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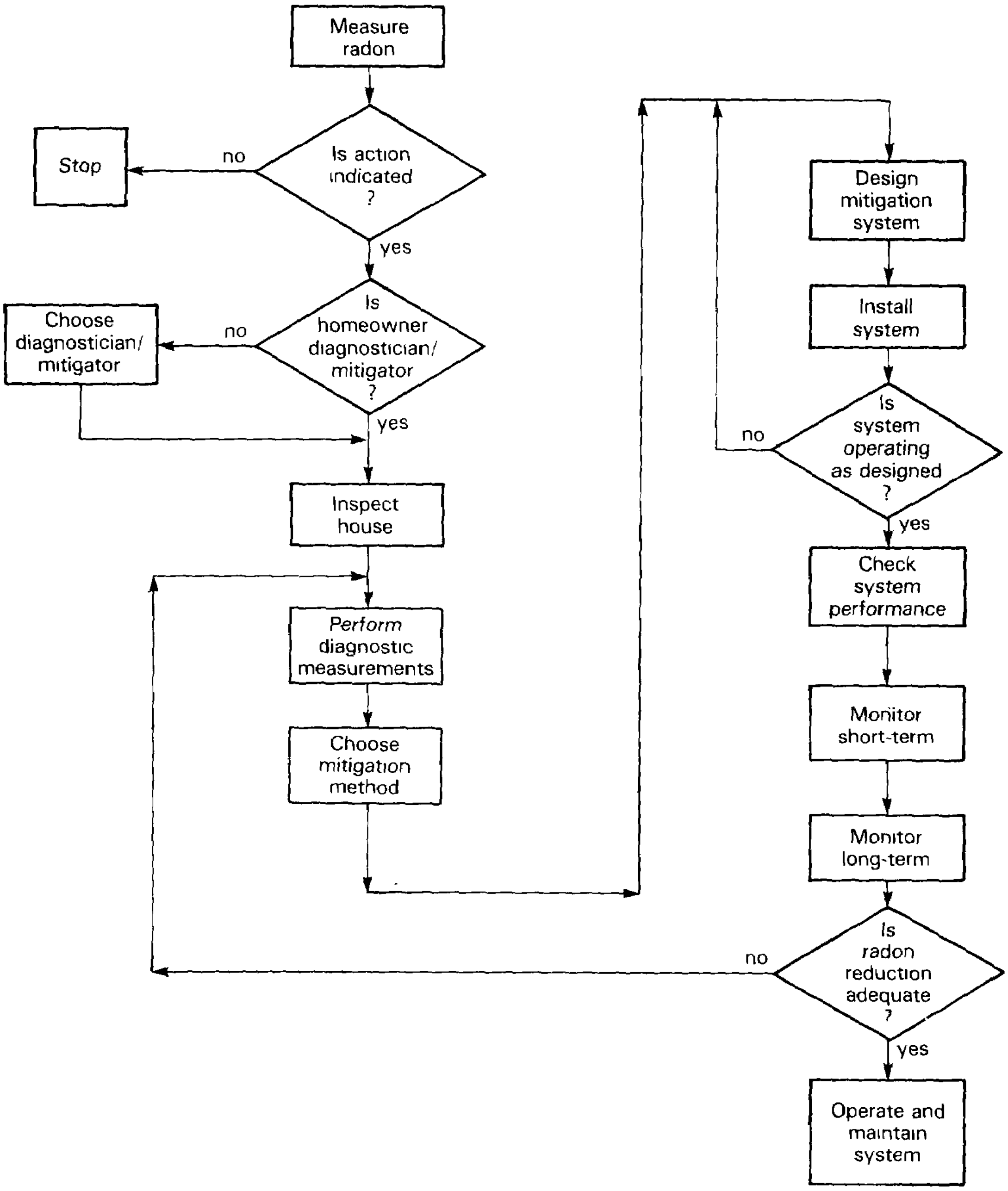
Application of Radon Reduction Methods



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Application of Radon Reduction Methods

by

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FOREWORD

This document is intended to aid homeowners and contractors in diagnosing and solving indoor radon problems. It will also be useful to State and Federal regulatory officials and many other persons who provide advice on the selection, design and operation of radon reduction methods for houses.

This document represents the third publication of EPA's technical guidance for indoor radon reduction methods. It is not intended to replace but rather to supplement the previous document, "Radon Reduction Techniques for Detached Houses: Technical Guidance (Second Edition)," (EPA/625/5-87-019) published in January 1988. While the present document incorporates updated information reflecting new results and perspectives gained since the previous document, its primary purpose is to address a broader audience by condensing and organizing the material to form a decision guidance instrument.

Several recent EPA publications on radon may be of interest to the reader. These publications and their contents are listed below:

- "A Citizen's Guide to Radon: What It Is and What to Do About It,"OPA-86-004 -- This brochure provides general information on radon and its associated health risks.
- "Radon Reduction Methods - A Homeowner's Guide (3rd Edition)," OPA-88-010 -- This booklet provides a concise overview of the radon reduction techniques available to homeowners who have discovered an indoor radon problem.
- "Radon Reduction Techniques for Detached Houses: Technical Guidance (Second Edition)," EPA/625/5-87/019 -- This reference manual provides detailed information on sources of radon and its health effects as well as guidance for selection, design, and installation of reduction techniques.
- "Application of Radon Reduction Methods," EPA/625/5-88/024 -- The current document is a decision guidance instrument intended to direct the user through the steps of diagnosing a radon problem and selecting a reduction method; followed by designing, installing, and operating a mitigation system.
- "Radon-Resistant Residential New Construction," EPA/600/8-88/087 -- This manual provides builders and new home buyers with information on materials and building techniques that are effective in reducing radon levels in new houses.

Copies of these documents can be obtained from the State agencies and the EPA Regional Offices listed in Section 11. Copies can also be obtained from EPA's Center for Environmental Research Information, Distribution, 26 W. Martin Luther King Drive, Cincinnati, OH 45268.

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ACKNOWLEDGMENTS

This manual compiles and documents the experience of many different individuals who have worked in radon mitigation and related fields. Many of these individuals are recognized in the list of references in Section 12. It is through the innovative efforts of these workers that this document is possible.

Drafts of this document have been reviewed by a large number of individuals in Government and in the private sector. Comments from these reviewers have helped significantly to improve the completeness, accuracy, and clarity of the document. Within EPA, reviews were provided by: AEERL's radon mitigation staff, the Office of Radiation Programs, and the Regional Offices. The authors wish to thank the following EPA personnel in particular for their substantive recommendations, comments, and guidance: A.B. Craig, M.C. Osborne, E.L. Plyler, J.S. Ruppersberger, M. Samfield, W.G. Tucker, and K.A. Witter of AEERL; D.M. Murane of the Office of Radiation Programs; P.A. Giardina and L. Koehler of Region 2; W.E. Belanger and L. Felleisen of Region 3; Paul Wagner of Region 4; R.E. Dye of Region 7; and J. Leiten of Region 10.

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GLOSSARY

Air changes per hour (ach) - The number of times within 1 hour that the volume of air inside a house would nominally be replaced, given the rate at which outdoor air is infiltrating the house. If a house has 1 ach, it means that all of the air in the house will be nominally replaced in a 1-hour period.

Air exchange rate - The rate at which the house air is replaced with outdoor air. Commonly expressed in terms of air changes per hour.

Airflow bypass - Any opening through the floors between stories of a house (or through the ceiling between the living area and the attic) which facilitates the upward movement of house air under the influence of the stack effect. By facilitating the upward movement, airflow bypasses in effect facilitate exfiltration at the upper levels, which in turn will increase infiltration of outdoor air and soil gas.

Alpha particle - A positively charged subatomic particle emitted during decay of certain radioactive elements. For example, an alpha particle is released when radon-222 decays to polonium-218. An alpha particle is indistinguishable from a helium atom nucleus and consists of two protons and two neutrons.

Back-drafting - A condition where the normal movement of combustion products up a flue, resulting from the buoyant forces on the hot gases, is reversed, so that the combustion products can enter the house. Back-drafting of combustion appliances (such as fireplaces and furnaces) can occur when depressurization in the house overwhelms the buoyant force on the hot gases. Back-drafting can also be caused by high air pressures at the chimney or flue termination.

Band joist - Also called header joist, header plate, or rim joist. A board the same width as the floor joist that rests (on its 2-in.* dimension) on top of the sill plate around the perimeter of the house. The ends of the floor joists are nailed into the header joist that maintains spacing between the floor joists.

Barrier coating(s) - A layer of a material that obstructs or prevents passage of fluid through a surface that is to be protected. More specifically, grout, caulk, paints, or various sealing compounds, perhaps used with polyurethane membranes to prevent soil-gas-borne radon from moving through walls, cracks, or joints in a house.

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*Readers more familiar with the International System of Units (SI) may use the equivalents listed at the end of the front matter.

Baseboard duct - A continuous system of sheet metal or plastic channel ducting that is sealed over the joint between the wall and floor around the entire perimeter of the basement. Holes drilled into hollow blocks in the wall allow suction to be drawn on the walls and joint to remove radon through the ducts to a release point away from the inside of the house.

Basement - A type of house construction where the bottom livable level has a slab (or earthen floor) which averages 3 ft or more below grade level on one or more sides of the house and is sufficiently high to stand in.

Blower door - A device consisting of an instrumented fan which can be mounted in an existing doorway of a house. By determining the air flows through this fan required to achieve different degrees of house pressurization and depressurization, the blower door permits determination of the tightness of the house shell, and an estimation of the natural in-filtration rate.

Cold air return - The registers and ducting which withdraw house air from various parts of the house and direct it to a central forced-air furnace or heat pump. The return ducting is at low pressure relative to the house because the central furnace fan draws air out of the house through this ducting.

Cold joint - The contact joint between two adjacent concrete slabs or parts of a slab that were poured at different times.

Convective movement - As used here, the bulk flow of radon-containing soil gas into the house as the result of pressure differences between the house and the soil. Distinguished from diffusive movement.

Crawl space - An area beneath the living space in some houses, where the floor of the lowest living area is elevated above grade level. This space (which generally provides only enough head room for a person to crawl in), is not living space, but often contains utilities. Distinguished from slab-on-grade or basement construction.

Cubic feet per minute (cfm) - A measure of the volume of a fluid flowing within a fixed period of time.

Depressurization - In houses, a condition that exists when the air pressure inside the house or in the soil is slightly lower than the air pressure outside. The lower levels of houses are almost always depressurized during cold weather, due to the buoyant force on the warm indoor air (creating the natural thermal stack effect). Houses can also be depressurized by winds and by appliances which exhaust indoor air.

Detached houses - Single family dwellings as opposed to apartments, duplexes, townhouses, or condominiums. Those dwellings which are typically occupied by one family unit and which do not share foundations and/or walls with other family dwellings.

Diffusive movement - The random movement of individual atoms or molecules, such as radon atoms, in the absence of (or independent of) bulk (convective) gas flow. Atoms of radon can diffuse through tiny openings, or even through unbroken concrete slabs. Distinguished from convective movement.

Duct work - Any enclosed channel(s) which direct the movement of air or other gas.

Effective leakage area - A parameter determined from blower door testing, giving a measure of the tightness of the house shell. Conceptually, this leakage area reflects the square inches of open area through the house shell, through which air can infiltrate or exfiltrate.

Entry routes - Pathways by which soil gas can flow into a house. Openings through the flooring and walls where the house contacts the soil.

E-Perm - The Electret-Passive Environmental Radon Monitor is a device that uses an electrostatically charged plastic disk--called an electret--to sense radon in air. When radon decays it produces ions, which are collected by the electret, resulting in a measurable decrease in the charge on the disk.

Exfiltration - The movement of indoor air out of the house. The opposite of infiltration.

Exhaust fan - A fan oriented so that it blows indoor air out of the house. Exhaust fans cause outdoor air (and soil gas) to infiltrate at other locations in the house, to compensate for the exhausted air.

Footing(s) - A concrete or stone base which supports a foundation wall and which is used to distribute the weight of the house over the soil or subgrade underlying the house.

Forced-air furnace (air conditioner or heat pump) - A central unit that functions by recirculating the house air through a heat exchanger. A forced-air furnace is distinguished from a central hot-water space heating system, or electric resistance heating.

French drain (also perimeter drain, channel drain, or floating slab) - A water drainage technique installed in basements of some houses during initial construction. If present, typically consists of a 1- or 2-in. gap between the basement wall and the concrete floor slab around the entire perimeter inside the basement to allow water to drain to aggregate under the slab and then soak away.

Gamma radiation - Electromagnetic radiation released from the nucleus of some radionuclides during radioactive decay.

Grab sample - A sample of air or soil gas collected in an airtight container for later measurements of radon concentration.

Grade (above or below) - The term by which the level of the ground surrounding a house is known. In construction typically refers to the surface of the ground. Things can be located at grade, below grade, or above grade relative to the surface of the ground.

HAC system - A heating and air conditioning system.

Heat exchanger - A device used to transfer heat from one stream to another. In air-to-air heat exchangers for residential use, heat from exhausted indoor air is transferred to incoming outdoor air, without mixing the two streams.

Heat recovery ventilators (HRVs) - Also known as air-to-air heat exchangers.

Hollow-block wall, Block wall - A wall constructed using hollow rectangular masonry blocks. The blocks might be fabricated using a concrete base (concrete block), using ash from combustion of solid fuels (cinder block), or expanded clays. Walls constructed using hollow blocks form an interconnected network with their interior hollow cavities unless the cavities are filled with concrete.

House air - Synonymous with indoor air. The air that occupies the space within the interior of a house.

HVAC system - The heating, ventilating, and air conditioning system for a house. Generally refers to a central furnace and air conditioner.

Indoor air - That air that occupies the space within the interior of a house or other building.

Infiltration - The movement of outdoor air or soil gas into a house. The infiltration which occurs when all doors and windows are closed is referred to in this document as the natural closed-house infiltration. The reverse of exfiltration.

Joist - Any of the parallel horizontal beams set from wall to wall to support the floor or ceiling.

Livable space - Any enclosed space that residents now use or could reasonably adapt for use as living space.

Microrem - A unit of measure of "dose equivalence," which reflects the health risk resulting from a given absorbed dose of radiation. A microrem (μrem) is 1 millionth (10^{-6}) of a rem (roentgen equivalent man).

Microrem per hour - A unit of measure of the rate at which health risk is being incurred as a result of exposure to radiation.

Mitigator - A building trades professional who works for profit to correct radon problems, a person experienced in radon remediation. At present, training programs are underway to provide working professionals with the knowledge and experience necessary to control radon exposure problems. Some State radiological health offices have lists of qualified professionals.

Neutral Plane - A roughly horizontal plane through a house defining the level at which the pressure indoors equals the pressure outdoors. During cold weather, when the thermal stack effect is occurring, indoor pressures below the neutral plane will be lower than outdoors, so that outdoor air and soil gas will infiltrate. Above the neutral plane, indoor pressures will be higher than outdoors, so that house air will exfiltrate.

Permeability (sub-slab) - A measure of the ease with which soil gas and air can flow through a porous medium. High permeability facilitates gas movement under the slab, and hence generally facilitates the implementation of sub-slab suction.

Picocurie (pCi) - A unit of measurement of radioactivity. A curie is the amount of any radionuclide that undergoes exactly 3.7 x 10^{10} radioactive disintegrations per second. A picocurie is one trillionth (10^{-12}) of a curie, or 0.037 disintegrations per second.

Picocurie per liter (pCi/L) - A common unit of measurement of the concentration of radioactivity in a fluid. A picocurie per liter corresponds to 0.037 radioactive disintegrations per second in every liter of air.

Pressure field extension - A spatial extension of a variation in pressure as occurs under a slab when a fan ventilates at one or a few distinct points.

Punk stick - A small tube used to generate smoke from smoldering materials.

Radionuclide - Any naturally occurring or artificially produced radioactive element or isotope which is radioactive; i.e., which will release subatomic particles and/or energy, transforming into another element.

Radon - The only naturally occurring radioactive element which is a gas. Technically, the term "radon" can refer to any of a number of radioactive isotopes having atomic number 86. In this document, the term is used to refer specifically to the isotope radon-222, the primary isotope present inside houses. Radon-222 is directly created by the decay of radium-226, and has a half-life of 3.82 days. Chemical symbol Rn-222.

Radon progeny - The four radioactive elements which immediately follow radon-222 in the decay chain. These elements are polonium-218, lead-214, bismuth-214, and polonium-214. These elements have such short half-lives that they exist only in the presence of radon. The progeny are ultrafine solids which tend to adhere to other solids, including dust particles in the air and solid surfaces in a room. They adhere to lung tissue when inhaled and bombard the tissue with alpha particles, thus creating the health risk associated with radon. Also referred to as radon daughters and radon decay products.

RPISU - A radon progeny integrated sampling unit is a radon decay product measurement system consisting of a low flow-rate air pump that pulls air continuously through a detector assembly containing a thermoluminescent dosimeter. The unit is operated for 100 hours or longer and then the detector assembly is returned to the laboratory for analysis.

Sill plate - A horizontal band (typically 2 x 4 or 2 x 6 in.) that rests on top of a block or poured concrete foundation wall and extends around the entire perimeter of the house. The ends of the floor joists which support the floor above the foundation wall rest upon the sill plate. For slab-on-grade, the sill plate is the bottom plate of the wall.

Slab - A layer of concrete, typically about 4 in. thick, which commonly serves as the floor of any part of a house whenever the floor is in direct contact with the underlying soil.

Slab below grade - A type of house construction where the bottom floor is a slab which averages between 1 and about 3 ft below grade level on one or more sides.

Slab on grade - A type of house construction where the bottom floor of a house is a slab which is no more than about 1 ft below grade level on any side of the house.

Smoke stick - A small tube, several inches long, which releases a small stream of inert smoke when a rubber bulb at one end of the tube is compressed. Can be used to visually define bulk air movement in a small area, such as the direction of air flow through small openings in slabs and foundation walls.

Soil gas - Gas which is always present underground, in the small spaces between particles of the soil or in crevices in rock. The major constituent of soil gas is air with some components from the soil (such as radon) added.

