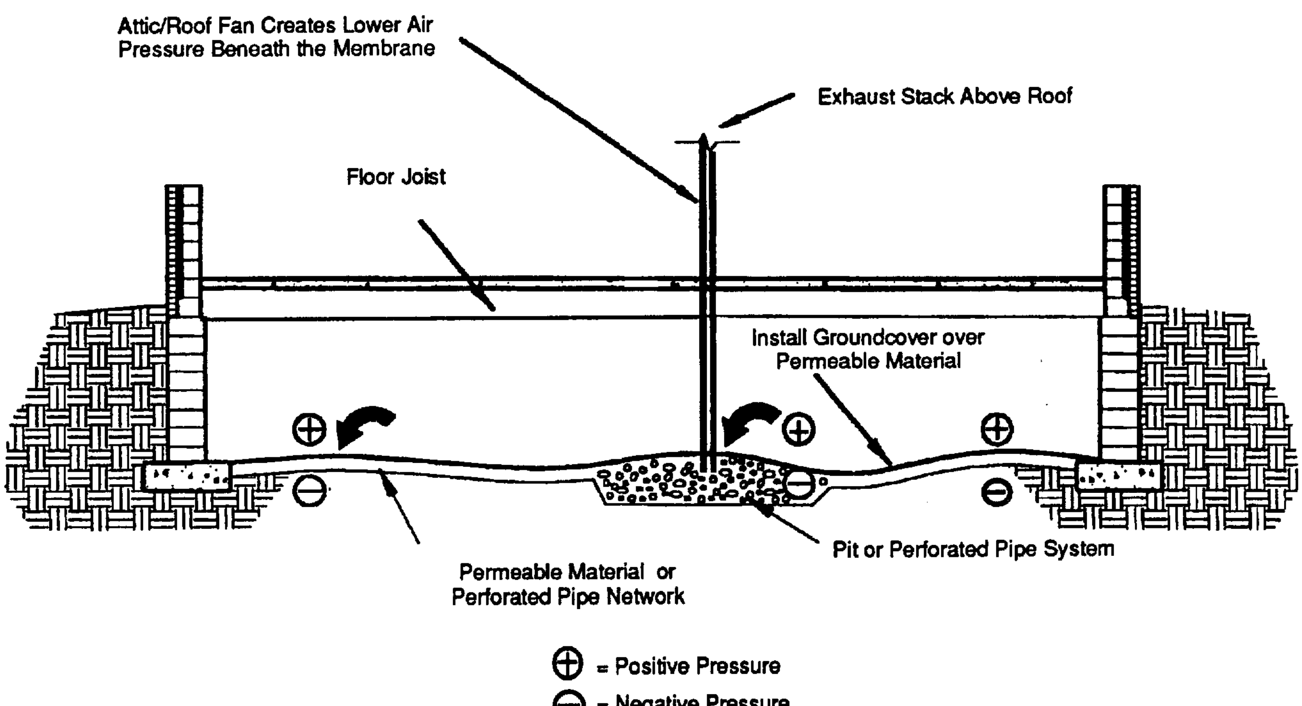

Figure 2-7. Submembrane depressurization in crawl space.

2.1.5 *ASD Cost Estimates*

Estimated typical cost ranges for the materials needed for an ASD system are presented in Table 2-1. Material costs and labor costs can vary widely by region. Also, remember that because many buildings normally use aggregate and a reinforced vapor retarder under the slab, they are not usually considered an additional cost of radon prevention.

The average total cost of conducting diagnostics and installing an ASD system in an existing building is about $0.50/ft² (9). The total cost of an ASD system for a new 60,000 ft² building was $5,000 (see Case Study, Appendix A).

2.1.6 *Summary of Guidelines for ASD Systems*

In areas where radon is known to be a problem, as a minimum, it is advisable to rough-in a soil depressurization system that can easily be made active with a fan. Attention to detail in the design stage of the soil depressurization system will help ensure its success. The following is a review of important guidelines for building and designing an ASD system.

- Place a continuous 4- to 6-in. layer of the specified aggregate under the slab. (Aggregate, Section 2.1.1.1)
- Eliminate barriers to subslab airflow such as subslab walls. (Subslab Walls, Section 2.1.1.2)
- Install a 4 by 4 ft suction pit under the slab. (Radon Suction Pits, Section 2.1.1.3)
- Run a 6-in. diameter radon vent pipe from the radon suction pit to the outdoors. (Radon Vent Pipe, Section 2.1.1.4)
- Install a suction fan designed for use in ASD systems. (Suction Fan, Section 2.1.1.5)
- Seal major radon entry routes including slab and foundation joints and cracks and utility and pipe penetrations. For basement substructure, also seal the basement walls. (Sealing Radon Entry Routes, Section 2.3)
- For crawl space substructures, provide for a submembrane depressurization system. (Section 2.1.4)
- Install an alarm system and, to ensure ASD system effectiveness and longevity, follow all operation and maintenance recommendations. (Section 2.1.2)

2.2 Building Pressurization and Dilution

The heating, ventilating, and air-conditioning (HVAC) system in a modern building has many functions; it must regulate temperature, humidity, air movement, and air quality inside the facility. A properly designed and operated HVAC system can be used to reduce radon levels by building pressurization and dilution.

New construction offers the opportunity to design and install the HVAC system so that it produces a slightly positive air pressure inside all areas of the building. Pressurization is accomplished by bringing more outdoor air into the building than is removed. This has been shown to reduce radon levels in existing schools. The outdoor air also increases building ventilation, and thus dilutes radon and other indoor contaminants.

The following subsections contain design recommendations, standards for ventilation, and guidelines for installation, operation, and maintenance of HVAC systems. As discussed in the overview of this document, in radon-prone areas we recommend a combination of ASD, HVAC pressurization and dilution, and sealing of major radon entry routes.

2.2.1 *Design Recommendations for HVAC Systems*

Building pressurization is accomplished by bringing in more outdoor air than is removed by mechanical exhaust systems. Excess air not removed by the exhaust system is forced out of the building through cracks and unsealed openings in the building shell, and is referred to as exfiltration.

The concepts of building pressurization and building depressurization are illustrated in Figures 2-8 and 2-9, respectively. In both examples the building HVAC system has a supply of 100,000 cfm and an exhaust fan that withdraws

Table 2-1. Estimated Costs for Primary ASD Components

ASD Feature	Material Cost	Comments
Crushed stone (4 in. deep	$0.10 to $0.25 per ft² ($4.50 to $11.32 per ton)	If aggregate is normally used, do not include as additional cost.
Radon suction pit (4 x 4 ft)	Minimal	As shown in Figure 2-5.
Vent stack (6 in. diameter PVC)	$2.00 to $3.00 per ft	Total cost depends on pipe run length.
Vent stack fittings (6 in. diameter PVC)	$20.00 to $30.00 each	Total cost depends on system design.
6 mil poly vapor retarder under slab	$0.10 to $0.30 per ft²	Normally included in construction.
Suction fan	$300 to $500 each	As discussed in Section 2.1.1.5.
Firebreaks	$100 to $150 each	At least one per stack and pit.
Sealing joints in concrete (typical 40 x 40 ft slab sections)	$0.40 to $1.50 per linear ft (includes material *and* labor)	Highly variable, depending on building design and location.

15,000 cfm. However, in Figure 2-8 there is an outdoor air supply of 20,000 cfm, or 20% of the total supply. As a result, the building illustrated in Figure 2-8 is under a positive pressure and 5,000 cfm of air will exfiltrate from the building. This positive pressure will keep radon from entering the building while the HVAC system is operating. On the other hand, the scenario in Figure 2-9 shows an outdoor air supply of only 5,000 cfm, or 5% of the total supply. In this case, the building is depressurized by 10,000 cfm. This depressurization will cause air to infiltrate into the building and can exacerbate radon entry into the building. The natural "stack effect" can also contribute to building depressurization.