Stack effect - The upward movement of house air when the weather is cold, caused by the buoyant force on the warm house air. House air leaks out at the upper levels of the house, so that outdoor air (and soil gas) must leak in at the lower levels to compensate. The continuous exfiltration upstairs and infiltration downstairs maintain the stack effect air movement, so named because it is similar to hot combustion gases rising up a fireplace or furnace flue stack.

Sump - A pit through a basement floor slab, designed to collect water and thus avoid water problems in the basement. Water is often directed into the sump by drain tiles around the inside or outside of the footings.

Sump pump - A pump to move collected water out of the sump pit, to an above-grade discharge remote from the house.

Thermal bypass - As used here, the same thing as an airflow bypass.

Tight house - A house with a low air exchange rate. If 0.5 to 0.9 air changes per hour is typical of modern housing, a tight house would be one with an exchange rate well below 0.5 ach.

Top voids, Block voids, Voids - Air space(s) within masonry walls made of concrete block or cinder block. Top void specifically refers to the air space in the top course of such walls; that is, the course of block to which the sill plate is attached and on which the walls of the house rest.

Unattached radon progeny - Refers to radon decay products which have not yet adhered to other, larger dust particles in the air (or to other surfaces, such as walls). Unattached progeny might result in a higher lung cancer risk than will progeny that are attached to larger particles, because the unattached progeny can selectively deposit in limited areas of the lung.

Veneer, Brick veneer - A single layer or tier of masonry or similar materials securely attached to a wall for the purposes of providing ornamentation, protection, or insulation, but not bonded or attached to intentionally exert common action under load.

Ventilation rate - The rate at which outdoor air enters the house, displacing house air. The ventilation rate depends on the tightness of the house shell, weather conditions, and the operation of appliances (such as fans) influencing air movement. Commonly expressed in terms of air changes per hour, or cubic feet per minute.

Warm air supply - The ducting and registers which direct heated house air from the forced-air furnace, to the various parts of the house. The supply ducting is at elevated pressure relative to the house because the central furnace fan is blowing air through this ducting.

WC - The height (in inches) of a water column that represents a unit of measure for pressure differences.

Working level (WL) - A unit of measure of the exposure rate to radon and radon progeny defined as the quantity of short-lived progeny that will result in 1.3 x 10^5 MeV of potential alpha energy per liter of air. Exposures are measured in working level months (WLM); e.g., an exposure to 1 WL for 1 working month (170 hours) is 1 WLM. These units were developed originally to measure cumulative work place exposure of underground uranium miners to radon and continue to be used today as a measurement of human exposure to radon and radon progeny.

METRIC EQUIVALENTS

Although it is EPA's policy to use the International System of Units (SI) in its documents, nonmetric units are used in this report for the reader's convenience. Readers more accustomed to the metric system may use the following factors to convert to that system.

Nonmetric	Times	Yields metric
atmosphere (atm)	101	kiloPascal (kPa)
British thermal unit (Btu)	1060	joule (J)
cubic foot (ft^3)	28.3	liter (L)
cubic foot per minute (cfm, or ft^3/min)	0.47	liter per second (L/sec)
degree Fahrenheit (°F)	5/9 (°F-32)	degree Centigrade (°C)
foot (ft)	30.5	centimeter (cm)
gallon (gal)	3.78	liter (L)
horsepower (hp)	746	watt (W), or joule/sec
inch (in.)	2.54	centimeter (cm)
inch of water column (in. WC)	248	Pascal (Pa)
microrem (μrem)	0.01	microSievert (μSv)
picocurie per liter (pCi/L)	37	Becquerel per cubic meter (Bq/m^3)
square foot (ft^2)	0.093	square meter (m^2)

Section 1

Introduction

1.1 Purpose

Much attention has been given recently to increased risks of lung cancer associated with elevated levels of radon gas in indoor air. Only in recent years has it been recognized that a large number of houses in the United States have elevated levels of indoor radon as a result of natural sources. Several comprehensive documents have been published recently (EPA88a, Br88a, Br88b) that describe the nature of the problem. The present document will not attempt a comprehensive description of the background information or health risks analysis associated with indoor radon, but will refer the reader to existing references for detailed information.

The purpose of this manual is to provide guidance in diagnosing radon problems in houses as well as in selecting, designing, and installing radon reduction systems. For an overview, see Figure 1, in which a flow chart illustrates the steps to take in analyzing and solving an indoor radon problem. The organization of this manual is designed to guide the user through decision making by stages to the point of operating and maintaining a successful radon reduction system. Note that advice is provided on choosing a professional mitigator to recommend and/or install a mitigation system.

This document is intended to condense the information contained in "Radon Reduction Techniques for Detached Houses: Technical Guidance (Second Edition)" (EPA88a). Particular emphasis is given to selecting, designing, and installing an effective radon reduction system. The earlier document (EPA88a) is viewed as a companion reference document with supporting information to aid in a more complete understanding of indoor radon problems. Much of the background information and details on sources of radon, the assessment of associated health risks, and mitigation design detail are not reproduced here. Rather, the present document focuses on actions that can be taken to reduce the risks associated with indoor radon exposure once a problem has been recognized.

1.2 Scope

A brief description of where radon comes from as well as its health risk implications and strategies for reducing radon levels in houses are discussed in Section 2. Radon measurements and EPA's recommended actions are presented in Section 3.

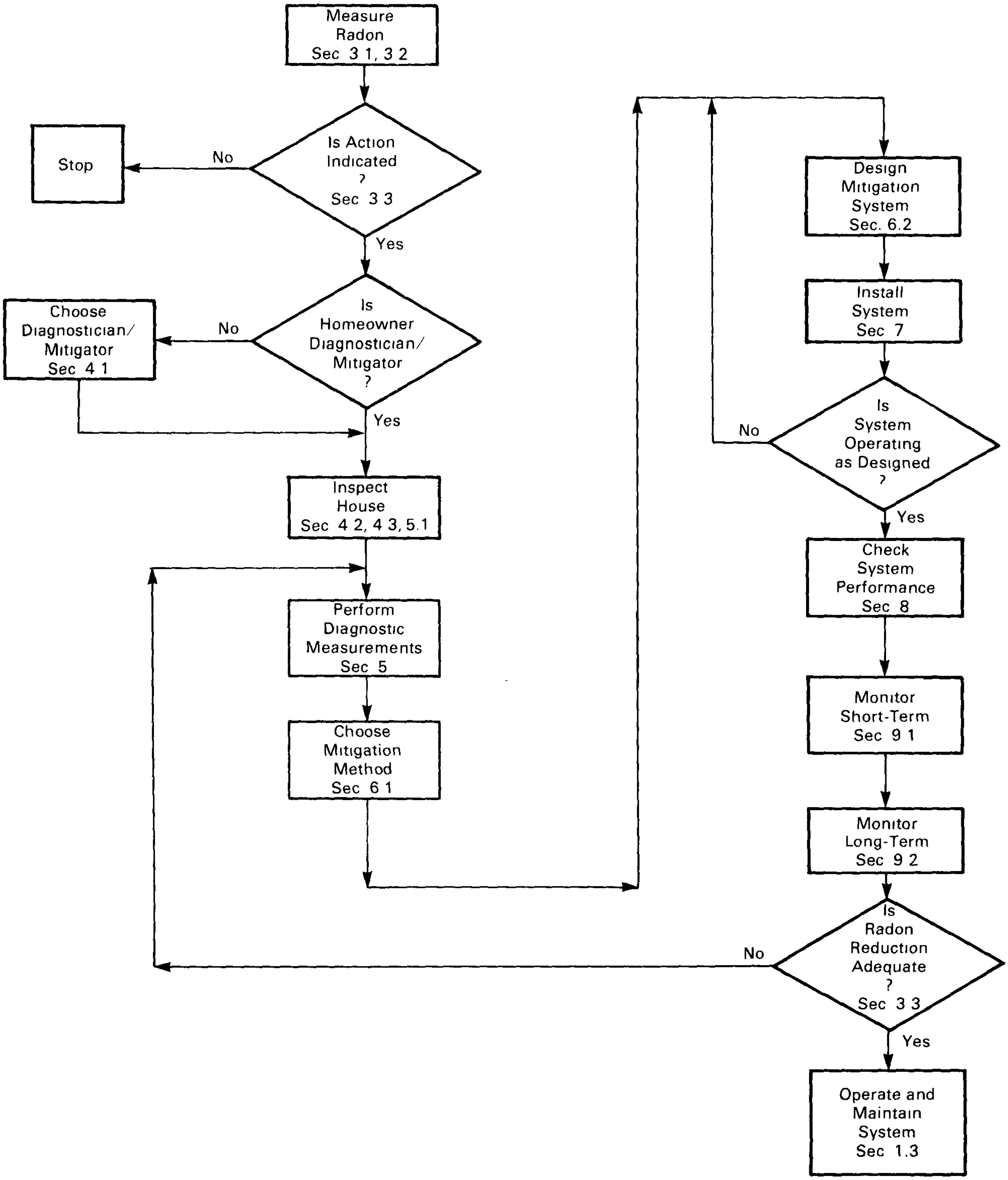
A critical step in developing a plan for reducing indoor radon levels is to identify the important radon entry routes and recognize the factors (e.g., weather effects, house construction features, and occupant activities) that influence the driving forces bringing radon into the house. These effects are discussed in Section 4.

A number of diagnostic measurements presented in Section 5 may be useful in selecting and designing a radon reduction system. Both the strategy and the specifics of designing a radon mitigation system are discussed in Section 6. Section 7 gives some detailed descriptions and recommendations for installing reduction systems. Post-installation diagnostics are presented in Section 8.

After installation, it is necessary to make both short- and long-term measurements and observations to determine whether the system is operating as intended. These measurements are described in Section 9. Once the mitigation system is operating, routine monitoring and maintenance must be carried out to ensure continued performance.

Several of the more frequently used reduction techniques are described at various points (especially in Sections 6 and 7) throughout the first nine sections. The methods of crawl-space ventilation, house ventilation, and house pressure adjustments are further developed in Section 10. Although sealing (or closure) is referred to throughout the document, the most complete presentation is in Section 10. The less frequently applied techniques of passive soil ventilation, air cleaning, removal of radon from well water, and radon reduction in new construction are treated almost exclusively in Section 10.

Figure 1. Steps involved in diagnosing and solving an indoor radon problem.



1.3 How to Use This Manual

This section describes the steps in the decision process illustrated in Figure 1 and directs the reader to other sections of the manual for additional information.

A step-by-step approach for using this document to identify and solve indoor radon problems is recommended below:

Step 1. Make radon (or radon decay product) measurements to determine the severity of the existing radon problem. This typically involves both screening and follow-up measurements.

Section 3.1 contains a brief description of methods commonly used to perform initial radon (or radon decay product) measurements. For more complete coverage of both initial screening measurements and follow-up measure-ments, see EPA's interim protocols (EPA86b, EPA87a). The radon levels determined by these measurements will aid in deciding upon the degree of radon reduction required and the urgency of the need for action. In cases of elevated radon levels in the indoor air, water supplied from a private or small community well should also be tested to determine whether the well water might be an important contributor to the airborne radon. Further guidance on measurements in water is available in Reference EPA87c. In most states, the health department, the radiation protection office, or the drinking water office have been designated to help in testing private water supplies.

Step 2. Decide whether action to reduce the radon level is required.

If the annual average radon concentration is greater than 4 pCi/L, action to reduce it is recommended. The urgency with which action is recommended depends upon how much the measurement exceeds 4 pCi/L.

1. For radon concentrations greater than 200 pCi/L, action is recommended within a few weeks.
2. For radon concentrations in the range of 20 to 200 pCi/L, action is recommended within several months.
3. For radon concentrations in the range of 4 to 20 pCi/L, action is recommended to reduce the levels below 4 pCi/L within a few years. The higher the value the more urgent the need for action (EPA86a).
4. If the radon concentration is less than 4 pCi/L, EPA does not specifically recommend that any action be taken. However, since there may be no safe level of indoor radon, some homeowners may wish to reduce the levels further. If action to reduce the radon concentration is taken, the goal should be to reduce the level as much below 4 pCi/L as reasonably possible because of significant health risks even at 1 pCi/L. It should be noted, however, that it is not very practical to try to reduce indoor radon levels below the ambient values.

Step 3. Choose an advisor/mitigator.

If, after studying this manual and Reference EPA88a, the reader does not feel confident in tackling the task of diagnosing the radon problems in the house, then guidance in choosing a professional advisor (diagnostician) is provided in Section 4.1.

Step 4. Inspect the house to identify radon entry routes, factors which influence the driving forces for radon entry, and construction features which lend themselves or present obstacles to specific mitigation techniques.

Section 4.2 provides a detailed discussion along with a checklist (Table 2) of many potential routes through which soil gas might enter a house, while Section 4.3 provides a checklist (Table 3) of appliances, house design features, and other factors which can contribute to depressurization. Knowledge of the processes through which the soil gas is entering will be important in the selection and design of any radon reduction system.

Step 5. Implement near-term radon reduction measures that can be applied fairly simply and at low cost.

A homeowner discovering elevated radon levels might wish to take some immediate action to reduce these levels before more comprehensive, permanent steps can be taken. Section 3.3 describes some techniques that can be readily implemented by a homeowner at limited cost, such as increased house ventilation and closure of major entry routes that are accessible. Some of these near-term approaches (in particular, house ventilation via open windows and doors) can be very effective, but are not practical as a permanent reduction method (e.g., during extreme hot or cold weather). Closure of major entry routes might provide significant radon reductions. However, these near-term approaches will often not be adequate by themselves to address the elevated levels permanently.

Step 6. Conduct diagnostic testing as warranted to aid in the selection and design of a radon reduction technique.

Section 5 describes some of the diagnostic testing that can be considered to provide information to aid in the selection and design of a mitigation system. Many of these diagnostic tests are intended to measure inherent properties of the house or soil (e.g., the permeability of the soil and crushed rock beneath the concrete slab) to determine suitability for sub-slab soil ventilation. Some of the tests are intended to evaluate the relative importance of different potential radon sources within the house. The particular diagnostic tests that are cost effective for a given house will depend upon the particular radon reduction techniques that are being considered and the construction features of the house. Some of this pre-mitigation diagnostic testing might best be completed before Step 7 is initiated to aid in choosing between radon reduction options. Other diagnostic testing would best be performed after the selection process is completed, to aid in designing (Step 8) the particular reduction options that have been selected. Therefore, Steps 6, 7, and 8 are not always distinct.

Step 7. Review the alternative radon reduction options that appear suitable for the particular house, and select a mitigation method. The radon reduction options available are summarized in Section 2.3 (Table 1).

Some of the less frequently used radon reduction options, including pertinent information for each (such as applicability, and estimated effectiveness), are summarized in Section 10. This selection will be based upon the degree of radon reduction desired, the construction features of the house, and the confidence levels, costs, and other factors acceptable to a particular homeowner. Such factors might include aesthetics, maintenance requirements, lifestyle adjustments, and noise. Where a combination of techniques is to be installed, or where a single technique can be designed in various ways with various costs, it might sometimes be cost-effective to install the system in phases. This topic is further explored in Section 7. Selection of the method is also discussed in Section 6.

Step 8. Design the radon reduction system.

Obviously, the design of the mitigation system depends upon which reduction method is selected. The details of the design depend primarily upon the construction features of the house and the results of the diagnostic measurements. The principles of design are to maximize the performance of the system while minimizing both the installation and the operating costs. The location, the appearance, and the noise level of an active system must meet the approval of the homeowner. Further guidance on the design of the mitigation system is offered in Section 6.

Step 9. Install the mitigation system.

Because the actual installation is often contracted to local building contractors or subcontractors, the supervision and inspection of the work is very important. The actual installer should be made aware of the objectives of the particular techniques being applied. For instance, when sealing is to be applied the installer must be aware not only of the characteristics of the sealant being used, but also of the degree of care required in applying the sealant. Minor modifications in the installation plans will often be required as obstacles are discovered during drilling or digging. It is important that these minor modifications be consistent with the principles of the original design, and not interfere with the performance of the final installation. When pipes and other parts of the system are to be hidden for aesthetic reasons, it is important that careful inspection and testing be performed before critical joints or other parts are obscured by finishing materials. Ventilation systems, as well as closures of radon entry routes, should be leak tested before being covered with finishing materials. Every effort should be made to provide access for inspection of any potentially major radon entry routes. Further discussion of the principles of installation can be found in Section 7.

Step 10. Check the installation and operation of the system.

A variety of diagnostic tests can be conducted on the system in order to confirm that it is operating as it should, and to identify modifications to improve performance. Such post-mitigation diagnostic testing is described in general in Sections 8 and 9, with specific applications described as warranted in the detailed discussions in Section 10.

Step 11. Determine the effectiveness of the mitigation system through both short- and long-term monitoring.

Following installation, the radon/progeny measurement methods described in Section 3 can be used to assess the degree of reduction and the final levels achieved. (Care must be taken to ensure that the before and after measurements can be reliably compared to yield a meaningful indication of the reduction achieved.)

1. Short-term performance measurements are required to determine whether further diagnostic, design, or installation work is required.
2. Long-term performance measurements are required to estimate the potential exposure to radon related health risks. Both the methods and rationales for these two types of measurements are discussed in Section 9.

Step 12. Establish a schedule for maintenance of the system.

All installed reduction techniques (active and passive) must be checked periodically to determine whether they are continuing to function properly. In this regard the mitigator should provide a checklist and schedule for regular inspection and maintenance of the installation. Materials used to seal radon entry routes should be inspected periodically for cracks or openings. Passive ventilation systems should be inspected periodically for cracks or blockage of the ventilation pipes. It would be desirable to measure the draft in the passive stack. Active ventilation systems should be inspected more often because of the potential for mechanical wear. In addition to looking for cracks and leaks in the pipes, it is necessary to ascertain that the fan is operating properly. With an active system, it is desirable to install an indicator (alarm) such as a light or buzzer to announce that the fan is not generating sufficient air flow for the system to perform adequately. The ultimate test for how well the mitigation system is working will be a periodic radon measurement such as a 3- or 4-month alpha-track measurement during winter.

Section 2
Background

2.1 Sources of Radon

Radon-222 is an inert radioactive gas resulting from the radioactive decay of radium-226. Since radium is naturally present at trace concentrations in most soil and rock, radon is continuously being released in the ground almost everywhere, becoming a trace constituent of the soil gas, and also dissolving in underground water. Soil gas containing radon can enter a house through any opening between the house and the soil. The pressures inside houses are often slightly lower than the pressures in the surrounding soil, so that the soil gas flows into the house as a result of the pressure difference. The amount of radon that can build up inside a house due to in-flowing soil gas will depend upon the radium content in the surrounding rock or soil (and, consequently, the radon level in the soil gas), the ease with which soil gas can move through the soil, the size and number of openings between the house and the soil, the extent to which the house is depressurized relative to the soil, and the above-grade ventilation rate in the house. If a house receives water from an individual or small community well, airborne radon can also occur as a result of radon's being released from water used in the house. However, well water is usually only a secondary radon source compared to soil gas.

2.2 Health Effects

Radon is a health concern because it decays into other radioactive elements (radon decay products) that are solid particles. These particles can lodge in the lungs when inhaled. Bombardment of sensitive lung tissue by alpha radiation released from these lodged particles can increase the risk of lung cancer. Current EPA guidelines suggest that remedial action be considered when radon concentrations inside a house exceed an annual average of 4 picocuries of radon per liter of air (4 pCi/L), or when the radon decay products exceed roughly 0.02 "working levels" (0.02 WL). See Reference EPA88a for a discussion of working levels. According to estimates (unpublished) based on screening measurements, 12% of U.S. houses may have radon concentrations exceeding this guideline.

The primary concern with radon in drinking water is that the radon will be released when the water is used in the house and will thus contribute to the airborne levels. Scientists have considered the alpha dosage received by various organs in the body--the stomach, for example--from the radon that remains in the water when it is ingested. The current conclusion is that the lung cancer risks from radon released into the air are much more significant than the risks from radon that remains in the water (Na85).

2.3 Potential Strategies for Reducing Indoor Radon Concentrations

A number of methods can be considered for reducing indoor radon levels. For radon from natural sources, these methods fall into two generic categories: methods aimed at preventing the radon from entering the house, and those aimed at removing radon or its decay products after entry. The selection and design of a cost-effective radon reduction system for a specific house will depend upon a number of factors specific to that house, including, for example, the initial radon concentration and a variety of house construction details. Table 1 summarizes the radon reduction methods that are most prevalent in current mitigation practices. Detailed discussions of these reduction methods are presented in Sections 6 through 10 of this document. Certain information, such as the degree of radon reductions achievable with specific techniques and estimated cost, is found almost exclusively in this summary table. It should be stressed that the order in which the techniques are presented is not intended to convey their relative priority for application.

The prevalent radon reduction strategy is to prevent entry into the house. Radon entry can be prevented by any one or combinations of the three processes: (1) remove the source of the radon, (2) eliminate or reverse the driving forces causing radon entry, or (3) eliminate the entry routes. Many of the reduction techniques discussed in this manual will address one or more of these processes. Soil ventilation, crawl-space ventilation, sealing, house pressure adjustments, and radon removal from water are all reduction techniques that attempt to prevent radon from entering the house, while house ventilation and air cleaning are techniques that attempt to remove radon (or its decay products) from inside.

Table 1. **Summary of Radon Reduction Techniques**

Method	Principle of Operation	Applicablity	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs**
House Ventilation						
-Natural (Sec. 10.3)*	Increased movement of fresh outdoor air into the house (or crawl space) without the use of fans. This reduces convective radon influx, and dilutes the radon that does enter.	All house types. All initial radon levels. Application would have to be limited during extreme weather conditions, or unacceptable energy and comfort penalties would result.	To 90 and above, depending upon extent to which inflow of fresh air is increased. In no case can radon levels be reduced below levels in outdoor air (usually a fraction of 1 pCi/L).	High	Open windows, doors, or vents uniformly around the house (not on one side only). Open especially on lower levels of house. Windows might be opened only slightly to reduce energy/comfort penalties in cold weather (reducing reduction performance). Can ventilate just crawl space, with insulation around water pipes and under subflooring, to permit ventilation during cold weather.	No (or minimal) installation cost. Easily implemented by homeowners. No operating cost during mild weather. During cold weather, heating costs could increase by a factor of 1.1 to 3 or more, depending upon extent of ventilation and efforts to maintain temperature in the ventilated part of the house. There would be a comparable increase in air conditioning costs in hot weather.
-Forced Air no heat recovery (Sec. 10.3)	Increased movement of fresh air into the house or crawl space, as above, except with the use of one or more fans.	All house types. All initial radon levels. Application would have to be limited during extreme weather conditions, or unacceptable energy and comfort penalties would result.	To 90 and above, depending upon increase in inflow of fresh air (i.e., size of fan).	High, if fan is large enough, and if forced air is distributed effectively.	Fan can be installed to continuously blow fresh air into house through existing central forced-air furnace ducting. Or window fans could blow air in through windows in lower levels of house. For typical house, fan capacity for 90% radon reduction would likely have to be greater than 500 to 1000 cfm, depending on house size and natural infiltration rate. Fans should always be oriented to blow outside air in. Commercial whole-house fans are not recommended because they typically suck indoor air out.	Installation costs vary from perhaps $30 to $200 for a single window fan, to perhaps as much as $1000 to modify a central furnace for fresh air addition. Operating costs include an increase in heating and cooling costs, comparable to those for natural ventilation, plus cost for electricity to operate fans (about $50/year for a less powerful window fan, $300/year for a more powerful window fan or a central furnace fan).

(continued)

Table 1. **Continued**

Method	Principle of Operation	Applicablity	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs**
House Ventilation (continued)						
-Forced Air with Heat Recovery (heat recovery ventilators or HRVs) (Sec. 10.3)	Increased movement of fresh outdoor air into the house; exhaust of a similar amount of house air, with transfer of heat from the exhausted house air to the incoming fresh air. Dilutes radon levels in the house; reduction of radon influx might not occur when exhaust flow equals intake flow.	All house types. Applicable as standard-alone method to achieve 4 pCi/L only when initial radon levels is below about 10-15 pCi/L in houses with typical infiltration rates. Best reductions in tight houses. Heat recovery might reduce energy and comfort penalties of ventilation during extreme weather, but there will still be some heat penalty (heat recovery efficiency is 50 to 80%). Also, the net savings in reduced heat penalty (relative to natural ventilation) can be offset by capital cost of HRV. Most likely to be cost-effective in cold or very hot and humid climates.	50 to 75 for houses having typical size and infiltration rate, assuming between 200 and 400 cfm or HRV capacity. Reductions can be greater in tight houses (low infiltration rate). Reductions can vary throughout house, depending on ducting configuration.	Moderate for fully ducted ventilators. Low to moderate for wall-mounted ventilators. Performance not always predictable, can vary over time.	Ducted ventilator supplies fresh air to all or part of the house, withdraws stale house air from all or part of house. Capacity of ventilator, location of supply/withdrawal vents must be selected based upon size and tightness of house, location of living areas most needing ventilation. Care is required to maintain the desired balance between inlet and outlet flows.	Contractor installed cost for a single 150-200 cfm fully ducted HRV might range from $800 to $2500, depending upon extent of ductwork installed, amount of wall/floor finish affected, and brand of HRV. The lower cost possible in cases where existing central forced-air furnace ducting use for HRV. Increasing capacity to 300-400 cfm would increase installed cost by roughly 25-50% if single larger unit used, or by roughly 100% if second 150-200 cfm unit installed. Operating costs include: an increase in heating and cooling costs (roughly 20 to 50% of the increase incurred by comparable ventilation without heat recovery); the cost of electricity for fans (roughly $50 per year for a 200 cfm unit) and for inlet air preheat (if used).
Sealing of Soil Gas Entry Routes (Sec. 10.4)	Reduce or eliminate convective and diffusive radon movement into the house by closing openings between the house and the soil.	All houses having the various individual types of entry routes. Can be effectively applied to individual entry routes, however, total sealing of all routes (to totally prevent all soil gas entry) is probably impractical.	0-90 extremely case-specific, depending on importance of entry routes sealed, nature of remaining unclosed entry routes, and effectiveness of closure.	Low to high, extremely case-specific (depending on importance of sealed route and residual unclosed routes). Some openings can be very difficult to seal effectively. Seals can reopen over time as house settles.	Major openings in floor and walls closed with mortar, caulk, or other sealants. Smaller openings closed by more extensive caulking effort, or sealed using coatings or membranes. Open water-collection systems (sumps, floor drains, French drains) covered and trapped	Highly variable. Costs can be low for do-it-yourself closure of accessible major entry routes. Costs can be low to moderate for trapping drains, covering sumps. Costs can be high for application of membranes and coatings.

(continued)

Table 1. Continued

Method	Principle of Operation	Applicablity	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs**
Active Soil Ventilation						
- Drain Tile Ventilation (Sec. 7.1 and 7.2)	Uses a fan to draw suction on the perforated footing drain tiles that surround some houses for water drainage. In this manner, uses the tiles to maintain a low-pressure field in the soil/aggregate under and around the house, drawing soil gas into the tiles and exhausting it outdoors, preventing it from entering the house.	Houses with slabs which have a reasonably complete loop of drain tiles around the outside or the inside of the footings. Any initial radon level.	90-99, if drain tile loop is reasonably complete. Lower (40-95) if loop only partial, depending on sub-slab permeability.	Moderate to high. (Confidence high when complete loop known to exist, permeability good, no major entry routes through slab remote from perimeter footings.)	Tap into drain tile loop with a PVC pipe which rises above grade level. Mount fan on riser capable of maintaining at least 0.5-1.0 in. WC suction at the soil gas flows encountered. If tiles drain to an interior sump, cap the sump and draw suction on the sump cavity.	Installation by contractor would likely cost between $700 and $1,500 where tiles drain to point outside house, and between $800 and $2,500 where titles drain to a sump. Costs depend upon: depth of tiles; height of, finish around exhaust stack; and (for sump systems) location of stack, location of fan, and interior finish. Operating costs roughly $30/year for electricity to run the fan, $100/year heating and cooling penalty resulting from increased house ventilation.
- Sub-Slab Ventilation (Sec. 7.3)	Uses fan to establish low-pressure field under slab, as above, but in this case by drawing suction on pipes inserted into the soil/aggregate under the slab.	Any house with a slab, having reasonable permeability under the slab (e.g., good aggregate on permeable soil). Moderate to high initial radon levels, in view of the cost of the system.	80-99, with high reductions expected when permeability good.	Moderate to high. (Confidence high when permeability is known to be good.)	Insert individual PVC pipes down through slab, or horizontally through foundation wall beneath slab. Mount fan capable of maintaing at least 0.5-1.0 in. WC suction at the gas flows encountered.	Installation by contractor would likely cost between $800 and $2,000, depending on system configuration and degree of house finish, if no unusual complexities are encountered. Poor sub-slab permeability, high degrees of finish could increase costs. Operating costs roughly $30/year for electricity, $100/year heating and cooling penalty.

(continued)

Table 1. **Continued**

Method	Principle of Operation	Applicablity	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs**
Active Soil Ventilation (continued)						
- Block-wall Ventilation (Sec. 7.4)	Use a fan to draw suction on, or to blow outdoor air into, the void network inside hollow-block foundation walls. In this manner, use the void network as a collector for soil gas (to establish a low-pressure field, drawing soil gas from entry routes into the house) or as a plenum to distribute air under pressure (to force soil gas away).	Houses having hollow-block foundation walls, where major wall openings can be reasonably closed. Houses where sub-slab suction is not adequate by itself (sub-slab suction would in many cases be the preferred choice, if applicable) Sub-slab suction and wall vent can be considered in combination. Moderate to high initial radon levels, in view of the system cost.	90-99 where walls adequately closed, and no major slab-related entry routes remote from walls. Lower (as low as 50-70) where walls not sufficiently tight, slab badly cracked.	Moderate (since ease of wall closure, importance of slab-related entry routes cannot always be reliably predicted)	Insert one or more individual PVC pipes into each perimeter foundation wall and interior block wall. Alternatively, install "baseboard duct" over wall/floor joint of all perimeter and interior walls, with holes drilled into the block cavities inside the duct. Connect piping to suitable fan in pressure (or suction).	Installation by contractor would likely cost between $1,500 and $2,500 for an individual-pipe system, and $2,000 and higher for a baseboard duct system. Additional wall closure efforts, other complexities, could increase costs. Operating costs roughly $30 to $60/year for electricity, $200 to $500/year heating and cooling penalty.
- Isolation/Venting of Area Sources (Sec. 10.2)	Install an enclosure over a floor or wall which is an area source; use a fan to ventilate the enclosure.	Houses with earthen-floored crawl spaces where crawl space ventilation is not preferred. Houses with badly cracked slabs or walls where sub-slab suction not an option. In general, isolation/ventilation would be considered only after other options are determined to be less cost effective.	Definitive data limited.	Moderate for crawl-space lining/venting. Low for other systems, due to limited nature of available data..	Install gastight liner over earthen floor of crawl space, with perforated vent pipes between liner and soil. Build gastight false floor or false wall over existing slab or foundation wall. Use fan to ventilate enclosed space.	Highly variable.

(continued)

***Table 1.* Continued**

Method	Principle of Operation	Applicablity	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estiamted Installation and Operating Costs**
Passive Soil Ventilation (Sec. 10.1)	Use systems similar to the active soil ventilation systems above, but rely on natural phenomena to draw the suction (wind-related depressurization near roofline, thermal stack effect). In this manner, avoid the maintenance requirements, noise, and operating cost of a fan.	Sump/drain tile suction in houses having complete drain tile loops and good sub-slab permeability. Sub-slab suction systems where an adequate perforated piping network is laid, and good permeability is ensured. Houses with poured concrete foundation walls and an integral slab, to reduce the treatment required from the system.	Insufficient long-term data to determine.	Cannot be stated at this time due to lack of data.	A network of perforated pipe laid under the slab is attached to a passive stack which rises through the house and terminates on the roof.	Installation by contractor roughly $2,000 where sub-slab tiles exist, drain into sump. If slab must be removed in order to lay new pipes, cost could be on the order of $10,000. No operating cost.
House Pressure Adjustments						
- Reduce Depressurization (Sec. 10.5)	Take steps to reduce the degree to which a house becomes depressurized, in an effort to reduce soil gas influx. Or, for a given degree of depressurization, take steps to reduce air movement out ot the house, to reduce soil gas influx.	All houses. Most applicable when can be implemented directly by homeowner at low cost, since radon reductions resulting from these steps are variable and since utility will be for short-term periods if source of depressurization is intermittent (e.g., use of fireplace). Most applicable when measurements have confirmed that source of depressurization is indeed increasing radon levels.	Insufficient data to cite reductions that can generally be expected with individual steps. Will depend on characterizatics of a specific house (e.g., tightness). However, benefits can sometimes be significant, at least for short periods, if depressurization is largely neutralized.	Cannot be stated at this time due to lack of data.	Slightly open windows near exhaust fans and combustion appliances (such as fireplaces and woodstoves) to facilitate flow of makeup air from outdoors. Install a permanent system to supply combustion air from outdoors for combustion appliances. Seal off cold air return registers in basement for central forced-air heating and cooling systems, and seal low-pressure return ducting in basement to reduce leakage of basement air into duct. Close airflow bypasses (openings through floors between stories) and openings through house shell on upper levels, to reduce air outflow resulting from buoyant forces. Other steps can also be considered.	Installation and operating costs will generally be relatively low for those systems which can be implemented directly by the homeowner (opening windows, sealing cold air return ducts, closing accessible airflow bypasses and upper house shell penetrations). Other steps will be more expensive, might not be warranted unless radon measurements confirm that the depressurization source being addressed is indeed a significant contributor to indoor radon levels.

(continued)

Table 1 **Continued**

Method	Principle of Operation	Applicablity	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs**
House Pressure Adjustments (continued)						
- House Pressurization (Sec. 6.1.3)	Maintain that part of the house which is in contact with the soil at a pressure higher than the soil, so that soil gas cannot enter.	Houses with tight basements or heated crawl space. This technique is developmental, should be applied as stand-alone measure only on experimental basis.	Insufficient long-term data to determine. Short-term reductions of about 90% have sometimes been observed.	Cannot be stated at this time due to lack of data.	Tighten basement (or crawl space) shell, between basement and upstairs and between basement and outdoors. Blow upstairs air down into basement.	Installation by contractor roughly $1,000 to $2,500, perhaps higher if greater tightening required. Operating cost roughly $40/year for electricity to run the fan, roughly $500/year heating and cooling penalty due to increased ventilation.
Air cleaning (Sec. 10.6)	Remove the particulate decay products of radon from the indoor air, by continuously circulating the house air through a particle removal device.	All houses. There are insufficient data to evaluate the health benefits of using particle removal air cleaners for radon progeny reduction. These cleaners can reduce the total decay product levels in the house air, but they will also remove the other dust particles to which the progeny atttach. Therefore, the amount of progeny which are unattached can increase. Unattached progeny are a potentially more serious health risk than attached progeny. Thus, while total progeny can be reduced, the health risk might be increased. EPA is not in a position	Up to 90% removal of total radon progeny (attached plus unattached) in a typical house, if a 2,000 cfm high efficiency air cleaner operates full time. 50 to 70% reduction of total progeny if the air cleaner capacity is 250-500 cfm. The concentration of *unattached* progeny could *increase* with the 2,000 cfm air cleaner and almost certainly would increase with the 250-500 cfm units. Performance is highly dependent upon the rate at which house air is circulated through the cleaning device.	The confidence that an air cleaner will reduce the heatlh risk from radon exposure cannot be stated at this time, due to uncertainty in the health risk resulting from the potentially increased levels of unattached progeny. Confidence that total progeny (attached plus unattached) will be decreased is moderate to high, if house air is circulated through the cleaner at a high enough rate.	A device such as an electrostatic precipitator or an efficient filter is placed in the ducting of the central forced-air furnace, treating all recirculating house air. Alternatively, smaller stand-alone units can be placed on the floor or in the ceiling in individual rooms.	Installation of an air cleaner in a central forced-air furnace system (capable of treating about 2,000 cfm) roughly $500 to $2,000. Stand-alone units capable of treating up to 250 cfm can be installed for $500-$1,000, depending upon amount of associated ducting (if any) and ease of mounting; eight such units would be required to treat 2,000 cfm. Operating cost include electricity to operate fan(s) circulating the air through the cleaner and to develop charge in cleaner where cleaner operates on electrostatic principles.