To minimize the amount of outdoor air needed to pressurize a building, the shell of the building must be tightly constructed. In addition to facilitating building pressurization, a tight building shell will reduce energy costs and allow for improved environmental control. For details on measuring air leakage rates, refer to ASTM E779 "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (18)." Note that large buildings may be difficult to test by this method because of the larger leakage area.

Measurements in existing schools show that a slight positive pressure (as little as +0.001 in. WC relative to subslab and outdoors) reduces radon levels by preventing radon entry. So, radon entry should be prevented while the HVAC system is operating if the building is pressurized.

The supply of outdoor air also helps to reduce radon levels by dilution. For a given constant rate of entry, radon concentrations in a building are inversely proportional to ventilation rates. Thus, for example, to reduce radon levels by a factor of 10, one would have to increase the air exchange rate by that same factor (19). In most cases, such a large exchange rate may be neither practical nor desirable.

Although building pressurization and dilution can reduce radon levels and improve indoor air quality, they do present some concerns as a stand-alone radon control technique. These include:

- If total building exhaust capacity is not balanced with an equal or greater amount of conditioned makeup air (outdoor air), the pressure in the building interior will be negative with respect to the subslab area. This negative pressure acts as a driving force for radon-containing soil gas to be drawn into the building.
- Open windows and doors make it very difficult to achieve a consistent positive pressure in the building.
- Start/stop operation of the HVAC system for various occupancy modes does not allow for continuous building pressurization. If the HVAC system is turned off or set back during unoccupied periods, then the specific hours of preoccupancy start-up to reduce radon levels that have built up while the system was off should be determined on a building-by-building basis.
- The design and operation limitations of different types of HVAC systems must be considered when designing a system to pressurize the building. For example, the design of variable air volume (VAV) systems must take into consideration the effects of minimum flow conditions on ventilation and pressurization of the building.

For additional information on the effects that different types of HVAC systems have on radon levels in schools, refer to the recent EPA report "HVAC Systems in the Current Stock of U.S. K-12 Schools" (20).

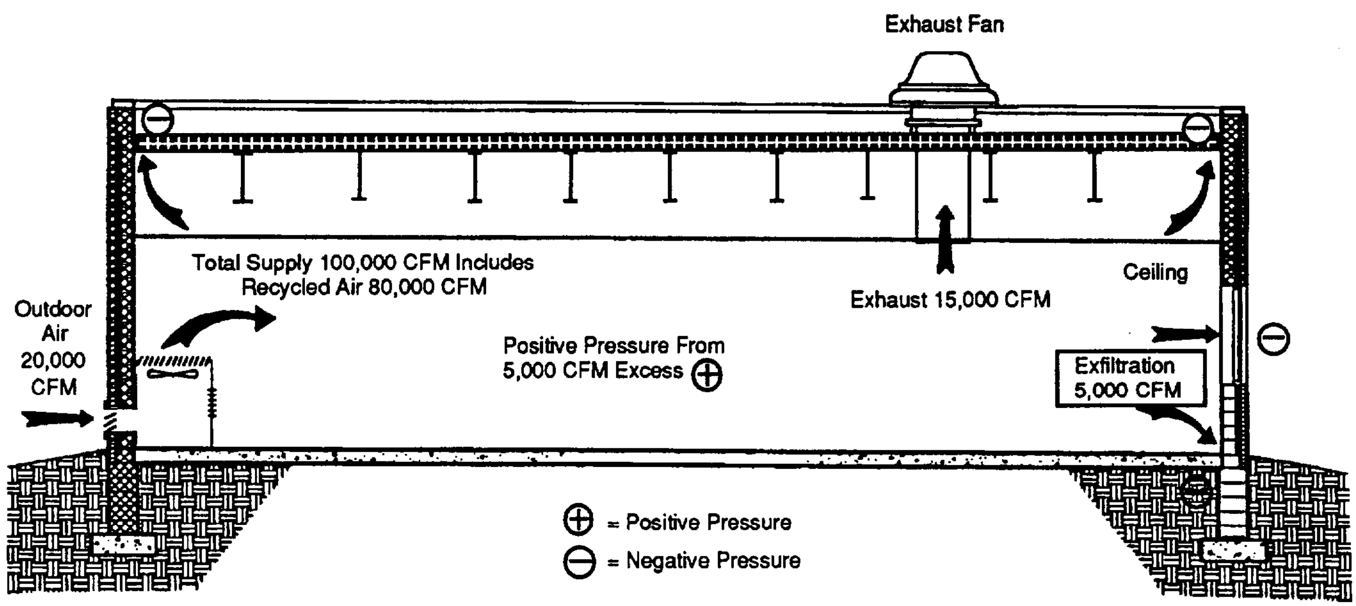

Figure 2-8. Building positive pressurization with HVAC system.

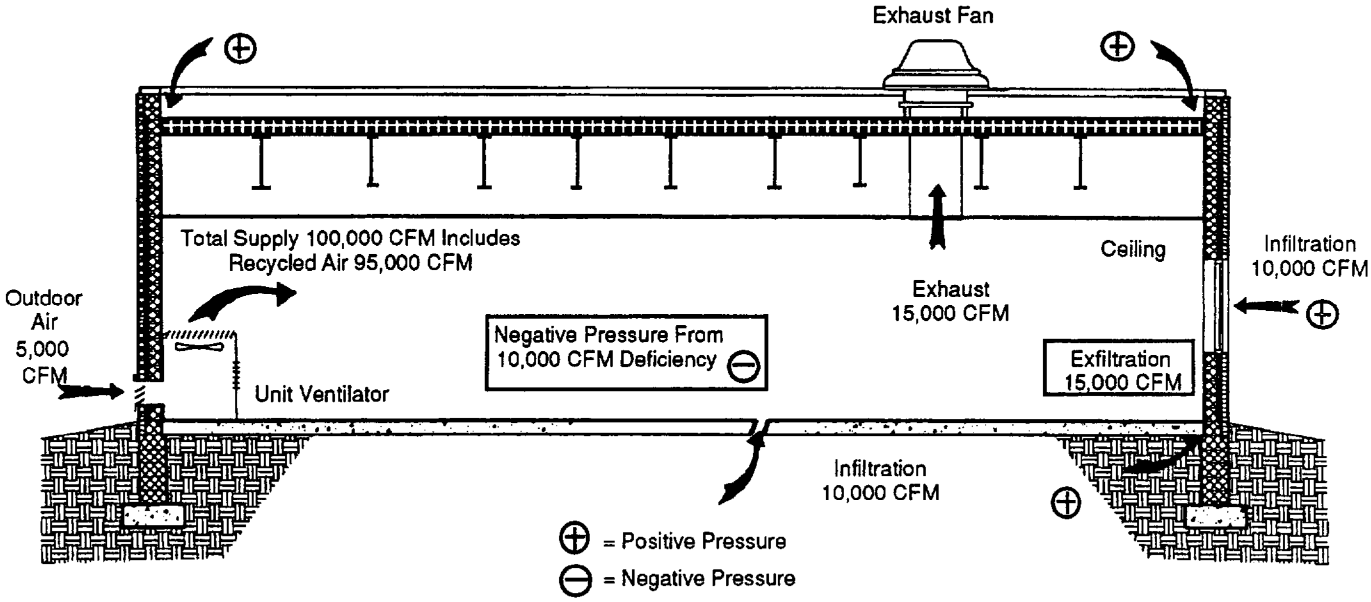

Figure 2-9. Example of building depressurization with HVAC system.