(continued)

***Table 1* Continued**

Method	Principle of Operation	Applicablity	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs**
House Pressure Adjustments (continued)						
Air Cleaning (Sec. 10.6 continued)		to recommend either the use of particle-removal air cleaners for radon reduction, or discontinued use of existing air cleaners.				
Removal from Water (Sec. 10.7)	Remove dissolved radon gas from well water before the water is used in the house, thus preventing the dissolved radon from being released into the house air.	All houses which receive water from an individual well (or perhaps a small community well), when radon levels in the water are high enough to potentially make a significant contribution to indoor airborne radon concentrations. On this basis, water treatment might be considered when water radon levels are above perhaps 40,000 pCi/L.	Above 99 with properly designed granular activated carbon (GAC) treatment unit. Up to 95 with currently available aeration units; higher removals achievable at increased cost.	Moderate to high for GAC units. Cannot be stated for aeration units due to limited experience with residential aerators. Confidence should increase after more extensive commercial experience with both GAC and aeration units.	Install GAC tank in incoming water line from well, immediately after pressure tank, to adsorb radon out of the water.Provide suitable shielding around tank to reduce gamma radiation. Replace spent carbon bed (with adsorbed radon decay products) when necessary, perhaps after a number of years. Waste carbon might have to be disposed of as radioactive waste. Or install suitably sized aerator in water line, usually prior to pressure tank, to release radon from the water before use in house. Depending on design, aerator could require air compressor and auxiliary pump to re-pressurize water after treatment. Vent released radon gas away from house.	Plumber installation of GAC unit $750 to $1,200, excluding gamma shielding; shielding could add about $200. Operating cost of GAC nominal. (Maintenance includes replacement of carbon bed, at infrequent intervals.) Installation of aeration unit $2,500 to over $4,000, depending upon type of aerator. Operating cost includes electricity to run compressor, pump. For either type of unit, pretreatment to remove iron or manganese, if needed, could add $600 to $1,000 to the installed cost.

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*Detailed discussions of the individual radon reduction methods can be found in the sections of this document indicated in parentheses.

**The costs shown here do not include: (a) estimates of maintenance and repair costs or (b) the costs of monitoring to ensure continued satisfactory performance.

Section 3

Measuring Radon Concentrations

In order to determine whether a particular house has elevated radon levels prior to a decision regarding the need for radon reduction, measurements of radon or radon progeny in the house air are required. Measurement techniques are divided into two categories: "active" and "passive." Passive methods do not require the pumps or specialized sampling equipment that active methods do. Charcoal canisters and alpha-track detectors are convenient measurement methods to use because, as passive methods, they are simple and relatively inexpensive for homeowners to use. These passive methods also have the advantage of providing averaged (integrated) measurements over a period of time (a few days for a charcoal canister, a few months for an alpha-track detector). Averaging over several months provides a meaningful measure of the concentration to which homeowners are exposed. Time averaging is important because radon concentrations often vary significantly over the period of a day as well as from season to season.

The EPA has recently issued a protocol for the use of a new passive radon measurement method. This new device, called an Electret-Passive Environmental Radon Monitor (E-PERM), is capable of making both short- and long-term radon measurements. The device works on the same principle as the ionization chamber detector, which has been used as a radiation detector for many years. Although EPA's experience with this measurement device (EPA88c) is limited, the device does have attractive features. It is reported to provide good integrated measurements of radon with time exposures that can range from 1 day to 1 year. The results can be read in the field (using a special surface potential voltmeter). It is also reported to be insensitive to relative humidity, which makes it a candidate for measuring in situ radon concentrations in soil gas.

Other measurement methods are also available. These methods, referred to as active methods, require an experienced sampling team with specialized equipment to visit the house (although it is possible for one person to set up and operate this equipment, it is more typical for two or more people to be involved). Active methods include continuous monitoring, grab sampling, and use of a Radon Progeny Integrated Sampling Unit (RPISU). Because of the need for special equipment and for a sampling team, these measurements are relatively expensive. Thus, active methods are less commonly used for initial radon measurements in a house. However, they find greater application in pre-mitigation diagnostic testing and in evaluation of the performance of installed radon reduction systems.

The EPA has issued protocols for making measurements in houses using alternative measurement methods, with the objective of determining occupant exposure (EPA86b, EPA87a). The EPA protocols recommend a two-step measurement strategy in which: (1) an initial screening measurement is made to provide a relatively quick and inexpensive indication of the potential radon/progeny levels in a house and (2) additional follow-up measurements are recommended, if the screening measurement is above about 4 pCi/L (about 0.02 WL). Persons making measurements are advised to apply the methods in a manner consistent with these protocols.

Two general types of passive measurement devices are currently in common use (with a third device gaining prominence):

1. The charcoal canister (or charcoal pouch), which uses activated carbon in a small container to adsorb radon;

2. The alpha-track detector, which consists of a container with a small piece of plastic sensitive to the alpha particles released by the radon and radon progeny. The user can purchase both devices from any one of a number of suppliers, generally through the mail. The user exposes the device in the house for a specified period The device is then returned to the laboratory for analysis. For both devices, the result is the radon gas concentration in pCi/L; these devices do not determine the concentration of radon progeny; and

3. The E-PERM, which uses an electret to detect the ions generated by radon decay.

The Agency has also established a Radon Measurement Proficiency Program enabling organizations which provide radon measurement services to voluntarily demonstrate their proficiency in making radon/radon progeny measurements (EPA86c). Lists of firms which have successfully demonstrated their proficiency under this program are published periodically (e.g., EPA87b). Anyone wishing to hire a firm to conduct indoor radon monitoring can check these periodic lists for the names and addresses of candidate firms. Publication of the next update (Round 5) is expected in October 1988. Copies of the current list can be obtained through the State contact or the appropriate EPA Regional office identified in Section 11.

3.1 Screening Measurements

A few of the key procedures indicated in the EPA protocol documents are listed below. If no prior radon measurement has been made in the house, the initial measurement should be viewed as a screening measurement, and the exposure times for the devices should be:

- Charcoal canister -- 2 to 7 days, as specified by supplier,
- Alpha-track detector -- 3 months to 1 year (or less, if specified by supplier), and
- E-PERM -- 1 day to 1 year depending on electret selected.

The objective of the screening measurement is to provide a quick and inexpensive indication of whether the house has the potential for causing high occupant exposures.

For the screening measurement, the device should be placed in the lowest livable space, such as the basement. Within that livable space, the device should be placed in the room expected to have the lowest ventilation rate. Livable space does not have to be finished or even be used as living space.

The devices should not be placed in sumps, or in small enclosed areas such as closets or cupboards. Further precautions and recommendations for locating the measurement devices are offered in Section 3.2. The objective is to measure the highest radon levels that might be expected anywhere in the livable part of the house. If low radon levels are found at the worst-case location, the house may be presumed to have low levels everywhere.

Screening measurements should be made under closed-house conditions (doors and windows closed except for normal entry and exit), with minimum use of ventilation systems that mix indoor and outdoor air (such as attic and window fans). Closed-house conditions should also be maintained for 12 hours prior to beginning the screening measurement, if the measurement is shorter in duration than 72 hours. If possible, it is recommended that measurements be made during cold weather, which usually corresponds to the highest radon levels. As above, the objective of maintaining these conditions is to obtain the highest expected radon measurement for the livable part of the house so that a low level measured under these conditions can be presumed to mean that the dwelling will likely remain at least as low under less challenging conditions.

3.2 Follow-Up Measurements

In selecting a measurement technique and a schedule for determining occupant exposure, the reader should be aware that radon levels in a given house can vary significantly over time. While the magnitude of this variation is house dependent, it is not uncommon to see concentrations in a dwelling vary by a factor of 2 to 3 or more over a 1-day period, even when the occupant has not done anything that might be expected to affect the levels (such as opening a window). Seasonal variations can be even more significant (sometimes as much as a factor of 10, with typical values in the range of 3 to 5). In some houses, the daily and seasonal variations will not be this great. If a meaningful measure of the occupants' exposure to radon is desired, it is best to obtain measurements over an extended period (3 months to 1 year) and during different seasons. Since the highest levels in most climates are likely to occur during cold-weather periods, it would be wise to ensure that some measurements are made during winter months.

If the screening result is greater than about 4 pCi/L, follow-up measurements should be considered to more rigorously determine the radon levels to which occupants are being exposed (and hence the urgency of remedial action). If the screening measurement yields a result less than about 20 pCi/L, follow-up measurements should include:

- Charcoal canister--canister measurements made once every 3 months for 1 year, with each canister exposed for 2 to 7 days, as specified by supplier.
- Alpha-track detector--alpha track device exposed for 12 months. This approach is preferred over the quarterly charcoal canister approach because the year-long alpha-track measures for the entire year rather than just for 2- to 7-day periods, thus giving a more reliable measure of occupant exposure.
- E-PERM -- exposed for 12 months.

These measurements should be made in the actual living area on each floor of the house that is most frequently used as living space. Measurements should be made under normal living conditions, rather than the closed-house conditions recommended for screening. The year-long measurement period is suggested because the health risks at 20 pCi/L and less are felt to be sufficiently low that the homeowner can take time to make a good measurement of annual exposure before having to decide upon action to reduce the levels.

If the screening measurement yields a result greater than about 20 pCi/L, but not greater than about 200 pCi/L, follow-up measurements are again suggested for confirmation before taking remedial action. However, an expedited schedule for these measurements is suggested due to the higher risks associated with continued exposure to these higher levels. Follow-up measurements should be completed within several months after obtaining the screening result. Suggested follow-up measurements are:

- Charcoal canister--a one-time measurement on each floor having living space, under closed-house conditions (during the winter if possible), with exposure for 2 to 7 days.
- Alpha-track detector--a one-time measurement on each floor having living space, under closed-house conditions, with exposure for 3 months (or less, if specified by supplier).
- E-PERM -- a one-time measurement on each floor having living space, under closed-house conditions, with exposure for 1 month.

If the screening measurement yields a result greater than about 200 pCi/L, the follow-up measurement should be expedited and conducted under closed-house conditions over a period of days or weeks; a 3-month alpha-track exposure might not be appropriate in this case. Short-term actions to reduce the radon levels should be considered as soon as possible. If this is not possible, it should be determined, in consultation with appropriate state or local health or radiation protection officials, whether temporary relocation is appropriate until the levels can be reduced.

In both screening and follow-up measurements, the charcoal, alpha track, and E-PERM should be positioned within a room according to the following criteria:

- The device should be in a position where it will not be disturbed during the measurement period;
- It should not be placed in drafts caused by heating/air conditioning vents, or near windows, doors, or sources of excessive heat (such as stoves, fireplaces, or strong sunlight);
- It should not be placed close to the outside walls of the house; and
- It should be at least 8 in. (20 cm) below the ceiling and 20 in. (50 cm) above the floor, with the top face of charcoal canisters at least 4 in. (10 cm) away from other large objects which might impede air movement.

For further details regarding the protocols for using charcoal canisters and alpha-track detectors, the reader is referred to References EPA86b and EPA87a.

3.3 EPA Action Level and Guidance for Action

The EPA has established an action level for indoor radon at 4pCi/L as an annual average. This means that, while the radon concentration may fluctuate from day to day and season to season, its yearly average should not exceed 4 pCi/L. If the annual average does exceed 4pCi/L, it is recommended that action be taken to reduce the radon level. If such action is initiated, the objective should be to reduce the radon concentration to as low a level as is practical. The bulk of this document is intended to provide advice on reducing the indoor radon concentration.

This action level of 4 pCi/L does not imply that radon levels below 4 pCi/L are safe. Exposure to any measurable level of radon has an associated health risk. There are no absolutely safe levels of exposure. The individual must judge whether it is prudent to further reduce radon levels that are below 4 pCi/L. Note that, with current technology, it is not practical to reduce indoor radon levels below the local ambient values (typically 0.25 pCi/L).

On the opposite end of the spectrum, where radon concentrations are significantly higher than 4 pCi/L, urgency of the recommendation to reduce the radon concentration increases with the level of the radon. For high radon concentrations, it is also more important to implement temporary measures to reduce radon.

In summary, it is recommended that:

- For radon concentrations greater than 200 pCi/L, action be initiated within a few weeks;
- For radon concentrations in the range of 20 to 200 pCi/L, action be initiated within several months;

- For radon concentrations in the range of 4 to 20 pCi/L, action be initiated within a few years (the higher the radon the more urgent the need for action); and
- For radon concentrations less than 4 pCi/L, no action is specifically recommended. However, many individuals may elect to further reduce radon concentrations in the range of 1 to 4 pCi/L.

Some radon reduction measures will require installation by a professional mitigation firm or by skilled homeowners. However, there are some steps which essentially any homeowner can take immediately, often at little cost. These steps might not always be sufficient by themselves to ensure an annual average of 4 pCi/L or less, but they should give some reduction, and they can be implemented fairly easily pending installation of more comprehensive measures. Such steps include:

- Increase ventilation of the house whenever possible, by opening windows on two or more sides of the lower level of the house (and on upper levels if these are the primary livingareas). In crawl-space houses, any existing crawl-space vents should be left open year- round (with insulation added around water pipes and under the sub-flooring if necessary).Properly implemented increases in ventilation should give major radon reductions for as long as the windows or vents remain open.
- Close major soil gas entry routes, such as open sumps, any distinct holes in slabs and foundation walls, untrapped floor drains, and any accessible open voids in the top course of block foundation walls. The radon reductions that can be achieved by such closure will be variable, but can be significant in some cases.
- Take steps to reduce the driving force for soil gas entry, including: closure of major accessible thermal bypasses (such as open stairwell doors, fireplace dampers, and laundry chutes); opening a nearby window to provide an outdoor air source when combustion appliances and exhaust fans are in use; and, where possible, placing ventilation fans such that they blow outdoor air indoors rather than exhausting indoor air. The radon reductions that might be achieved will be variable, but short-term effects could be significant in some cases.

Section 4

Determining the Sources of Radon

4.1 Choice of Diagnostician/Mitigator

The person primarily responsible for diagnosis of the problem is called the "diagnostician." The person who will be primarily responsible for the design, installation, and post-installation evaluation of the radon reduction system is referred to here as the "mitigator." These may or may not be the same person.

Depending upon the types of radon reduction systems that are being considered for a particular house, and depending upon the skills of the individual homeowner, some might feel that they can install a system in their house on a do-it-yourself basis, without a professional mitigator's help. The steps involved in installing these systems are all consistent with common construction practice (although special equipment is desirable in a few cases). Thus, homeowners with knowledge and experience in house repairs and improvement may be able to install some of these systems themselves. Effective, professional-looking, and successful systems have been installed by homeowners.

If the radon reduction steps that homeowners feel comfortable in undertaking themselves are not sufficient to reduce indoor radon concentrations to acceptable levels, then the homeowners should hire a mitigator experienced in house diagnostics and radon mitigation. To obtain a list of candidate mitigators who can do this type of work in the area, the homeowner might have to inquire through a number of channels, since no one organization maintains a list of active contractors on a national basis. To obtain a local list, contact state radiological health officials, local public health officials, local building trade associations and realtor associations, local building supply houses, chambers of commerce, house improvement firms, or perhaps energy conservation consultants. A list of state contacts can be found in Section 11. Companies listed in the most recent report by EPA on measurement proficiency (e.g., EPA87b) may also be a good source to consult. However, the potential for conflict of interest with a company doing both radon measurements and mitigation work should be noted. Neighbors who have had mitigation work performed are also a good source.

Radon mitigation is a relatively new field. Consequently, many contractors have been in this particular field for a relatively short time (although some may have been involved in related building trades for a number of years). Contractor experience varies widely. Currently, no organization certifies mitigation contractors on a national basis as being qualified and experienced, although some States are developing contractor certification programs. Thus, the responsibility for evaluating candidate contractors will often fall on the homeowner. The homeowner should attempt to obtain a list of other buildings that each contractor has mitigated. The mitigation contractor may be unable to provide a comprehensive list of references because many homeowners consider the work that the mitigator has done for them to be confidential. However, a mitigator who has done work on a large number of houses should have a few clients willing to serve as references. Other sources with which the homeowner might check include state radiological health officials, the Better Business Bureau, and perhaps some of the other sources identified in the previous paragraph.

Other factors that homeowners might consider in evaluating mitigators are suggested below.

1. How many houses has the mitigator worked on? How many of the houses were similar to yours, in terms of substructure type and design features? What were the radon levels before and after mitigation?
2. Is the mitigator able to clearly explain the proposed work? If the approach differs from the recommendations given here, are the reasons clear? Does the proposed design include features that would alert you if the reduction system were to malfunction?
3. How will the performance of the system be determined after installation? Will radon measurements of sufficient duration be conducted after installation?

4. What type of "guarantee" is provided? The state of knowledge regarding radon mitigation is such that many contractors will generally not be able to guarantee the degree of radon reduction that will be achieved (unless the house presents a particularly clear-cut case, or unless the cost estimate includes a cushion to cover potential additional work that might be needed). However, a contractor could guarantee the cost of the specific proposed installation. The mitigator could also ensure that the installation will meet certain criteria (e.g., that all sealing will be completed satisfactorily, or that any associated fans will function for a specified period of time).

5. If the cost estimate is significantly different from that of other prospective contractors, is it apparent why? Is the mitigator proposing more or less work than the others? Is the additional work needed? One bidder might be proposing more diagnostic testing, while another bidder might be devoting more effort in improving aesthetics. Also, one bidder may route exhaust pipes above the eaves, while another may have them exit at ground level. After proposals from different contractors have been received, a homeowner might wish to discuss the proposed systems with, say, state radiological officials or other homeowners who have had mitigation work done.