2.2.2 Standards for Ventilation

For many years it has been common practice to design large buildings with approximately 10% more supply air than return air in order to reduce drafts from infiltration. Following this same procedure in a building with a tight shell is likely to produce a net positive pressure in the building during normal operation. Examples of recommended ventilation standards for commercial buildings, from ASHRAE Standard 62-1989: "Ventilation for Acceptable Indoor Air Quality" (10), are summarized in Table 2-2. The ASHRAE guidelines are being adopted by many states and national building codes as a standard in new construction. The application of this standard, coupled with "tight" construction, is expected to reduce entry of soil gas and increase dilution of building contaminants. Both the increased ventilation and the pressurization should help to reduce indoor radon levels.

2.2.3 Guidelines for Installation and Operation

It is not practical to provide specific radon control guidelines for designing and operating every type of HVAC system. However, the following basic guidelines for achieving building pressurization should be discussed with the design engineers during the planning stage.

- Plan the HVAC systems so that the building interior in all ground contact rooms is at least slightly pressurized (for example, 0.005 to 0.010 in. WC). Any effect on moisture dynamics and code acceptability must also be addressed by the building designers.
- Avoid subslab supply and/or return ductwork.
- In radon-prone areas, do not locate air supply or return ductwork in a crawl space (10).
- Seal all supply and return ductwork at all seams and joints.
- Seal all floor and wall penetrations (especially under through-wall units and in mechanical rooms, see Section 2.3).
- Construct the building "tightly."
- Control operation of the HVAC relief dampers so that they modulate to maintain a positive building pressure of 0.005 to 0.010 in. WC. Relief dampers should be controlled by sensing the differential pressure across the building shell and modulating the relief damper to maintain positive pressure in the building.
- Be sure all applicable building and safety codes, standards, and guidelines are followed. Especially important in this regard are fire codes, fuel use codes, the National Electrical Code, and other safety and mechanical codes.
- Be sure to preserve the intended indoor air quality purposes of mechanical ventilation devices. Exhaust fans should remove the moisture, fumes, and other contaminants generated within the building. Supply air systems should provide tempered air, free of objectionable quantities of contaminants.

2.2.4 Maintenance

Proper HVAC system maintenance is essential to ensure continued reduction of radon levels and adequate indoor air quality. This is especially important in areas known to have radon problems. The following items are intended for building owners and operators to assist in proper operation and maintenance of HVAC systems.

Table 2-2. Examples of Outdoor Air Requirements for Ventilation in Commercial Facilities (Source: ASHRAE Standard 62-1989)

Type of Facility	Estimated Occupancy, Persons per 1000 ft² of Floor Area	Outdoor Air Requirements (cfm/Person) Non-smoking Area
Lobbies	30	15
Conference Rooms	50	20
Assembly Rooms	120	15
Dormitory Sleeping Areas	20	15
Office Spaces	7	20
Reception Areas	60	15
Smoking Lounges	70	60
Barber Shops	25	15
Beauty Shops	25	25
Supermarkets	8	15
Ballrooms & Discos	100	25
Transportation Waiting Rooms	100	15
School Classrooms	50	15
School Laboratories	30	20
School Auditoriums	150	15
Hospital Patient Rooms	10	25
Operating Rooms	20	30
Correctional Cells	20	20

Note: For complete listing refer to ASHRAE Standard 62-1989 (10).

Annually

- Replace air filters at least twice a year if high quality, medium efficiency pleated air filters are used and more frequently if non-pleated or disposable low efficiency filters are used.
- Check the HVAC system and exhaust fans to determine if they are being operated as designed. Excessive exhaust without adequate makeup air will depressurize the building, rendering building pressurization ineffective.
- Inspect the HVAC system components and controls for failure or signs of faulty operation (such as loss of damper control) that would restrict the supply of outdoor air. Note: two states, California and Maine, currently require annual inspections for correct operation of the ventilation systems in schools; other states are considering similar requirements.
- If an ASD system is also installed, inspect the discharge location of the ASD vent pipe to ensure that an air intake has not been located nearby, or building usage change has not placed the exhaust near operable windows.

Once Every 5 Years

- Test and balance the HVAC system. Rebalance the system as renovations and usage changes occur.

2.2.5 Summary of Building Pressurization Guidelines

In a building with a tight shell, slight positive pressurization can be achieved by supplying about 10% more outdoor air than is mechanically exhausted when the building is operating under minimum outdoor air conditions. This positive pressurization will reduce radon entry, and the additional outdoor air will help to dilute radon that does enter the building.

A building designed to control indoor air contaminants (including radon) should include:

- Pressurized ground contact rooms
- A well-balanced air distribution system
- Adequate makeup air
- A tight building shell (less than 1.0 ach at 25 Pa)

Mechanical systems should be designed and installed to meet the needs of occupant health, safety, comfort, energy conservation, and building longevity. Meeting these needs requires an understanding of how the climate, the building, and the occupants interact. Building pressurization alone, however, cannot always consistently prevent radon entry. For example, operable windows can make it very difficult to achieve pressurization. A properly designed and operated mechanical system, in conjunction with an ASD system and sealing of major radon entry routes, should provide cost-effective radon prevention in new buildings.

2.3 Sealing Radon Entry Routes

This section on sealing radon entry routes covers the following topics:

- Recommended Sealants (2.3.1)
- Sealing Concrete Slabs (2.3.2)
- Sealing Below-grade Walls (2.3.3)
- Sealing Crawl Spaces (2.3.4)

Recommended sealants for radon-resistant new construction are briefly covered in Section 2.3.1. Sections 2.3.2, 2.3.3, and 2.3.4 cover sealing the most common radon entry routes. Section 2.3.2 is applicable to all three substructure types — slab-on-grade, basement, and crawl space — that are constructed with poured concrete slabs. Section 2.3.3 is applicable to basement substructures. Section 2.3.4 provides additional sealing recommendations for limiting radon entry from the crawl space into the building interior.

On-going EPA research on radon-resistant new construction in homes has encountered numerous difficulties in achieving a reliable, gastight physical barrier between the soil gas and the building (5). This research indicates that a near perfect sealing job is necessary to achieve high radon reduction in homes using sealing as a stand-alone radon reduction technique in radon-prone areas. Because of the difficulties of achieving complete sealing, it is normally much more cost effective to include ASD (Section 2.1) and adequate HVAC system design and operation (Section 2.2) in the design of new buildings in radon-prone areas. However, sealing of major radon entry routes (as discussed below) and good construction practice will enhance the performance of both ASD and HVAC radon prevention techniques.

2.3.1 Recommended Sealants

Sealants used for radon-resistant applications must have good adhesion to concrete and be durable and elastic. The popularity of polyurethane as a suitable elastomeric joint compound is based on a combination of strong adhesion to concrete under difficult conditions, long service life, and good elasticity (5). Avoid silicone caulks because they do not adhere to concrete well.

When you apply sealants, be sure surfaces are clean, dry, and free of grit and that the surface temperature is above freezing. Apply sealants in accordance with the manufacturer's recommended practice. Typical dimensions for caulk beads are 1/2 in. deep by 1/4 in. to 1/2 in. wide. It may be necessary to use backer rod when applying sealant in wide gaps.

2.3.2 Sealing Concrete Slabs

This section covers all buildings constructed with concrete slabs: slab-on-grade, basement, and crawl space.

Concrete is normally a good radon barrier. The major problems with concrete slabs are joints, slab penetrations, and cracks. The following subsections provide guidance on avoiding these problems by: 1) sealing slab joints, penetrations, and openings; 2) preventing random cracks in slabs; and 3) using subslab membranes. For additional information, refer to *Concrete Floors on Ground* (21) and *Guide for Concrete Floor and Slab Construction* (22).

2.3.2.1 Slab Joints

Slab joints of concern for radon entry include the floor/wall joint, pour joints, and control saw joints.

Floor/Wall Joint

The floor/wall joint (also called perimeter crack) of a slab is located between the edge of the floor slab and the interior or exterior load bearing walls. As a cold joint, the floor/wall joint is always a potential radon entry point. To facilitate sealing of this joint after construction, contractors have deliberately created a significant floor/wall joint detail so that it will be easy to work with and seal. One approach is to install an expansion joint with the top 1/2 to 3/4 in. of the joint removable after the concrete sets. This approach leaves enough space for sealing with a suitable polyurethane caulking before floor covering is installed. Another approach is to round the slab at the floor/wall joint with an edging tool and seal it with polyurethane joint compound. The expansion joint should be as thin as possible (or eliminated if code permits) to make sealing easier. It is important to seal this joint during construction because the joint is often inaccessible after the building's walls are raised and floor covering is laid.

Architects and engineers should also be aware that buildings constructed with a combination of different substructures may have additional entry routes at the interface between the two types of substructures.

Pour Joints and Control Saw Joints

Cracks are difficult to avoid when large concrete slabs are poured. To minimize cracking, builders either use pour joints because the slab was poured in sections, or saw-cut the slab (control saw joints) to control where a crack will occur, or both. If neither of these techniques nor post-tensioning has been employed, larger slabs will crack unevenly in unpredictable locations. To facilitate sealing these cracks, make the joint or saw-cut large enough to seal with polyurethane caulk after the slab sets. To seal properly, both sides of cold joints should be tooled when poured and then sealed when cured.

2.3.2.2 Slab Penetrations and Openings

Major slab penetrations and openings should be sealed to reduce radon entry and to improve ASD and building pressurization system performance. These slab penetrations and openings include utility penetrations and sump holes.

Utility Penetrations

Examples of utility penetrations through the slab include water and sewer lines, utility lines to unit ventilators and radiators, electrical service entries, subslab conduits, air conditioner condensate drains, and roof drains. The openings around these slab penetrations should be sealed with polyurethane caulks. Many builders use plastic sleeves to protect metal pipes from corrosion when they pass through the concrete slab. These sleeves can be removed after the concrete is set, and the space around the pipe can then be sealed with polyurethane caulk. The same techniques should be used for pipes passing through block walls.

In most construction, floor drains empty into a sewer pipe rather than the soil. In these cases, the drain itself is not of concern as a radon entry route. The only concern is the opening around the pipe penetration as discussed above. Where the floor drain does drain into the soil, the drain should include a filled water trap to prevent soil gas from entering the building.

Sump Holes

Although sump holes are rare in new construction of large buildings, they are occasionally used as collection points for a subslab drainage system. The sump hole can create a radon collection system that should not be open to the building interior. An alternative subslab drainage system is one that drains by gravity to daylight, serving the same purpose as a sump hole without the radon entry routes. If draining to daylight is not possible, then seal the sump hole so that there are no air leaks to the building interior. Seal the sump hole with a gasket and lid, and vent the sump to the outdoors using plastic pipe (as discussed in Section 2.1.1.3). Also install a submersible sump pump to remove any water collected in the sump through a check valve to approved disposal. Sealed sumps have been used as suction pits for ASD systems in houses by attaching a fan to the PVC pipe (15); however, this approach has not been field-tested in schools and is not recommended.

Radon mitigators sometimes use silicone rather than polyurethane caulks for sealing sump lids and access ports because they make a tight fitting gasket that can be removed at a future date. This is satisfactory if the sump cover is bolted down and the seal is airtight.

2.3.2.3 Crack Prevention

Cracking of concrete is a natural result of the curing process. Factors that affect the curing process include water content, cement content, aggregate content, humidity, temperature, carbon dioxide levels, air movement over the slab surface, and preparation of the subslab area. Reinforcement is one of the methods typically used in large slabs to reduce cracking. Concrete should be reinforced and placed in accordance with American Concrete Institute (ACI) codes and standard practice. ACI publishes a number of documents outlining standard practice. A number of these apply to crack prevention. Specifically, the reader is referred to ACI 302.1R-89, Guide for Concrete Floor and Slab Construction (22).

The builder should treat the slab in one or more of the following ways to reduce slab cracking.

Reinforce with ferrous metals: Imbed a combination of rebar and woven wire mesh in the slab to increase its strength.

Reinforce with fibers: Various fiber additives are available to reinforce poured concrete and reduce cracking. These fibers are discussed in ACI 544, State-of-the-Art Report on Fiber-Reinforced Concrete.

Use water-reducing admixtures: These admixtures (also known as plasticizers) retain workability at a lower water content, increasing the strength of the concrete slab. See ACI 212.1R-89, Admixtures for Concrete, for more information (23).

Cure properly: Proper curing is critical to the strength and durability of poured concrete. Stronger concrete can be achieved by slowing the drying rate. Approaches include watering the slab during drying, covering it with wet sand, wet sawdust, or a waterproof film, or coating it with a curing compound.

Use higher strength concrete: Typical school concrete slab construction uses concrete with a 28-day compressive strength of 3,000 to 3,500 psi. Concrete can be made stronger by increasing the cement content, by reducing the water/cement ratio, or both.

2.3.2.4 Subslab Membranes

Membranes of plastics used to control liquid water penetration and water vapor diffusion also are effective in controlling air movement. If they can be adequately sealed at the joints and penetrations and installed intact, membranes can be used in conjunction with the sealed concrete slab to help provide a physical barrier to radon entry. The use of a polyethylene vapor retarder will also enhance the effectiveness of an ASD system by keeping wet concrete out of the aggregate during pouring.

Many types of membranes are available including: polyethylene film, reinforced polyethylene film, polyethylene-coated kraft paper, PVC membranes, and EPDM membranes. Polyethylene sheeting is commonly used as a subslab vapor retarder in most areas of the country. The current prevalence and low cost of this material indicate it is worthwhile to continue its use even though it is an imperfect barrier for radon.

2.3.3 Sealing Below-Grade Walls

Below-grade walls and stem walls are normally constructed of either poured concrete or masonry blocks. Because these walls are in direct contact with the soil, they can be major radon entry routes. This section discusses the different types of below-grade walls and the coatings that can be used to seal these walls. Penetrations and openings through below-grade walls into the soil can also be major radon entry routes. These penetrations and openings should always be sealed as discussed in Section 2.3.2.2.

2.3.3.1 Wall Types

Poured Concrete Walls

In schools and other large buildings, foundation walls made of poured concrete are generally constructed to a minimum compressive strength of 3,500 psi. A poured concrete wall can be an excellent barrier to radon; however, as with concrete slabs, the major problems are cracks, joints, and penetrations. We recommend that concrete walls be built in compliance with guidelines established by ACI to ensure a strong foundation and to minimize cracking (24, 25).

Masonry Block Walls

Foundation walls built of concrete masonry units can be designed with open cores, filled cores, or cores closed at or near the top course or at slab level. In addition, masonry walls are frequently coated with an exterior cementitious material (referred to as "parging") for water control. This coating is usually covered at the bottom of the wall to make a good exterior seal at the joint between the footing and the block wall. Other types of coatings are discussed below in Section 2.3.3.2. Uncoated blocks are not effective water or soil-gas barriers.