4.2 Identification of Radon Entry Routes

If elevated indoor radon levels are discovered, a logical next step is to identify where the radon might be entering. Radon-containing soil gas can enter a house anyplace it finds an opening where the house contacts the soil. Some such openings will always be present, even in well-built houses. Potential entry routes include:

- Openings in the foundation wall (such as holes around utility penetrations, unclosed voids in the top course of hollow-block foundation walls, pores and mortar joint cracks in block walls, and settling cracks in block or poured concrete walls);
- Openings in concrete slabs (such as holes through the slabs, sumps, untrapped floor drains which connect to the soil, the joint between the slab and the foundation wall, cracks, and cold joints);
- For crawl-space houses, openings between the crawl space and the living area (such as utility penetrations through the subflooring);
- For crawl-space houses, leakage of crawl-space air into the cold air return ducts of a central forced-air furnace located in the crawl space;
- For slab-on-grade houses, openings in the slab around penetrations (such as under commodes and bathtubs, utility penetrations, and heating ducts under the slab).

The void network inside hollow-block foundation walls (or inside block fireplace structures) can serve as a hidden conduit for soil gas into the house.

Table 2 is a checklist of possible entry routes that might exist in a given house. If elevated radon levels have been measured in a house, this checklist can be used in inspecting the house to identify likely entry routes. While not all of the entry routes into a house can be sealed effectively, knowledge of where entry is occurring (or might be occurring) will be important in the ultimate design of a radon reduction system.

This checklist is subdivided according to routes associated with the foundation wall, routes associated with the concrete slab (including routes unique to slab-on-grade houses), and routes unique to crawl-space houses (which may have neither a slab, nor a foundation wall, extending up into the living area). In this discussion, the foundation wall is defined as the wall which rests upon underground footings, and which supports the weight of the house. Foundation walls can be constructed of hollow construction blocks, poured concrete, or (less commonly) fieldstone or treated wood. Internal walls should be treated as foundation walls if they penetrate the slab and rest on footings.

Figure 2 depicts many of the entry routes listed in Table 2. For convenience, this illustration shows a hybrid house with some hollow block foundation walls, and some poured concrete walls in order to aid depiction of the full range of entry routes. Probably no house would be built with all these construction features. The entry routes shown in the figure are identified according to their number in Table 2. Not all entry routes in the table are identified.

The building substructure plays an important role in determining the number and type of entry routes. Table 2 indicates which entry routes are applicable to the various substructure types. The three basic types of substructures are:

1. basement, in which the floor (slab) is below grade level;
2. slab on grade, in which the floor (slab) is at grade level; and
3. crawl space, in which the floor is above grade level, and the enclosed region between the floor and the soil (the crawl space) is not livable area.

Table* 2. Possible Soil Gas Entry Routes into a House

A. *Entry routes associated with the foundation wall*

Applicability: Wherever the foundation wall forms any portion of the wall area in the living space, including houses in which a portion or all of the house includes:

- a basement (over 3 ft below grade),
- a slab below grade (1 to 3 ft below grade),
- a slab on grade with hollow-block foundation wall in which the foundation wall extends up to form the wall for the living area, or
- a crawl space with hollow-block foundation walls where the foundation wall extends into the living area, or in which the crawl space is open to the living area.

1. Holes in foundation walls around utility penetrations through the walls (water, sewer, electrical, fuel oil, natural gas lines).
2. Any other holes in the walls (such as defects in individual blocks in hollow-block walls, holes drilled for electrical junction boxes or for other purposes, chinks between fieldstones in fieldstone foundation walls).
3. Any locations in which the wall consists of exposed soil or outcroppings of rock.
4. With hollow-block walls, unclosed voids in the top course of block, at the top of the wall (i.e., absence of a solid cap block).
5. With hollow-block walls, unclosed voids in blocks around window and door penetrations.
6. With hollow-block walls, pores in the face of the blocks. (All hollow blocks are porous, but some blocks are more porous than others. For example, true cinder block is generally more porous than concrete block.)
7. With hollow-block walls, cracks through the blocks or along the mortar joints (including fine cracks as well as wider cracks and missing mortar).
8. With poured concrete foundation walls, settling cracks in the concrete, pressure cracks, and flaws from imperfect pours.
9. In a split-level house in which a slab-on-grade or partial basement section adjoins a lower basement, the joint between the lower basement wall and the floor slab of the next higher level.
10. Any block or stone structure built into a wall (in particular, a fireplace structure, or a structure supporting a fireplace on the floor above), where a cavity can serve as a hidden conduit permitting soil gas to migrate into the house (also ash pits).

Note: With hollow-block walls, the above list applies not only to the exterior perimeter walls, but also to any interior block walls which penetrate the floor slab and rest on footings underneath the slab.

B. *Entry routes associated with concrete slabs*

Applicability: Wherever the floor of all or a portion of the house consists of a poured concrete slab in direct contact with the underlying soil, including houses with:

- a basement,
- a slab below grade,
- a slab on grade, or
- a paved crawl space which opens to the living area.

1. Any exposed soil and rock in which concrete is absent and a portion of the house has an earthen floor, such as sometimes found in fruit cellars, attached greenhouses, and earthen-floored basements. Rock outcroppings protruding through the slab are another example.
2. Any holes in the slab exposing soil. These might be due to wooden forms or posts which have been removed or have rotted away, or due to openings which were made for some particular purpose during construction but were never filled in.
3. Sumps (a special case of B.2 above) which have:
   - exposed soil at the bottom, and/or
   - drain tiles opening into the sump.

   Where drain tiles drain into the sump, the tiles (installed to collect water) are probably serving as a collector for soil gas, routing it into the house via the sump.
4. Floor drains, if these drains are untrapped (or if there is not water in the trap), and if the drain connects to the soil in some manner (i.e., if the floor drain connects to perforated drain tiles, to a septic system, or to a dry well). Trapped drains which are equipped with a cleanout plug might still be a source of soil gas, even if there is water in the trap, if the plug is missing.
5. Openings through the slab around utility penetrations (e.g., water, sewer).
6. Cold joints in the slab.
7. Settling cracks in the slab.
8. The wall/floor joint (i.e., the crack around the inside perimeter of the house where the slab meets the foundation wall). In some houses, this perimeter crack is in fact a gap 1 to 2 in. in width, for water drainage or soil expansion (alternatively referred to as a French drain, channel drain, or floating slab). The wall/floor joint associated with any interior wall which penetrates the slab can also be an entry route, not just the joint associated with the perimeter walls.
9. Any hollow objects which penetrate the slab and provide a conduit for soil gas entry. A few examples are:
   - hollow metal load-bearing posts which rest on a footing under the slab (and which support a crossbeam across the ceiling above the slab),
   - hollow concrete blocks which penetrate the slab (e.g., serving as the base for a furnace or water tank), with the open central cores exposing earth,
   - hollow pipes which penetrate the slab (e.g., serving as the legs for a fuel oil tank), or
   - heating ducts under the slab.

(continued)

***Table** 2.* **Continued**

10. Hole in the slab under the tub for installation of the trap.
11. Hole under the commode on a slab.

C. *Entry routes associated with decoupled crawl-space houses*
Applicability: Houses with crawl spaces which do not open to the living area (i.e., which are decoupled from the living area):
1. Seams and openings in the subflooring between the crawl space and the living area (e.g., openings around utility penetrations through the floor, hole under the tub for the trap, and leaks around floor heating vents).
2. If a central forced-air HAC system is situated in the crawl space, leaks in the cold-air return ducting which would permit crawl space air to leak into the house circulating air.

*Some entry routes are illustrated by number in Figure 2.

There are many variations and combinations of these three basic substructure types. For example, some common combinations of these basic substructures include a basement with an adjoining slab on grade, or a slab on grade with an adjoining crawl space. Some houses include different wings representing all three substructure types. A split-level house is a common and somewhat unique combination of substructure types. These houses have a basement adjacent to a wing that is either a slab on grade or a crawl space. The uniqueness of these houses lies primarily in the openness of the internal space, which means the separate sections of the house do not interact like a normal upstairs and basement. Sometimes the distinction between the substructure types becomes blurred, as when the bottom level of a house has a front foundation wall completely below grade (thus having the characteristics of a full basement) and a rear foundation wall totally above grade (similar to a slab on grade). For the purposes of this document, the following terminology is used to distinguish between houses having lower levels at varying depths below grade:

- The house is considered to have a basement if the floor (slab) of the lower livable level averages 3 ft or more below grade level on one or more sides of the house.
- The house is considered a slab on grade if the floor slab is no more than 1 ft below grade level on any side.
- The house is considered a slab below grade if the floor slab averages between 1 and 3 ft below grade level on one or more sides.

Thus, the example cited above (of a house with the front wall below grade and the rear wall above grade) would be considered a basement house by this terminology. Although the description of houses near the borders of these three categories may be less than ideal, they are accepted here for the convenience of having only three categories.

If all other factors were equal (i.e., the soil radium content, the soil permeability, the degree of house depressurization, and the house's ventilation rate) then the house with the greatest number of entry routes (assuming the distribution of entry route sizes is the same for all houses) would probably have the greatest indoor radon level. Basement houses provide the greatest amount of contact between the house and the soil, and thus generally offer the greatest opportunity for entry routes to exist. Thus, one might anticipate that basement houses would tend to offer the greatest risk of elevated radon. By comparison, a crawl-space house where the crawl space does not open into the living area, and where vents for natural circulation are kept open, will have a ventilated, pressure-neutral buffer space between the living area and the soil. Crawl-space houses with ventilated crawl spaces would be expected to offer the least risk of elevated radon. However, crawl-space houses are often observed to have elevated radon levels. Since the type and size distribution of entry routes depend, among other things, on the house design and local construction practices, all other factors are not likely to be equal. Consequently, the expected trend for highest radon levels in basement houses may be partially obscured by variations in construction practices. Limited and statistically nonsignificant data collected by EPA suggest that basement houses may have the highest radon levels.

The type of foundation wall can also play an important role in determining the entry routes. When the foundation wall is made of poured concrete, soil gas will generally be able to move into the house through the wall by pressure-driven flow only at those points where there is a complete penetration all the way through the wall somewhere below grade level. However, when the foundation wall is made of hollow blocks, soil gas can enter more easily. The voids within the blocks form an interconnected network throughout the wall. Once soil gas has entered that void network (by penetrating through accessible pores, mortar joint cracks, etc., in the exterior face of the blocks below grade), the gas can move anywhere within that network. The network, however, does not extend around a corner from one perpendicular wall to another. The soil gas can then enter the house anywhere it finds an opening in the interior face of the blocks, even above grade. The interior opening might be a utility penetration, a mortar joint crack, or the pores in the interior face. If the top course in the block wall is open, the easiest place for the gas to enter the house will be the open voids in the top of the wall. Even if the top voids appear to be covered by the sill plate, the soil gas can still make its way out of the blocks at that point. Since the sill plate does not seal the open voids, the block wall serves as a chimney, providing a convenient conduit for soil gas entry.

Likewise, even if the foundation wall is largely above grade, soil gas entering the blocks at footing level underground can move up into the above-grade portions of the wall and emerge into the house through, say, the uncapped top voids 8 ft above grade level. Or if there is a load-bearing block wall inside the house (a wall which penetrates the concrete slab and rests on footings underneath the slab), soil gas can enter the blocks below the slab and move up into the house through the wall. Therefore, the wall can be a soil gas entry route, even though no face of the wall appears to be contacting soil. This ability of hollow blocks to serve as a conduit for soil gas is illustrated in a number of instances in Figure 2, and is reflected in a number of the entry routes listed in Part A of Table 2.

In some cases a block foundation wall with open top voids can serve as a conduit in a slab-on-grade or crawl-space house even when the blocks do not extend up into the living area. Depending upon how the sill plate, outer sheathing, and any brick veneer are configured at the top of the block foundation wall, soil gas moving up through the open top voids could enter the space between the sheathing and the wallboard in the living area, and then migrate into the house.

One potentially important entry route which will sometimes be present is associated with hollow-block structures which contain fireplaces and chimneys, or which support fireplaces on the floor above. Such block structures are commonly built into the perimeter foundation wall, an interior load-bearing wall, or sometimes a free-standing central structure. These structures are of potential concern whenever they penetrate the slab (or flooring) and rest on footings of their own, which is often the case. The potential problem is that there can be openings concealed within the structure which can provide a ready conduit for soil gas up into the basement or into the upper living area of the house. For example, if the structure consists of a block-walled chimney of rectangular cross section, with a firebrick fireplace built into one face of the chimney, there can quite possibly be a space between the back of the firebrick and the block wall of the surrounding chimney. The exact nature and extent of such concealed openings will depend upon the specific procedures used by the masons during construction. If present, these openings cannot be effectively closed without at least partially dismantling the structure.

Another type of entry route is that in which underground perforated drain tiles connect into the house, thus serving as a soil gas collector facilitating entry. Sumps (B3 in Figure 2) and floor drains (B4 in Figure 2) are the two specific examples of this type of entry route. Many sumps (although not all) connect to perimeter drain tiles which surround at least part of the house at footing level (B3 in Figure 2). These tiles can be located on the outside of the footings, on the inside (underneath the slab), or on both the outside and the inside. Their purpose is to drain water away from the vicinity of the foundation. The water collected by the tiles drains to the sump, from which a sump pump lifts the water to an above-grade discharge remote from the house or to the house sewer line (see sump in Figure 2). These drain tiles can also collect soil gas, which can then move into the house via the sump. Thus radon can enter the house through the sump not only as the result of any exposed soil which might be visible in the sump itself, but also from soil around the entire foundation (through drain tile). As a consequence, sumps are almost universally a major radon source when they are present and not sealed.

Some floor drains (B4 in Figure 2) also drain to the perimeter drain tiles, to a separate segment of drain tile, and/or to a dry well (sometimes under the floor). In some cases, the floor drain might drain to a septic tank, a storm sewer, or a sanitary sewer. Whenever the floor drain connects to the soil in this manner, soil gas can be drawn into the house via the drain unless the drain includes a trap which is always full of water, a waterless trap, or a reverse flow valve. Floor drains which connect to a septic tank sometimes are installed with a trap that includes a cleanout permitting the trap to be bypassed for purposes of cleaning the line. This cleanout extension is normally blocked with a removable plug. If this cleanout plug is missing, then soil gas (and septic odors) can enter the house via the cleanout extension even if the trap is filled with water. Floor drains which drain via non-perforated pipe to an above-grade discharge would not be expected to be a source of soil gas. However, unless it is known that the drain definitely does not connect to the soil in some manner, the drain should be viewed as a potential entry route.

In using Table 2 to inspect a house for soil gas entry routes, the reader should recognize that, in many cases, some entry routes will be hidden. For example, they may be concealed behind or under paneling, carpeting, wood framing, or other structures or appliances. Using the table, it should be possible to identify where such entry routes might be hidden, as well as to identify the major visible potential entry routes. Understanding where important entry routes are, and where they might be concealed, is important

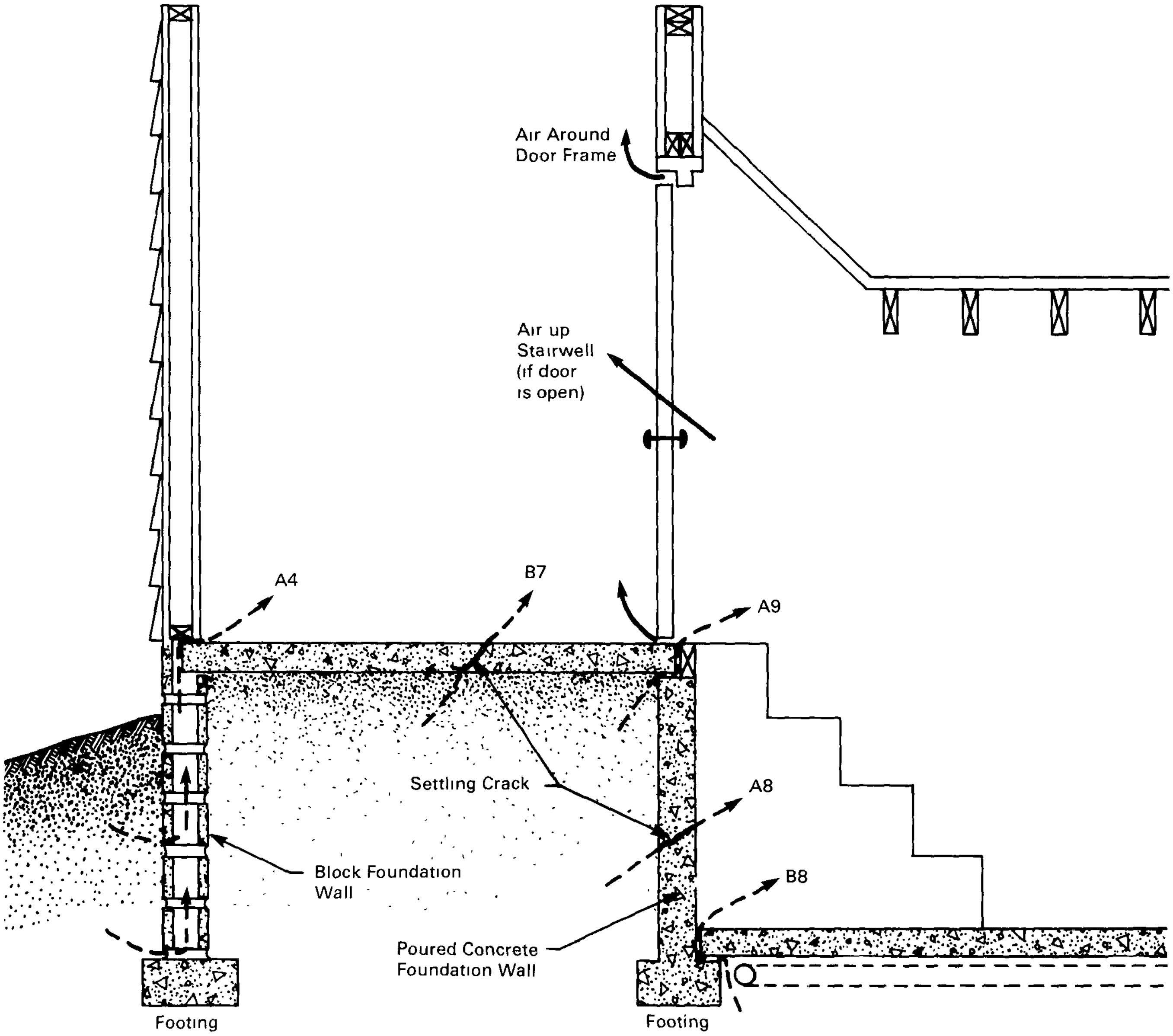
Figure 2. **Some potential soil gas entry routes into a house.**