Concrete blocks are more porous than poured concrete, although the parge or waterproofing coats can moderate the difference. Recent EPA laboratory tests have confirmed that concrete masonry walls can allow substantial airflow, although there is a great deal of variation in the porosity of blocks (26).

When masonry construction is used, it is mandatory that concrete block walls be built according to guidelines issued by the National Concrete Masonry Association (NCMA) and American Concrete Institute/American Society of Civil Engineers. Their publications cover thickness of block, reinforcing, pilaster location, control joints, sequencing and other issues that influence cracking and foundation strength (5).

Stemwalls and Interior Walls

Stemwalls, also called frost walls, are below-grade foundations that support the load of the above-grade walls, and thereby, the roof. There is a footing beneath stemwalls below the frost line. The sealing of the slab/stemwall joint is covered under Section 2.3.2.1.

If stemwalls are constructed of concrete blocks, then the top blocks must be solid. This solid block can help prevent radon from entering the building; it will also make the building easier to mitigate if it has elevated radon. Sealing the bottom course should prevent soil gas beneath the slab from entering the block wall.

2.3.3.2 Coatings For Below-Grade Walls

There are building codes that dictate dampproofing or waterproofing treatments for foundations. Any waterproofing material that provides adequate protection against water should greatly reduce convective soil gas movement. Properly applied waterproofing materials will help block the pressure-driven entry of soil gas. Waterproofing barriers against pressure-driven gas flow should meet the following criteria: good adhesion, crack-spanning ability, flexibility and elasticity through a wide temperature range, puncture resistance, and chemical and structural stability over time. The advantages and disadvantages of various types of coatings for exterior and interior below-grade walls are discussed below.

Exterior Wall Coatings

- Bituminous asphalt: the most common exterior dampproofing treatment for foundation walls is a parge or spray coat cover using bituminous asphalt. The parge coat is most often used for concrete masonry walls. However, data from Oak Ridge National Laboratory indicate that bituminous asphalt can be attacked by soil and groundwater chemicals, specifically acids (5). Bituminous materials may also lose their elasticity at below-freezing temperatures. These features render bituminous asphalt an undependable waterproofing treatment; thus, builders should not use bituminous asphalt for sealing radon entry routes. Bituminous asphalt is listed by code organizations such as Building Officials and Code Administrators (BOCA), Council of American Building Officials (CABO), and Southern Building Code Congress International (SBCCI) only for dampproofing.
- Coal tar modified polyurethane: coal tar modified polyurethane is a cold-applied liquid waterproofing system. The coating dries hard but has some elasticity. One problem with this material is that it can be attacked by acids in groundwater, but it can be defended by a protection board. The performance of any liquid-applied waterproofing system is limited by the capabilities of the applicator, and it is difficult to achieve even coats on vertical surfaces (5).
- Polymer-modified asphalt: polymer-modified asphalt is another cold-applied liquid waterproofing system. As with the system mentioned above, the quality of the installation depends on the applicator, and it is difficult to achieve an even coating on a vertical surface. High grade polymer-modified asphalt is superior to coal tar modified polyurethane in elasticity, crack-spanning ability, and re-sealability, but inferior in its resistance to chemicals (5).
- Membrane waterproofing systems: membrane waterproofing is advantageous over liquid-applied systems in that quality control over thickness is ensured by the manufacturing process. Most membrane systems are also chemically stable and have good crack-spanning ability. Effective waterproofing demands that concrete seams be smooth so the membrane is not punctured. Reinforced thermoplastic membranes can be applied in various ways: affixed to walls, laid beneath concrete slabs, or on a layer of sand. Thermoplastic membranes are rated highly for resistance to chemicals and longevity. Rubberized asphalt polyethylene membranes have superior crack-bridging ability, compared to fully adhered thermoplastic membranes (5). However, seams and overlaps must be carefully and completely sealed for membranes to function as complete radon barriers. Manufacturers' recommendations for sealant, application procedures, and safety precautions should be followed.
- Surface bonding cement: surface bonding mortar or cement is approved by some building codes as dampproofing treatment, but not as a waterproofing treatment. A number of manufacturers produce cements and mortars impregnated with fibrous glass or other fibers. Some of these may be chemically unstable in the alkaline environment of Portland cement (5).

Interior Wall Coatings

- Cementitious waterproofing: a number of additives can be mixed with concrete to create cement-like "waterproofing." This type of waterproofing is appropriate only for interior applications because it is inelastic, does not have good crack-spanning ability, and cannot resist hydrostatic pressure.
- Interior paint as a barrier: a variety of interior applied masonry paints are available. Some of these have been tested by EPA's Air and Energy Engineering Research Laboratory. Results of these tests show that a number of interior paints can be effective radon barriers if properly applied (26).

2.3.4 Sealing Crawl Spaces

Elevated levels of radon can also build up inside a crawl space, especially if the crawl space has an earthen floor rather than a poured concrete slab. Radon in the crawl space can then enter the occupied area above the crawl space through cracks and openings in the floor. Thorough sealing of these cracks and openings will help to reduce radon entry into the occupied area.

In schools and other large buildings, the floor above the crawl space is typically a suspended concrete slab rather than a wood floor (as in houses). A poured concrete floor slab is a good barrier to radon; however, as discussed in Section 2.3.2, joints and cracks in the slab are potential radon entry routes and must be sealed. Sealing and crack prevention techniques for slabs, covered in Section 2.3.2, should be followed.

Openings and penetrations between the crawl space and the occupied area above should be eliminated where possible. All other openings and penetrations should be carefully sealed during construction. Openings and penetrations of particular concern are similar to those covered in Section 2.3.2.2 and include:

- water and sewer lines
- utility lines to unit ventilators and radiators
- electrical service entries

In areas with a high potential for elevated radon levels, it may also be necessary to take a more direct approach by installing a submembrane depressurization system in the crawl space. This technique actually reduces radon levels in the crawl space rather than reducing radon entry from the crawl space into the building and is covered in Section 2.1.4.

Radon in the crawl space can also enter the occupied area above if duct work for the HVAC system is located in the crawl space. Therefore, in radon-prone areas, neither air supply nor return duct work should be located in the crawl space. For additional information, refer to ASHRAE Standard 62-1989 (10).

2.3.5 Summary of Sealing Recommendations

While physical barriers and sealing entry routes will reduce radon levels, the primary importance of sealing is to enhance the effectiveness of ASD systems and building pressurization. The following lists summarize guidelines for recommended sealants and for sealing concrete slabs, below-grade walls, and crawl spaces.

Recommended Sealants

- Use polyurethane sealants since they adhere well to concrete, have a good service life, and good elasticity.
- Sealants should be applied, according to manufacturers' recommendations, onto a clean dry surface.

Sealing Concrete Slabs

- Slab joints (floor/wall joints, pour joints, and control saw joints) should be tooled when poured and sealed with polyurethane caulk after curing.
- Openings around utility penetrations that pass through the slab should be thoroughly sealed.
- Drain footing and interior drainage systems to daylight if possible. If a sump hole is necessary, a submersible pump should be used, the hole sealed airtight to the building, and the sump vented to the outdoors.
- To reduce slab cracking the builder can reinforce the concrete with ferrous metals or fibers, use water reducing admixtures, use higher strength concrete, and make sure that the concrete is cured properly.
- Subslab membranes can be used under the slab to help provide a physical barrier to radon entry; however, their most useful purpose is probably to prevent wet concrete from seeping into the aggregate during construction.