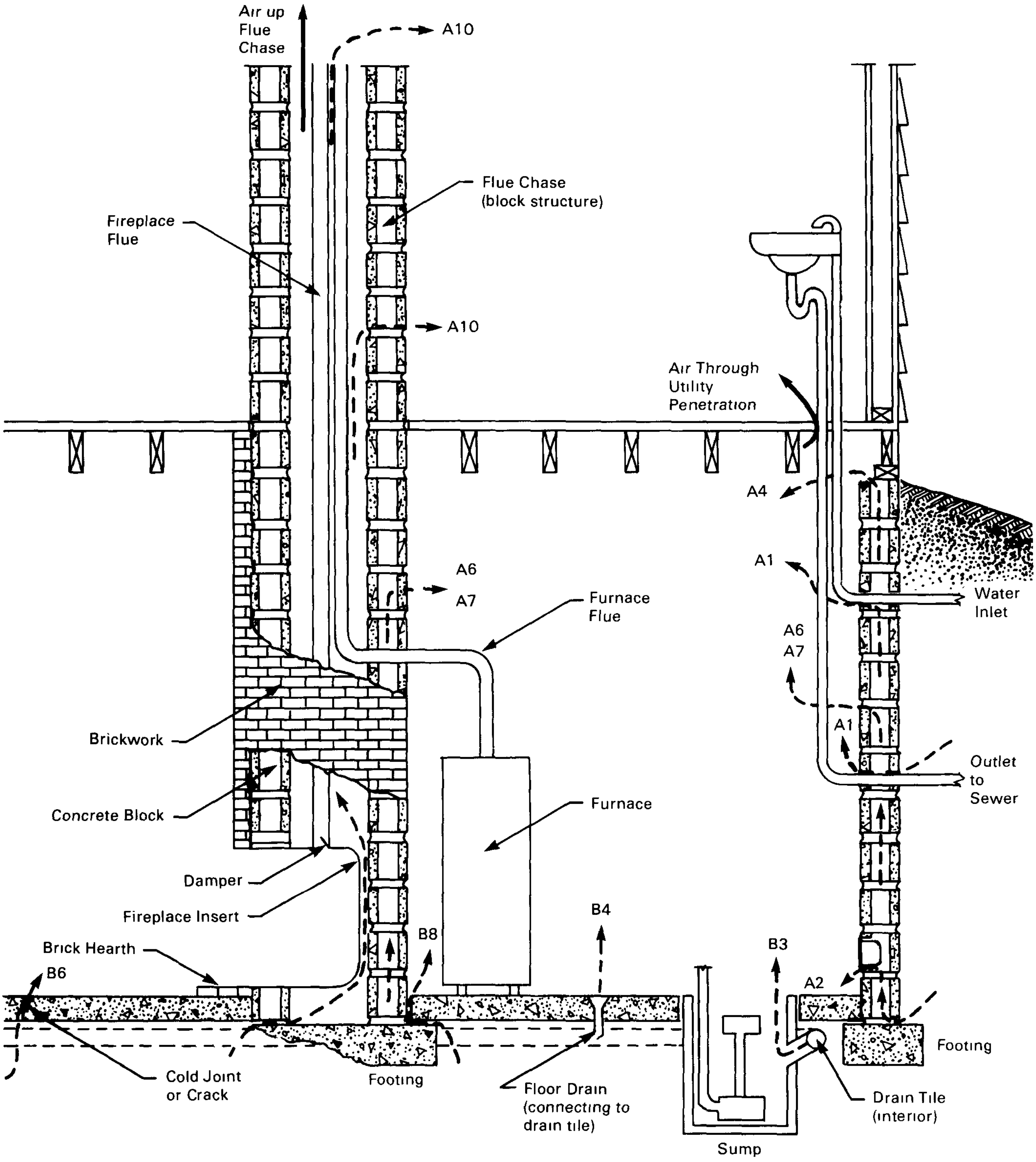
Key

- - → Soil Gas Flow

A1 Identifier of Soil Gas Entry Route, from Table 2

━━► House Air Flow Through Airflow Bypass





Note: Hybrid house containing both hollow-block and poured concrete foundation walls shown for convenience to illustrate range of entry routes in selecting the diagnostic testing which should follow and in determining the logical radon reduction alternatives for that house.

4.3 Factors Influencing Driving Forces

Along with the identification of soil gas entry routes, it is also important to identify those features which might be contributing to the driving force which is causing soil gas to flow into the house through these entry routes. The features influencing the driving force include: (a) those which increase the soil gas flow by contributing to depressurization of the house; and (b) those which facilitate the flow of soil gas without increasing depressurization.

Specific potential contributors to the driving force are listed in Table 3. The contributors are subdivided into three categories: those associated with the weather, those associated with house design features, and those associated with homeowner activities. The contributors in the weather and homeowner activity categories directly influence house depressurization. Contributors in the house design category facilitate house air exfiltration (and hence, perhaps, soil gas infiltration) under the depressurization created by the contributors from the other two categories. While nothing can be done to alter the weather, some steps can be taken to reduce some of the individual contributors in the other categories.

4.3.1 Weather Effects

Low outdoor temperatures contribute an important driving force. Whenever the indoor temperature is maintained at a level higher than the outdoor temperature, the buoyancy of the warm indoor air will tend to cause it to rise. The colder the temperature outdoors, the greater the buoyancy of the indoor air. The warm air leaks out of the house through openings in the upper levels (e.g., around upstairs windows, and through penetrations into unheated attics). To compensate for the warm air that is thus lost, outdoor air leaks into the house around doors and windows at the lower levels (and through the seam between the house frame and the foundation wall). Also, soil gas leaks in through entry routes. Once inside, the infiltrating air and soil gas themselves become heated, then rise and leak out through the upper levels, thus continuing the process. The shell of a closed house can thus be pictured as a chimney through which air is constantly moving upward whenever the temperature is warmer indoors (although the air movement is too small for the homeowner to notice). Due to the similarity of this process to that of warm air rising up a chimney or smokestack, the effect is commonly referred to as the natural stack effect.

The buoyant force on the warm house air depressurizes the lower levels of the house, sucking in the outdoor air and soil gas needed to replace the out-leaking (exfiltrating) warm air. On the other hand, the buoyant force pressurizes the upper levels of the house (relative to the outdoors), forcing heated air upstairs and out.

In addition to temperature, another weather-related contributor to the driving force for soil gas entry is the wind. Winds create a low-pressure zone along the roofline and on the downwind side of the dwelling. Depending upon the air exfiltration routes existing on the roof and on the downwind side, portions of the house can become depressurized.

4.3.2 House Design Effects

Nothing can be done to prevent the natural buoyant force that makes warm indoor air want to rise during cold weather. However, the air flows created by this buoyant force (and hence the infiltration of soil gas) can potentially be reduced by appropriate attention to certain house design features. The principles involved in reducing these air flows have been applied for some time by energy conservation consultants whose objective has been to reduce the amount of warm air flowing out of the house, to improve energy efficiency. These same steps can simultaneously reduce the amount of soil gas flowing in.

Openings through the house shell (between indoors and outdoors) above the neutral plane will facilitate the exfiltration of warm house air. The neutral plane is an effective horizontal plane in the house located at the height at which the inside pressure is equal to the outside pressure. To the extent that such openings through the shell can be closed above the neutral plane, the effect will be to partially cap the "chimney" created by the house shell, reducing the temperature-induced flows. Also, many concealed openings cannot easily be closed; for example, efforts to make the upper levels almost gastight (by installation of plastic sheeting as an air barrier inside the walls and over the attic floor) would be expensive, and perhaps not cost effective. Note that, if openings to the outdoors are closed below the neutral plane, the effect would be to reduce the openings available for outdoor air to infiltrate in order to compensate for the exfiltrating warm air at higher levels. Hence, closure of openings (e.g., around windows and doors) below the neutral plane could increase the amount of infiltrating soil gas, relative to infiltrating outdoor air, making radon problems worse. Closure of openings through the house shell can also reduce exfiltration (and depressurization) caused by low-pressure zones created by winds.

If the upper portion of a house can be pictured as a cap over a figurative chimney, then the floors between stories might be pictured as dampers in this chimney. Just as openings through the upper house

***Table 3.* Factors That Might Contribute to the Driving Force for Soil Gas Entry**

A. Weather factors

1. *Cold temperatures* outdoors (creating an upward buoyant force on the warm air inside the house, thus causing depressurization of the lower levels of the house).
2. High winds (depressurizing the roofline and downwind side of the house) can be important if the downwind side of the house has more openings through the shell than does the upwind side.

B. Design factors

1. Openings through the house shell (between indoors and outdoors). Openings above the neutral plane (i.e., openings in the attic and upper levels) contribute to the out-leakage (exfiltration) of rising warm air resulting from temperature-induced buoyant forces, potentially increasing soil gas infiltration. Such openings can include:
   - Spaces between windows and window frames.
   - Uncaulked gaps between window frames and the exterior house finish.
   - Penetrations through roofs (e.g., where attic ventilation fans are mounted).
   - Attic soffit vents, gable vents, passive roof vents, and ridge vents (must remain open for moisture control reasons).
   - Open dampers in chimneys and flues (permitting house air to flow directly from lower levels of the house to the outdoors above the roofline).
   - Concealed openings through walls and roof (e.g., openings around electrical junction boxes and switch plates in the walls, seams between strips of siding).

   Openings through the house shell on the downwind side of the house, and through the roof, can increase exfiltration and depressurization due to wind effects.
2. Openings through the floors and ceilings inside the house, facilitating the movement of air between stories (also between the living space and the attic, as well as basement and first floor). Such internal openings--referred to as airflow (or "thermal") bypasses--facilitate the rise of warm air resulting from the temperature-induced buoyant forces, and thus can potentially increase warm air exfiltration and soil gas infiltration. Internal airflow bypasses include:
   - Stairwells between stories which cannot be closed off.
   - Chases for flues, ducts, and utilities.
   - Laundry chutes.
   - The cavity inside frame walls, where the walls penetrate the floor above (especially in the case of internal frame walls, where the cavity is not partially blocked).
   - Attic access doors that are not weatherstripped.
   - Recessed ceiling lights, which require a penetration through the sheet rock.
   - Openings concealed inside block structures which penetrate floors between stories.
   - Central forced-air heating/air conditioning ducts which connect upstairs, downstairs, and basement.

C. Homeowner activities and appliance use

1. Using combustion appliances which draw combustion air (and flue draft air) from inside the house and exhaust the products of combustion outdoors.
   - Fireplaces.
   - Wood or coal stoves.
   - Central gas or oil furnaces or boilers for house heating, if air is drawn from inside the livable area.
   - Fuel-fired water heaters, if air is drawn from livable area.
   - Gas dryers.

   A separate supply of combustion air from outdoors can reduce the depressurization caused by these appliances.
2. Using any exhaust fan (a fan which sucks air from indoors and blows it outdoors).
   - Window fans or portable fans for home ventilation, when operated to blow indoor air out.
   - Clothes dryers which exhaust outdoors.
   - Kitchen exhaust fans (especially high-volume range exhaust hood fans).
   - Bathroom exhaust fans.
   - Attic exhaust fans, including fans intended to ventilate just the attic (sized below 1,000 cfm) and fans intended to ventilate the entire house (up to several thousand cfm).
3. Using the fan in any central forced-air heating/air conditioning system where the return ducting preferentially withdraws house air from the lower story of the house (due either to the location of the return air registers or to leaks into the return air ducting). Depressurization of the basement can arise, for example, when the central fan and much of the return ducting is located in the basement; basement air can be sucked into the return ducting (e.g., via unsealed seams in the ductwork and poor connections) and "exhausted" to the upstairs by the central fan.
4. Leaving doors open in the stairwell between stories (thus creating an internal airflow bypass).
5. Opening of windows or doors on just the downwind side of the house.
6. Operating a heat recovery ventilator in an unbalanced mode resulting in exhausting more air than is brought in.

shell permit rising warm air to escape, openings through the floors facilitate the upward flow of warm air inside the house, thus also facilitating the ultimate escape of the air through the shell. Such openings through the floors-- which are effectively holes through the damper--are referred to here as internal airflow bypasses (since they permit the rising warm air to bypass the damper). They are also commonly referred to as thermal bypasses, since they facilitate the flow of heated air up and out of the house. Where major airflow bypasses can be closed, the upward air movement can be reduced--and, as a result, the exfiltration of warm air and the infiltration of outdoor air and soil gas can be reduced. Some bypasses cannot be closed easily, due either to inaccessibility or to practical considerations. For example, houses having large open stairwells without doors between stories offer a major flow route for rising warm air which cannot be closed without installing a wall and door across the stairwell. In houses having such major bypasses, it might not be possible to significantly reduce the upward air movement by closing other, secondary, bypasses so long as the stairwell remains open.

4.3.3 Homeowner Activity Effects

As listed in Item C of Table 3, a number of appliances remove air from the house, and thus might have a depressurizing effect. Fans which draw air from the house and exhaust it outdoors are present in most houses, in the form of window and attic fans, range hoods (not all range hoods are exhaust fans; some merely recirculate the air through a filter), and bathroom exhaust fans. A clothes dryer is a form of exhaust fan whenever the moist air leaving the dryer is exhausted outdoors. A stove, fireplace, furnace, or boiler inside the house also removes air in order to burn the fuel, and in order to maintain the proper draft up the flue. This air (including products of combustion) goes up the flue and is exhausted outdoors. These appliances are important in daily living, so that ceasing their use is generally not an acceptable option. Some of these appliances are used only intermittently (e.g., fireplaces are often used only occasionally during the winter); thus their impact on indoor radon levels may sometimes be of limited duration.

The Appendix is an example of a house inspection form that can be used during a visual inspection. Not all parts of the form are applicable to every house. However, much of the information on this form will be useful to a diagnostician in selecting and designing a radon reduction system. Along with the checklists in Tables 2 and 3, this inspection form directs the inspector's attention to the variety of issues that may be important in diagnosing the house's radon problems and then mitigating them.

Section 5

Diagnostic Testing to Select a Mitigation Method

A collection of observations and measurements (referred to as "diagnostic tests") can be made prior to mitigation to aid in the selection and design of the radon reduction method for a particular house. The type and extent of diagnostic measurements conducted by radon diagnosticians and remediation firms currently varies among individuals. While no one set of diagnostic testing procedures can be considered universally applicable, EPA is compiling an appropriate set of diagnostics to be used in Agency-sponsored projects. This will not necessarily be the most appropriate set for other mitigators. Several studies in progress (Ma87, Se87, Tu87, Ha87) are attempting to identify the minimum set of diagnostic measurements needed to design an efficient mitigation system for a given house. One important consideration in choosing the appropriate diagnostic procedures is cost effectiveness to the homeowner, since the time spent by diagnosticians will generally be paid for by the homeowner. Unless a specific diagnostic test offers some reasonable potential for leading to a successful installation in a given house more efficiently and more cheaply, the need for conducting that diagnostic test should be questioned.

Since there is not currently a universally accepted set of diagnostic protocols, the following discussion can list only some of the specific diagnostic tests that have been used by various diagnosticians and EPA engineers, with a discussion of the conditions under which the individual tests might be most applicable. Diagnostics described in this section fall into two groups: one contains the minimum set required for the simplest diagnosis, while the other contains additional procedures to be performed by more experienced mitigators especially when a house is expected to present difficulties in mitigation. Figure 3 shows a logical sequence of steps that could be followed in performing diagnostic measurements. These observations and measurements are discussed in the following subsections.