Sealing Below-grade Walls

- Poured concrete walls are good barriers to radon as long as cracks and openings around utility penetrations are sealed.
- If masonry block walls are used, select blocks with low air flow permeability and apply exterior and/or interior coatings to the walls.
- If stem walls and interior walls are constructed of concrete blocks, the top blocks should be solid.

Sealing Crawl Spaces

- Thoroughly seal all cracks and openings in the floor above the crawl space.
- Crawl space buildings constructed in radon-prone areas should use suspended concrete floors (rather than wood) above the crawl space and a submembrane depressurization system.

2.4 Guidelines for Measuring Radon Levels

EPA is currently revising their guidelines for conducting radon measurements in schools. Contact your local, state, or EPA Regional Office for a copy of these updated guidelines for radon measurements in schools and for radon measurement guidelines for large buildings.

In addition to measuring radon after the building is constructed, EPA recommends that schools be retested sometime in the future. This is particularly important if there are any changes to the building structure or HVAC system. A suggested schedule for retesting is:

> If the results of the initial testing were all below 4 pCi/L, retest all frequently occupied ground-contact rooms sometime in the future. As a building settles, cracks in the substructure or other structural changes may increase radon entry.
>
> If any areas initially tested above 4 pCi/L, requiring radon mitigation, retest these areas periodically. Specific guidelines on post-mitigation testing will be provided in an updated EPA manual on radon mitigation in schools.

If major renovations to a building or HVAC system are planned, retest the building beforehand. If elevated radon levels are detected, incorporate radon-resistant features as part of the renovation.

Appendix A
Case Study

Application of Radon Prevention Design Features to a Johnson City Rehabilitation Hospital Building

Background Information

In late 1990 and 1991, EPA had the opportunity to demonstrate ASD in a large hospital building under construction in Johnson City, Tennessee (6, 7). The hospital building is one story with a floor area of about 60,000 sq ft. The building is slab-on-grade construction with no foundation walls penetrating the slab. Mechanical piping, electrical conduit, and structural columns penetrate the slab with the columns sitting on footings beneath the slab. These columns support steel beams overhead which in turn carry the bar joists for the roof (post-and-beam construction).

This type of construction is used in most commercial and industrial buildings currently being built in the U.S. where dimensions are large in both directions (length and width). All internal walls are gypsum board on metal studs, and the exterior walls are metal stud supporting gypsum board on the inside surface and an exterior insulation finish system on the outside.

The 4-in. thick slab was poured over a 6 mil vapor barrier underlain with a 4-in. layer of coarse, crushed aggregate that was continuous under the entire slab. The slab was divided into about 15 ft squares by a combination of pour joints (1,000 linear ft) and control saw joints (5,000 linear ft). No expansion joints were used. Turned down exterior foundation walls were used, eliminating an exterior floor-to-wall joint. In other words, the slab, exterior foundation walls, and footings were poured monolithically.

EPA was requested to review the plans and specifications and to recommend a radon mitigation system since the region was known to have high radon potential. After this review, five recommendations were made to the architect designing the building and incorporated in the plans and specifications.

1. Good compaction of the clay soil under the aggregate to decrease permeability of the material under the aggregate.
2. Minimum of 4 in. of crushed aggregate—meeting Size #5 specifications as defined in ASTM C-33-90 (11)—carefully placed so as not to include any soil. The stone was not tamped after it was placed, and a vapor retarder was placed on top of the aggregate prior to pouring the slab.
3. Sealing of all pour and control saw joints and any slab penetrations with a polyurethane caulking. (No expansion joints were used in the building.)
4. Installation of one subslab radon suction pit, as shown in Figure 2-5. The pit was located in the approximate center of the slab and had a 6-in. stack leading to the roof. If a radon problem were found when the building was completed, plans were to install a turbo fan capable of moving 500 cfm of soil gas at zero static pressure.
5. Continuous operation of the HVAC fans in order to pressurize the building in all areas except those where negative pressure is necessary to control odors, noxious chemicals, or infectious diseases (toilets, kitchen, pharmacy, soiled linens area, isolation wards, etc.).

Results

All of the above recommendations were accepted and incorporated into the building design. Upon completion of the shell of the building and sealing of the slab, EPA made diagnostic measurements to determine effectiveness of the ASD system in depressurizing the entire subslab area. (Refer to "Measure Subslab Pressures" in Section 2.1.2.1.) Test holes were drilled through the slab at varying distances from the radon suction pit, including a series around the entire perimeter about 6 ft from the slab edge. Radon levels below the slab were measured by "sniffing" with a continuous monitor and ranged from about 200 to 1,800 pCi/L.

A suction fan was attached to the radon vent stack in order to determine the subslab pressure field. The suction fan moved about 200 cfm of soil gas at a vacuum of about 1.5 in. WC. Subslab pressure measurements were made using a micromanometer. Negative pressure was 0.47 in. WC in the radon suction pit, 0.22 in. WC 50 ft from the radon suction pit, and 0.18 in. WC at the farthest point on the perimeter (a distance of 185 ft). This is considered extremely good extension of the negative pressure field. Extrapolation of these data indicates that the mitigation system could mitigate a slab as large as 1,000,000 ft^2.

Upon completion of the building, radon levels were measured in half of the building using open-faced charcoal canisters. The HVAC and the ASD systems were off for this first set of measurements. Radon levels ranged from less than 0.5 pCi/L (lowest detectable level with the open-faced canisters used) to 53 pCi/L. The highest levels were in the bathrooms, particularly those attached to the patient rooms. The patient room with the highest bathroom radon level had a radon reading of 10 pCi/L. This was the highest radon level found in any non-bathroom area in the building.

To determine the effect of the HVAC system alone, the entire building was then measured with the HVAC system on and the ASD system off. Again, some of the bathrooms had elevated radon levels as did some of the patient rooms. The bathroom with the highest radon reading was again the highest in the building with the HVAC operating, testing 6 pCi/L.

The final series of tests were made with both the HVAC *and* ASD systems operating. The 20 bathrooms with the highest radon levels in the second series of tests and many of the patient rooms were remeasured. No measurable radon levels were found in any of the rooms tested. This is not surprising in view of the relatively high negative pressure under the entire slab with the ASD system in operation.

In the Indoor Radon Abatement Act of 1988, the U.S. Congress set a long-term goal of reducing the radon level in all buildings in the U.S. to a level as low as that surrounding the buildings (i.e., ambient). This building, built in a radon-prone area, appears to meet the long-term ambient goal.

Conclusions

Incremental costs of these radon prevention features were easily tabulated since the contract for the building had been let before the ASD system was added to the design. Hence, the cost of the ASD system and sealing was covered by four change orders for which the construction contractor charged an additional $5,300. This is less than $0.10 per sq ft of floor space. Specifications had already called for 4 in. of aggregate under the slab, and there was no charge for the change in aggregate size used. The other three change orders covered installation of the radon suction pit and stack to the roof, sealing of all pour and control saw joints with a polyurethane caulking, and installation of the suction fan and alarm system.

The costs of the four change orders are summarized in Table A-1. A survey of eight recently constructed school buildings showed that the cost of installing radon mitigation systems during construction ranged from $0.30 to over $1.00 per sq ft (8). Hence, the mitigation system installed during construction in this new building cost only a fraction of the cost of systems installed in the eight schools.

Table A-1. Cost of Mitigation System in Johnson City Hospital

Change Order Description	Cost ($)
Change aggregate to ASTM Size #5 stone	0
Seal all slab cracks and penetrations with polyurethane caulking	2583
Install subslab suction pit and stack to roof	1275
Install suction fan and alarm system	1510
Total cost	$5368

A low cost, single point ASD system, installed during construction, has lowered radon levels in a one-story 60,000 ft² hospital building to near ambient levels. Levels as high as 53 pCi/L were measured in the building with both the HVAC and ASD systems off, and levels as high as 16 pCi/L were measured with the HVAC system operating and the ASD system off.

The features of this radon-prevention system are:

1. Slab-on-grade post-and-beam construction with no barriers to soil gas flow below the slab.
2. Continuous layer of coarse, narrow particle size range crushed aggregate a minimum of 4 in. thick.
3. Careful sealing of all slab cracks and penetrations and the use of a 6-mil plastic film between the slab and the aggregate.
4. Low permeability layer beneath the aggregate. (In this case, the compacted clay beneath the aggregated itself was highly impermeable.)
5. A subslab radon suction pit having a void to aggregate interface area of 5 to 7 ft² and a 6-in. diameter stack to the roof.
6. An exhaust fan (on the stack) capable of exhausting a minimum of 500 cfm at no head.

For additional details on this and other case studies, refer to References 3, 4, 6, 7, 8, and 16.

Appendix B
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Appendix C
EPA Regional Offices and Contacts

Region 1

(CT, ME, MA, NH, RI, VT)
JFK Federal Building
Boston, MA 02203
Attention: Radiation Program Manager
(617) 565-4502

Region 2

(NJ, NY)
26 Federal Plaza
New York, NY 10278
Attention: Radiation Program Manager
(212) 264-4418

Region 3

(DE, DC, MD, PA, VA, WV)
841 Chestnut Building
Philadelphia, PA 19107
Attention: Radiation Program Manager
(215) 597-8320

Region 4

(AL, FL, GA, KY, MS, NC, SC, TN)
345 Courtland St. N.E.
Atlanta, GA 30365
Attention: Radiation Program Manager
(404) 347-3907

Region 5

(IL, IN, MI, MN, OH, WI)
77 West Jackson Blvd.
Chicago, IL 60604
Attention: Radiation Program Manager
From: IN, MI, MN, OH & WI:
(800) 621-8431
From: IL:
(800) 572-2515

Region 6

(AR, LA, NM, OK, TX)
1445 Ross Ave.
Dallas TX, 75202
Attention: Radiation Program Manager
(214) 655-7223

Region 7

(IA, KS, MO, NE)
726 Minnesota Ave.
Kansas City, KS 66101
Attention: Radiation Program Manager
(913) 551-7020

Region 8

(CO, MT, ND, SD, UT, WY)
999 18th St.
Denver Place, Suite 500
Denver, CO 80202-2405
Attention: Radiation Program Manager
(303) 293-1709

Region 9

(AZ, CA, HI, NV)
75 Hawthorne St.
San Francisco, CA 94105
Attention: Radiation Program Manager
(415) 744-1045

Region 10

(AK, ID, OR, WA)
1200 Sixth Ave.
Seattle, WA 98101
Attention: Radiation Program Manager
(206) 442-7660

Addendum

This addendum to the technical guidance manual, "Radon Prevention in the Design and Construction of Schools and Other Large Buildings," is included in this printing of the manual in order to make available new technology which has been developed and field-verified since the manual was initially printed. In the future, the entire manual will be revised and all new technology, including this addendum, will be incorporated into the body of the manual.

Increasing Pressure Field Extension by Modifying Subslab Walls

Section 2.1.1.2 describes the effect of subslab barriers on pressure field extension (PFE). It states, "...the designer should consider 'connecting' subslab areas by eliminating subslab walls...under interior doors....Subslab communication could also be facilitated by using subslab 'pipe sleeves' to connect areas separated by subslab walls."

Another technique, now field-tested, has been shown to be extremely effective in improving PFE through block walls. Every other concrete masonry unit (CMU) is turned on its side in the first row of block below the slab in interior walls. This allows soil gas to pass through the subslab wall, significantly improving PFE. PFE tests have shown that this essentially makes the wall disappear as far as PFE is concerned. This technique is shown in Figures 2-10 and 2-11. In one field test, adequate negative pressure was still maintained after the pressure field had passed through four successive walls with CMUs turned on their sides. In the school where this was first demonstrated, the contractor made the change to all interior walls at no extra cost. Based on these results, we recommend that blocks be turned on all interior walls in buildings in which ASD is installed except toilet walls serving as pipe chases. These should not be turned and should be sealed from any open contact with the subslab aggregate.

Improved Suction Pits

The suction pit recommended in the manual is described in Section 2.1.1.3 (page 13) and illustrated in Figure 2-5 (page 20). Since the manual was issued, two new suction pits of improved design have been developed and field-tested. The first is shown in Figure 2-12. It is constructed from angle iron which supports a covering of expanded metal decking. This new suction pit is smaller (3 by 3 ft in area and 12 in. deep) but has the same void-to-aggregate interface (7 ft^2) as the one shown in Figure 2-5.

The second new suction pit is smaller and much simpler to construct. It is shown in Figure 2-13. It is constructed from a rolled cylinder of expanded metal decking with a sheet metal top and bottom. When it is 8 in. tall and fitted with a 6 in. stack, it will exhaust an area of at least 20,000 ft^2. When the area to be covered is less than about 10,000 ft^2, the pit can be 6 in. tall and fitted with a 4 in. stack and a smaller fan if the distance between the pit and the fan is not too great (less than about 20 ft).

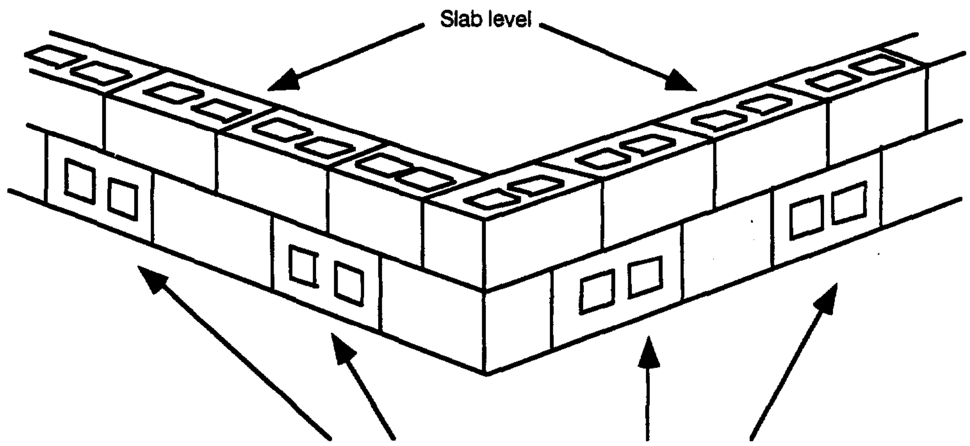

Figure 2-10. Every other interior wall block is turned on its side to allow soil gas to pass through.