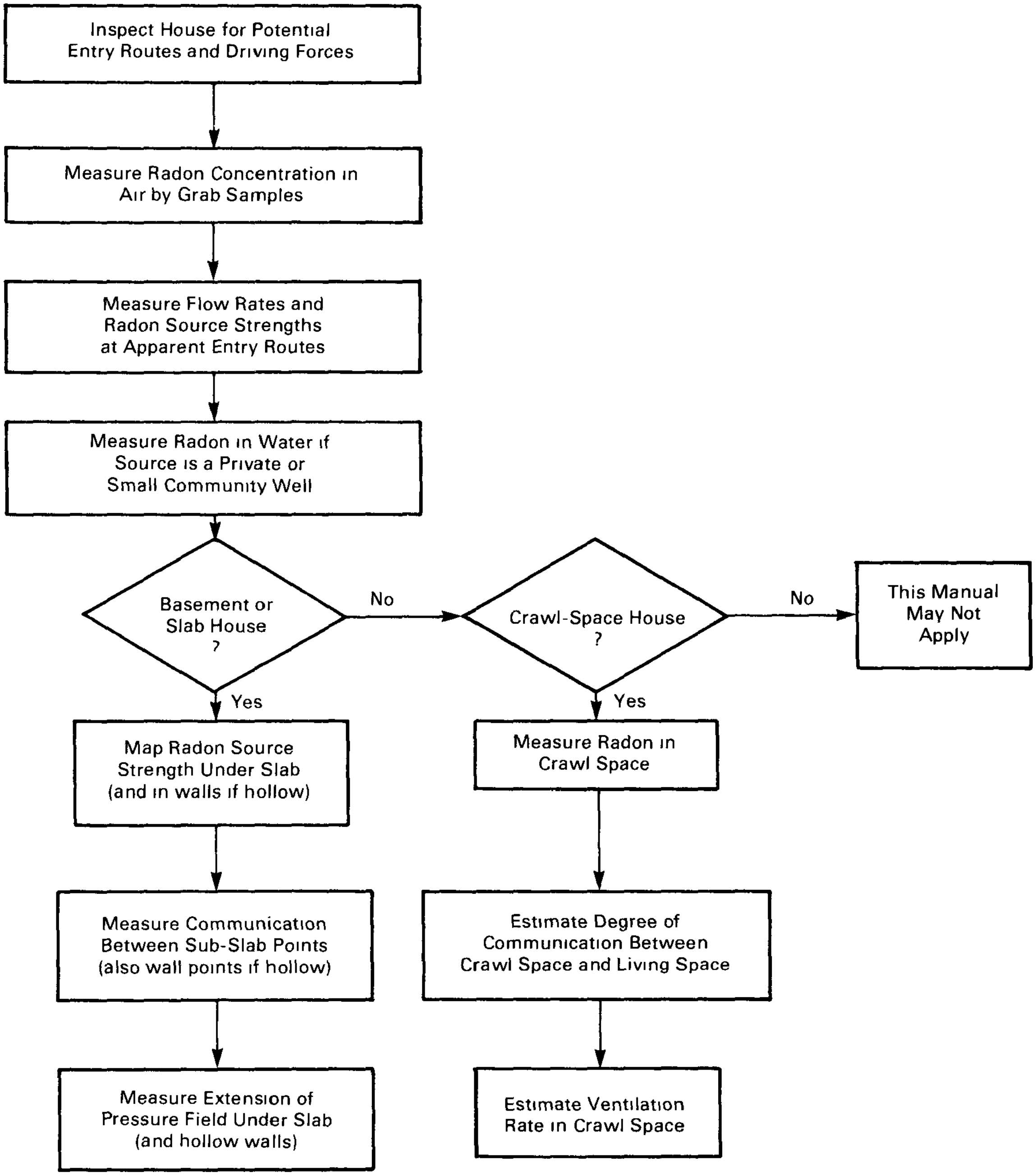
5.1 Visual Survey of Entry Routes and Driving Forces

The first and most important step in the diagnosis is an inspection of the house to identify potential radon entry routes and driving forces. During this step one notes both the general and the unique features of the house which could be important in the selection and design of a mitigation system. From these features, potential strategies of mitigation are formulated, and specific system designs are visualized. These visualizations of system designs are then used to develop a plan of action for diagnostic testing either to confirm the applicability of the most promising reduction method or to distinguish between competing designs. Additional features to be observed are whether extensive wall and floor finishes exist in the lowest level. From the house plan or from the homeowner, it may be possible to determine whether a complete loop of drain tile exists around the footings. A major difficulty in diagnosing radon problems in a house is that entry routes, certain house features contributing to the stack effect, and other structural features influencing mitigation design are often concealed behind or under wall paneling, carpeting, wood framing, and plumbing fixtures.

In many such cases, the cost-effective approach will be simply to make some reasonable assumptions about the concealed features, and to design the radon reduction system to be modified if performance after installation suggests that the assumptions were not correct. If large hidden openings in the slab or foundation walls prevent an active soil ventilation system from maintaining adequate depressurization, the paneling, flooring, commode, etc., may have to be temporarily removed so that the openings can be closed. If the current homeowner observed the house being built, or if the builder is available, information about some of these and other concealed features might be obtainable from them (such as whether a good layer of clean, crushed rock was placed under the slab, or whether there is a complete loop of drain tile around the footings).

In conducting the visual inspection, the primary tools required will generally be a flashlight, a screwdriver, and a stiff wire, or other similar tool for probing in joints and openings. A small stepladder can sometimes be useful. A mirror to enable viewing features in difficult-to-reach locations is advisable, since hidden crevices could contain mouse traps or worse hazards to bare fingers. A plumber's "snake"

Figure 3. **Steps in diagnostic testing.**



can be valuable for probing the extent of openings (for example, the extent of the drain tiles that open into a sump). Another very useful tool is a smoke stick or a punk stick, which generates a small stream of smoke. When released next to cracks and other openings, the smoke can reveal whether there is a distinct movement of air into or out of the opening. This indicates whether there might be a significant soil gas flow into the house through that opening. A smoke stick uses chemicals to produce smoke without generating significant heat. A punk stick generates smoke from a smoldering substance. Since the punk stick generates heat, the smoke tends to rise, which may interfere with the proper interpretation of the air flows. Punk sticks are more readily available. Despite the fact that smoke sticks are less common, they are preferred over punk sticks.

However, the smoke flow can sometimes be ambiguous. Moreover, the fact that a distinct smoke flow is not observed at a given time does not necessarily mean that that opening is not an important entry route. Conversely, in some locations, an observed smoke flow might be attributable to outside air or house air flow, not soil gas. Therefore, smoke testing is not always definitive, but it can be useful when distinct air movement is present. (Note: Whenever a smoldering object such as a punk stick is used as a smoke source, care should be taken to prevent fires--for example, in basements cluttered with flammable materials. It also is not advisable that the diagnostician breathe excessive amounts of the fumes from chemical smoke sticks.)

In many cases, the mitigator will be sufficiently confident of his initial diagnosis that additional testing will not be considered necessary. Rather than spending additional time performing diagnostic measurements, the mitigator begins immediately to install the reduction system. A number of mitigators have been quite successful with this approach (especially with sub-slab depressurization systems). Their success is based primarily upon their knowledge of local building codes and practices. For instance, the mitigator may know that in a certain locality there will almost always be a good layer of aggregate under the slab. In some localities, the mitigator may be aware that the soil is sufficiently permeable that aggregate is not required to ensure the applicability of a sub-slab system. Similarly, if there is no central air circulation system and the basement is well isolated from the upstairs, one might be inclined to try basement pressurization without further diagnostic testing. Natural or forced ventilation of the crawl space might also be attempted without further testing, if no appliances or air handling systems are located in the crawl space.

However, in many circumstances, some minimal number of diagnostic measurements are needed to guide the design and installation of the radon reduction system. One of the most universal diagnostic measurements will be a simple test of sub-slab communication. In a simple form, this test consists of using a vacuum cleaner or other fan at a single location to depressurize the region beneath the slab, while smoke sticks or other devices are used to determine whether air flow from the basement to the sub-slab region is induced at some distance through existing holes or through drilled test holes. Good air movement induced at large distances indicates good sub-slab communication and, consequently, high probability of success for a sub-slab ventilation system.

5.2 Radon Measurements in Room Air

The initial measurements that a homeowner makes to determine occupant exposure inside the house are not considered in this discussion to be part of diagnostic testing. If radon measurements in the bulk house air have already been completed in accordance with the EPA protocols, there will generally not be a need for a diagnostician to repeat them. However, there may be individual cases where further measurements in the house air are desirable as part of the diagnostic process. For example, grab samples for radon in the room air might be taken at the same time that entry route radon measurements are made, to permit a direct comparison of the entry route concentrations with the simultaneously existing room air concentrations. Grab samples are samples of air collected in a container during a short period of time (nominally 5 minutes) to be analyzed for radon concentration. These grab samples are usually stored in an airtight container and measured for radon concentration at a later time using a scintillation counter.

5.3 Radon Measurements at Potential Soil Gas Entry Points

Some diagnosticians believe that radon measurements made in (or near) suspected entry routes are useful in suggesting the relative importance of the various routes, as an aid in the design of the radon reduction system (Tu87). Grab samples can be taken from: inside the sump; inside floor drains; inside the voids of each block foundation wall (via small holes drilled in the face of the wall); in the space between paneling/wallboard and the foundation wall behind; and from cracks and joints in the slab and walls (including French drains), by taping over a segment of these openings and drawing the sample from within the taped area (Tu87). Those entry routes exhibiting higher radon concentrations might reasonably be assumed to be relatively more important than those having lower concentrations. Thus, the routes with higher concentrations might receive some priority in the design of the mitigation system. For example, if an active sub-slab suction system is planned, more suction points might be placed near the block foundation walls that appear to have the higher radon levels in the voids.

If holes are being drilled through the slab in order to measure the sub-slab pressure field extension, as discussed in Section 5.6 below, the radon levels under the slab can be measured by grab samples taken through the several holes. If the results show that radon levels are distinctly higher under certain segments of the slab, the sub-slab suction points can be placed in (or biased toward) those segments.

Note that these measurements only suggest the relative importance of an entry route. They do not provide a rigorous measure of the actual contribution of that route to the radon levels in the house. The actual amount of radon entering a house through a given opening is determined not only by the radon concentration in the entering gas, but also by the flow rate of the gas through the opening. For example an opening with a less elevated radon level, but a high flow, might be more important than one with a higher level but a low flow. Since flow rates are not easily measured in these circumstances, the actual amount of radon entering through a given opening is not known. It is being assumed that two similar types of entry routes (e.g., two block walls or two slab cracks) probably have similar entry flow rates. Thus, the one with the higher radon concentration is probably the more important contributor to indoor levels. This assumption, while reasonable, will not always be correct. Two dissimilar types of routes (e.g., a block wall versus a slab crack) cannot reliably be compared based on radon measurements alone.

5.4 Radon Measurements in Well Water

If a house receives its water from a private or small community well, it will generally be necessary to measure the water radon level as part of the diagnostic effort. A qualitative test can be performed by using either grab samples or a continuous radon monitor (EPA86b, EPA87b) to measure the radon concentrations in a closed bathroom before and after the hot shower runs for 10 to 15 minutes. If the well water contains more than, say, 40,000 pCi/L of radon, the water might be contributing a significant portion of the indoor airborne radon. Under these conditions, water treatment will be required in addition to (or rather than) soil-gas-related reduction measures. For more information, see References EPA87c and EPA88a. The only documented health risk associated with radon in the water is from its release into the air and, consequently, from lung cancer. There is no documented health risk from ingestion of the radon in the water. The commonly used rule of thumb is that 10,000 pCi/L of radon in water will result in about 1 pCi/L of radon in the indoor air. The actual range is 0.2 to 3 pCi/L. This rule of thumb relates to the average concentration in the house. Local concentrations in the bathroom may be much higher.

5.5 Pressure Measurements

Since most mitigators agree that radon entry into houses is controlled primarily by a pressure-driven flow of soil gas into the house, useful information can be obtained by measuring appropriate pressure differentials. For example, the pressure differential between indoors and outdoors during a radon measurement will give some perspective regarding the degree of house depressurization and, consequently, the strength of the driving forces bringing outside air into the house. Pressure differentials measured while air-exhausting appliances are in operation indicate the degree of depressurization caused by these appliances. The mitigation system must be designed to counteract these pressure differences. Pressure differences between the house and the soil give a more direct measure of the driving force bringing soil gas into the house (at the time of measurement). The mitigation system also must be designed to offset this driving force.

The small pressure differences that exist in these situations, no more than a small fraction of an inch of water, expressed as in. WC (water column), can be measured using either a micromanometer or a pressure transducer.

5.6 Measurement of Sub-Slab Communication

If a sub-slab ventilation system is being considered, it is helpful to know the ease or difficulty with which gas can move through the soil and crushed rock under the slab (i.e., the sub-slab "communication"). Sub-slab systems rely upon the ability of the system to draw (or force) soil gas away from the entry routes into the house. If an active (fan-assisted) sub-slab ventilation system is to be used, and if this system is to maintain reduced pressure at all of the entry routes around the slab, the number and location of the needed ventilation points will depend on the communication under the various portions of the slab. The better the communication, the easier it will be for a ventilation point to maintain reduced pressure at an entry route remote from that point.

In some cases, some diagnosticians might feel that it would be more cost effective to install a sub-slab ventilation system without measuring communication. By that approach, the initial sub-slab installation would be made using best judgment (based upon visual inspection) and experience. If radon levels are not sufficiently reduced by the initial system, post-mitigation diagnostics (including sub-slab pressure measurements) could then be conducted to determine where additional ventilation points are needed. This approach avoids the cost of the pre-mitigation communication measurement, but increases the risk that the initial installation will have to be modified later at some expense. Among the circumstances under which it might be a reasonable risk to skip the pre-mitigation communication testing would be when it is reasonably certain that there is a good layer of clean, coarse aggregate under the slab.

Evaluation of sub-slab communication can consist simply of visually inspecting the nature of the aggregate under the slab, by drilling several small test holes through the slab at several points. This approach would not necessarily detect some barriers to gas flow that might exist under the slab such as heating ducts, interior footings, or bedrock with no aggregate over it.

A more quantitative approach for assessing sub-slab communication is to measure what is referred to as the "pressure field extension." The pressure field extension reflects the ability of ventilation applied at one point under the slab to maintain reduced pressure at various other points remote from the first. One convenient technique for measuring the pressure field extension (Ha87) involves the use of an industrial vacuum cleaner, capable of producing up to 80 in. WC of pressure differential, to depressurize a hole through the slab at some central location. The vent hole through the slab should be as large as 1.5 in. in diameter, in which case the hose from the vacuum cleaner can be inserted all the way through the slab and temporarily sealed using putty. Care must be exercised to ensure that a reliable seal is obtained. While the vacuum cleaner operates, pressure differences are measured across the slab at several test points around the perimeter of the slab, remote from the vent point. The pressure difference is also measured at a closer point, within perhaps 8 to 12 in. of the vent point.

These pressure differences can be measured using a suitably sensitive micromanometer or pressure gauge sealed with putty into 3/8- or 1/2-in. holes through the slab. Some diagnosticians use a smoke stick, rather than a pressure measurement, to determine qualitatively whether the depressurization is capable of inducing an air flow down into the test hole. If this condition were maintained under the most adverse conditions of basement depressurization (during winter, with appliances operating), a distinct flow into the test holes should be adequate to ensure good performance of a mitigation system producing equivalent sub-slab depressurization. The exhaust from the vacuum cleaner should be vented outdoors, since it will consist of soil gas from under the slab which can be very high in radon. Of course, all holes must be permanently closed after testing.

The primary objective of this test is to determine the degree of depressurization to be maintained under the slab to ensure that the direction of flow at the remote perimeter points will be from the basement into the sub-slab region, despite the thermal stack effect, the wind, or appliance operation. At present, it is estimated that the sub-slab pressure differential depressurization around the slab perimeter must be at least 0.015 in. WC (about 4 Pa) to prevent soil gas entry when the basement becomes depressurized under normal conditions.

The results of this diagnostic test include the pressure differences in the closer test hole, and in the remote perimeter test holes. Under favorable conditions (good communication), the pressure difference in the closer test hole will be no greater than several tenths of an inch of water, despite the high depressurization in the vacuum cleaner. The pressure differences at the remote points will often not be much greater than 0.015 in. WC, and will sometimes be less. The reduction in pressure difference between the closer and the remote test points is a measure of the flow resistance under the slab. If the slab contains cracks and other openings, this reduction in pressure difference may also be a measure of the amount of house air leaking down through the slab openings.

A sub-slab ventilation installation can be more effective by using a hole excavated in the soil under the slab having a radius equal to the distance to the closer test point discussed above (see Section 7.3 for an illustration). The pressure at the closer test point (8 to 12 in.) can be viewed as the pressure which the sub-slab ventilation system must maintain in that vent hole if the sub-slab depressurization around the slab perimeter is to be maintained at 0.015 in. WC. The manufacturer's performance curve of the fan and the diameter and length of the ventilation pipe (and hence the pipe pressure loss) can be used to determine the needed pressure difference in the vent hole at the indicated flows.

This diagnostic test procedure has been used by private mitigators in designing a number of sub-slab ventilation installations. Where sub-slab communication is relatively good, the procedure appears fairly successful. When the pressure field extension is good, indicating high sub-slab communication, one sub-slab ventilation point is often adequate to treat an entire slab in a small- to medium-sized house. In large houses, or where the communication is lower (although still good), a second ventilation point may be needed. The second point might be installed without any further vacuum diagnostic testing, on the assumption that the flow resistance under the slab near the second point will be generally similar to that where the vacuum test was conducted. This assumption is probably reasonable when communication is good.

The rationale for pressure field extension measurements as a cost-effective diagnostic test lies in the argument that the system can be properly sized and located based on these measurements. If more vent points and a larger fan than necessary are installed, both the initial cost and the operating costs will be greater than for an optimized system. The excess operating costs include not only the additional energy required to operate the larger fan but also the heating and cooling penalties associated with removing excessive amounts of conditioned indoor air. On the other hand, if the system is undersized there are both capital and labor costs associated with modifying the system.

The greatest difficulties with sub-slab pressure field measurements arise where communication is not good. When the pressure field extension is poor, a vacuum cleaner test at one or two vent holes will generally not give the mitigator much information with which to design a sub-slab ventilation system. The vacuum cleaner depressurization might not extend at all to any of the remote test points. Thus, calculation of sub- slab flow resistance near those test points is impossible (one just knows that resistance is high); and one cannot reliably determine from the results where sub-slab suction points would have to be located to adequately treat those remote areas of the slab. The pressure field extension test here simply serves as a warning that permeability is poor (and probably variable from place to place), and that the sub-slab system will thus have to be designed conservatively including multiple suction points, careful placement of the points, and perhaps fans. Sometimes less remote test points could be used to estimate the maximum extent of the pressure field.

Testing has shown that "poor" pressure field extension does not necessarily mean that sub-slab depressurization is not applicable. One option for obtaining more quantitative design guidance when the permeability is poor might be to conduct vacuum cleaner tests through a number of test holes around the slab, more extensively mapping the distribution of sub-slab flow resistance. However, so many test points might be required that this approach would not be cost effective, since diagnostic time and costs will rise with the significantly increased effort. Also, some sections of the slab might not be accessible, due to carpeting or other floor finish. Moreover, the results may not be accurately interpreted. Results from some installations suggest that a sub-slab system might still be reasonably effective even if the system does not maintain 0.015 in. WC suction everywhere (Sc87). Thus, if the results from the pressure field mapping suggest that many suction points would be needed to achieve 0.015 in. WC everywhere, a mitigator might be inclined to start with fewer points in the initial installation with the location of the points selected using best judgment. The number of points could be increased later if warranted. This approach is what the mitigator would have done in the absence of extensive mapping.

Therefore, if the initial test of sub-slab pressure field extension shows poor extension (poor communication), some mitigators might decide that the most cost-effective approach would then be to install a system based on best judgment and experience, rather than proceed with further pressure field diagnosis. Developmental work is underway to define what further pressure field testing is cost effective and practically useful where permeability is poor.