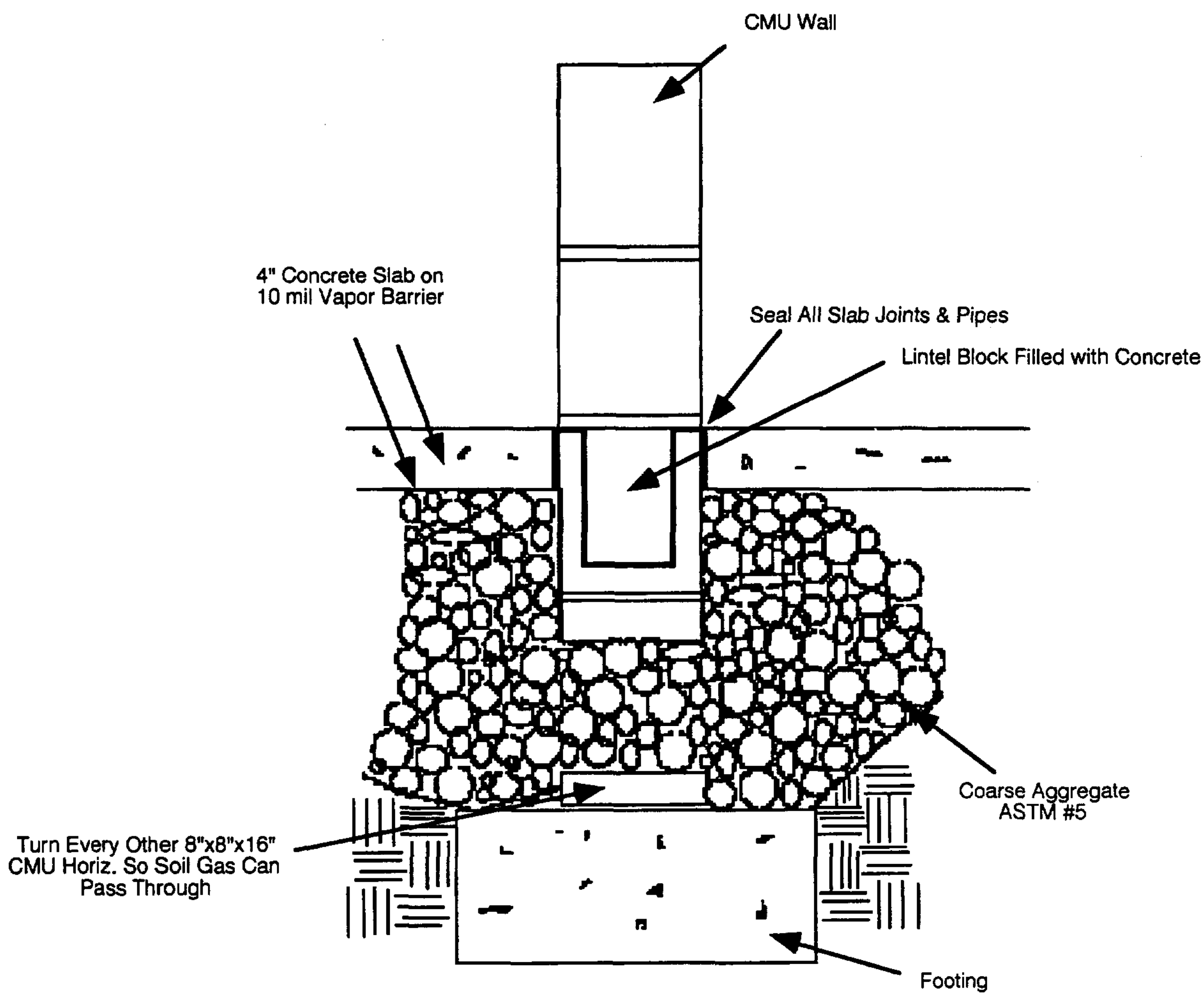

Figure 2-11. Interior CMU wall.

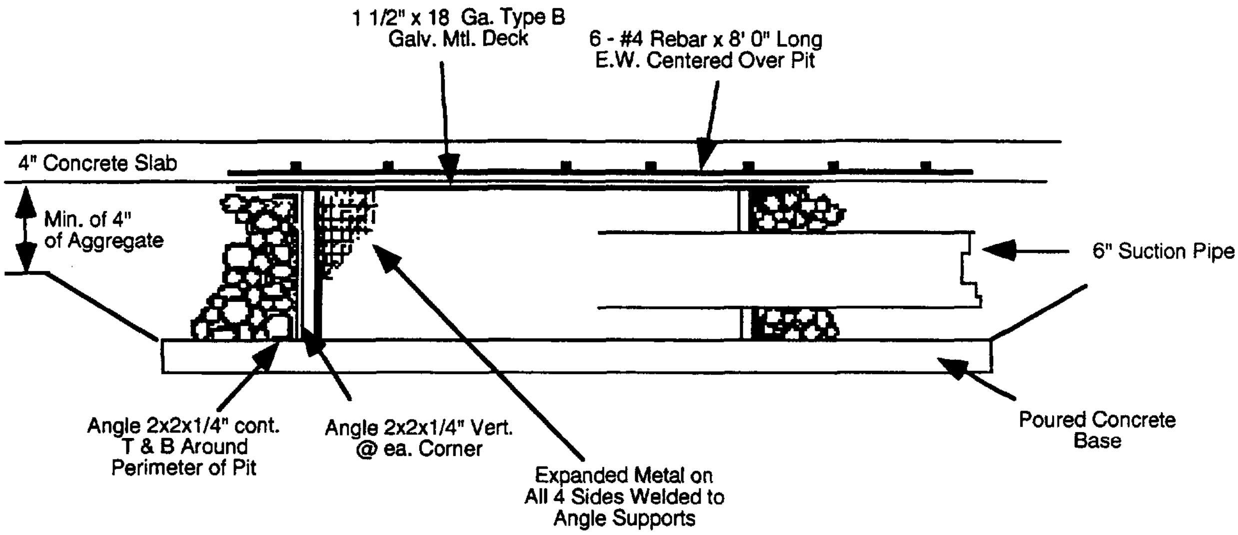

Figure 2-12. Revised subslab suction pit.

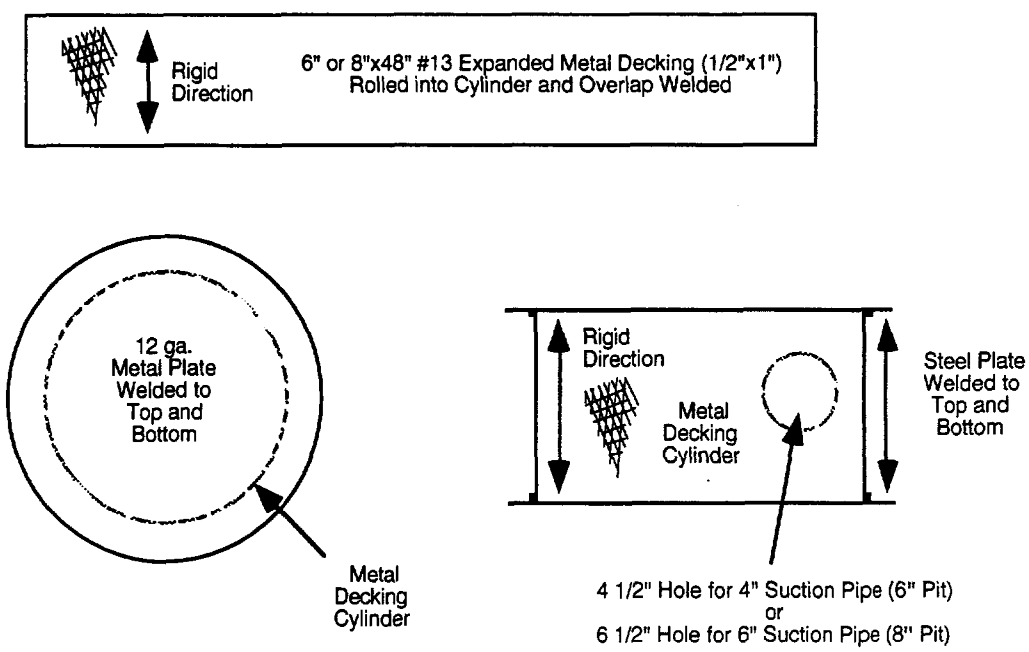

Figure 2-13. Smaller subslab suction pit.

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