5.7 *Measuring the Pressure Field Inside Block Walls*

If active ventilation of the void network inside hollow-block foundation walls is planned, it might be useful to make measurements on the wall voids, analogous to those described above regarding sub-slab communication. The objective would be to determine how far any pressure effects within the voids (either depressurization or pressurization) extend out from the wall ventilation point. The concern with wall voids is not whether flow resistance will be too high to permit good pressure field extension (as can be the case under the slab), because the flow resistance in the void network will be quite low. Rather, the concern is that the pressure field might not extend very far because the walls can permit so much air to leak into (or out of) them when depressurization (or pressurization) is applied (Mar88). The information on pressure field extension could be used to help select the number and location of wall ventilation points needed to handle this leakage, and thus to adequately treat all of the wall-related entry routes. The results might also help identify major wall openings that must be closed.

For wall testing, the industrial vacuum cleaner would be connected to the void network by holes drilled into the block cavities at appropriate points around the foundation walls. The small test holes would also penetrate into block cavities at appropriate locations radiating out from the vent holes. Again, some diagnosticians feel that this type of testing might not be cost effective unless poor performance of the initial mitigation system suggests that it is needed.

Measurement of pressure field extension inside block walls has not been widely used. Thus, its practical usefulness as a diagnostic test procedure cannot be confirmed at present.

Section 6

Selecting and Designing a Mitigation System

6.1 Selecting a Technique

The selection of a radon reduction method for a given house by the owner or mitigation contractor will be determined by a number of factors including: the degree of reduction required; the degree of reduction that the homeowner is willing to pay for; the desired convenience and appearance of the installed system; the desired confidence in system performance; the construction features of the house; and the results of the pre-mitigation diagnostic testing. Figure 4 illustrates a number of the decisions involved in selecting a mitigation approach. Considerations leading to the choice of specific techniques are discussed below.

6.1.1 Soil Ventilation

When radon reductions of more than 80% are required (i.e., when the initial radon levels are above about 20 pCi/L assuming a target level of 4 pCi/L), some type of active soil ventilation approach is usually used. From a risk standpoint, the target level should be as low as reasonably achievable, rather than 4 pCi/L. The effectiveness of alternative techniques to active soil ventilation for achieving such high reductions is not well demonstrated. If smaller reductions are sufficient, other techniques can more readily be considered (e.g., heat recovery ventilators, sealing of entry routes, or perhaps passive soil ventilation). These methods are discussed in Section 10. However, if the homeowner is willing to pay the price, an active ventilation system should be considered for maximum risk reduction.

The radon reduction approach that has received the greatest amount of attention to date is active soil ventilation. If the initial radon concentrations (from an appropriate follow-up test) are greater than 20 pCi/L and the homeowner is willing to spend $800 to 2,000, an active soil ventilation system should be considered. Also, if maximum reduction regardless of cost is the goal, active soil ventilation should be considered. Figure 5 illustrates the considerations applicable in choosing the most appropriate soil ventilation technique.

Since drain tile ventilation systems are often the least expensive and the easiest to install, they are usually the first choice, if the tiles are present and accessible. If the drain tile installation is not viable, the second choice is usually sub-slab ventilation. The applicability of a sub-slab system depends primarily on whether there is good air communication under the slab. If the communication under the slab and with the walls is poor, the slab has no cracks or apparent entry routes, the radon levels in the block walls are very high, and the tops of the blocks are sealed or are sealable, a wall ventilation system may be indicated. For poured basement walls with poor communication under the slab, consider a baseboard duct ventilation system or, alternatively, a sub-slab ventilation system with ventilation points about every 20 ft around the perimeter. This spacing assumes that no detectable communication was observed with a smoke test. Often, multiple sub-slab points around the perimeter will compete favorably with point-penetration wall ventilation systems.

6.1.2 Crawl-Space Ventilation

For a crawl-space house, ventilation of the crawl space is usually the first option. Figure 6 shows how to choose the type of ventilation system. If the radon concentrations in the living space are comparable to those in the crawl space, the following considerations will apply. As a rule, reductions by dilution become difficult when the required reductions exceed 90%. Consequently, when the radon concentrations in the crawl space exceed about 40 pCi/L, an alternative to simple dilution should be considered. When the concentration in the living space is much less than that in the crawl space, this critical value, 40 pCi/L, could be somewhat greater. The first alternative to simple dilution might be to cover the soil with an impermeable film and ventilate the soil beneath the film. Six mil polyethylene film is often used for this purpose. Although the film has proven adequate so far, its durability is unknown. In principle, this technique is very similar to sub-slab ventilation. Whether it is necessary to seal the edges of the film and overlaps depends on the radon level, the permeability of the soil, the number of piers, and the size of the crawl space. For maximum efficiency in radon reduction, both (edges and overlaps) should always be sealed.

Figure 4. Selecting a mitigation approach (see Table 1 for a summary of the mitigation techniques).

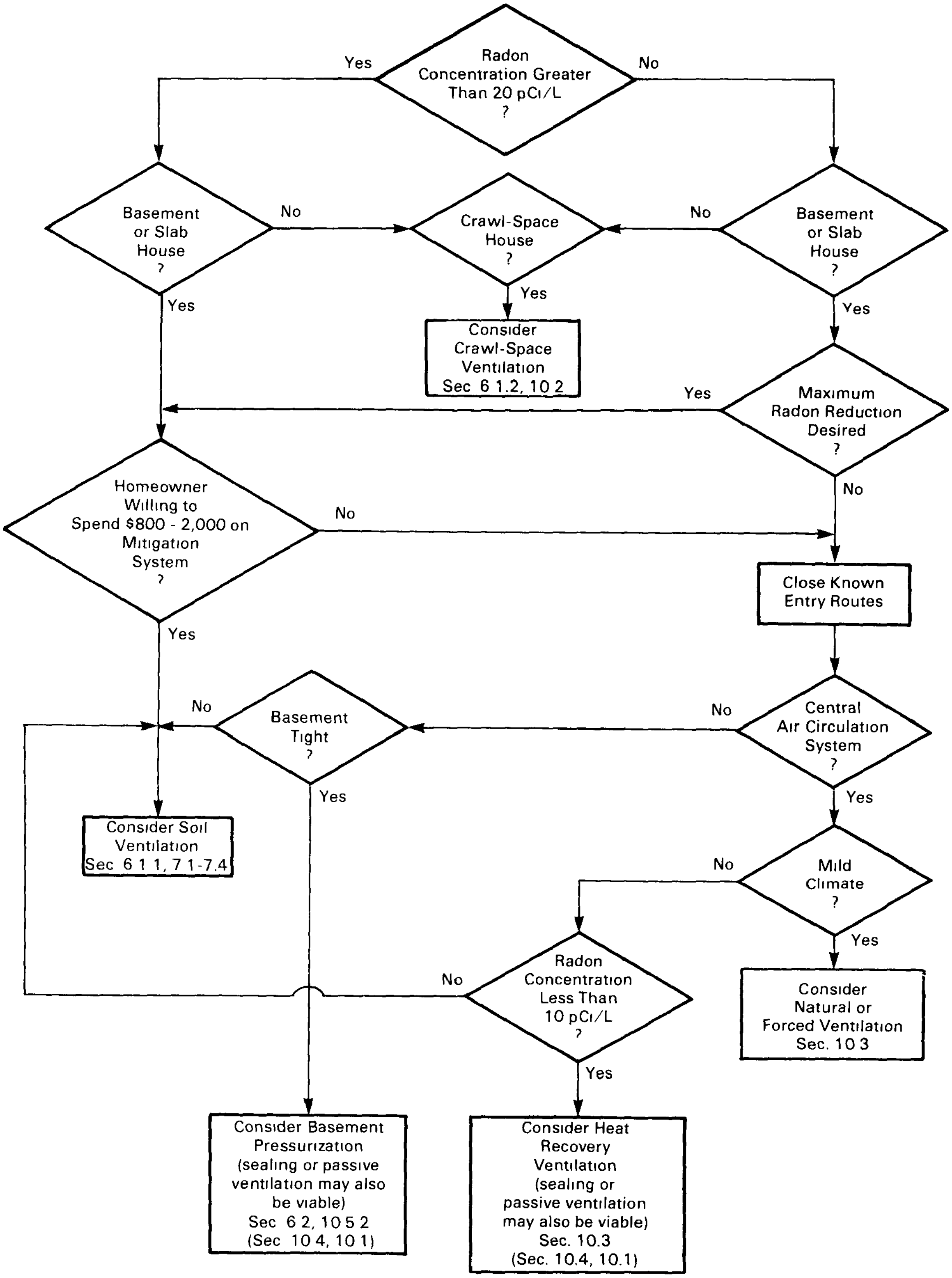


Figure 5. **Choosing a method of soil ventilation (details of these installations are presented in Section 7).**

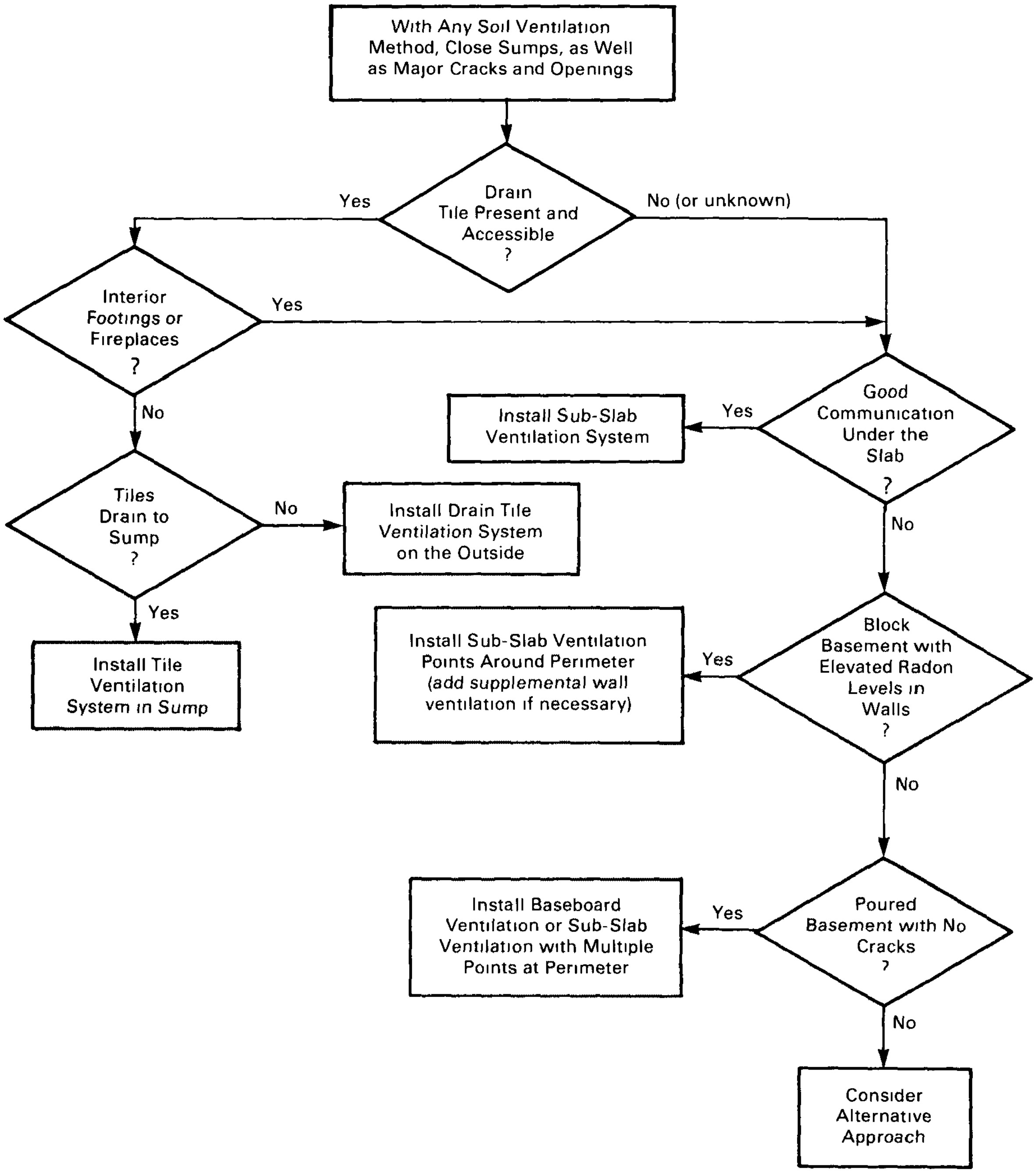
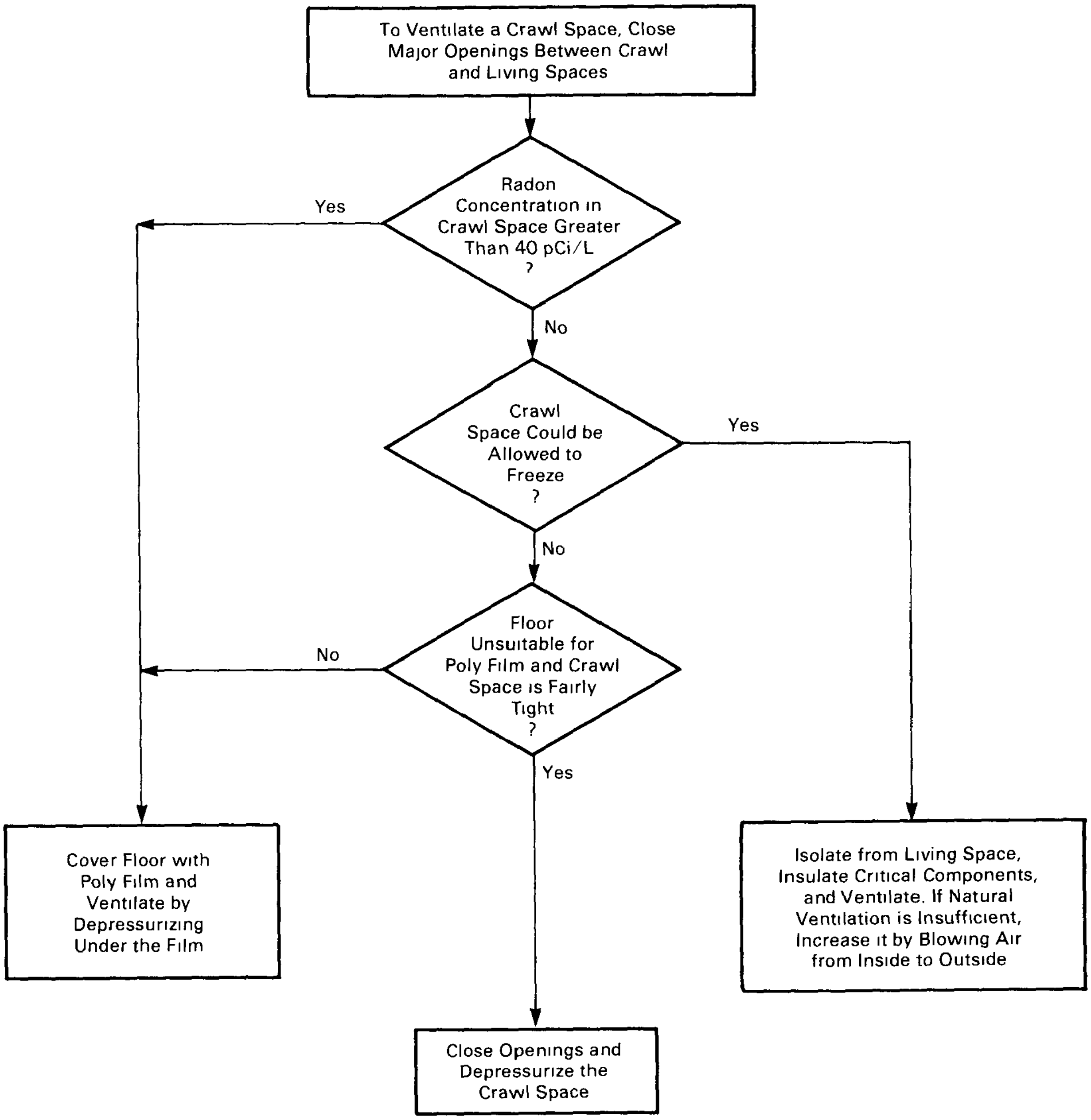


Figure 6. Choosing a crawl space ventilation system (for additional information see Section 10.2).



One important consideration relating to crawl-space ventilation is whether the crawl space can be allowed to freeze. If certain components such as water lines and fuel lines can be insulated (heat tracing may be required), allowing the remainder of the crawl space to freeze, then a possible mitigation technique is to isolate the crawl space from the living space, insulate critical components, and ventilate the crawl space. If natural ventilation is insufficient, it can be increased by blowing air from inside to outside. Exhausting air from inside the crawl space may result in a slight depressurization which ensures that the flow of crawl-space air to the living space is not increased. This does not mean that pressurization of the crawl space would not prevent radon entry in many cases. Experience with crawl-space pressurization, however, is very limited. If the crawl space cannot be allowed to freeze and sub-film ventilation is not appropriate, but it is relatively leaktight, then all openings should be closed and the crawl space depressurized or pressurized.

Depressurizing the crawl space is likely to increase its radon concentration. Consequently, this technique should not be applied when the crawl space is entered often; for example, when the washer and dryer are located there. This technique also should not be used when the air circulation system has the cold air return ducts in the crawl space. In fact, no technique that allows high concentrations of radon in the crawl space should be used when the cold air return ducts are located there because radon could be transported into the living space through leaky return ducts.

Where the living space can be effectively isolated from the crawl space, it may be possible to reduce the radon significantly by reducing the depressurization in the crawl space using a single vent to the outside without inducing freezing in the crawl space. This would work only in mild climates and for soils with moderate concentrations of radon.

6.1.3 *Basement Pressurization*

An alternative to depressurizing under a basement slab to reverse the direction of flow of soil gas is to pressurize the basement relative to the sub-slab region. Many basements are not appropriate for this technique. Figure 7 illustrates how to decide whether to apply basement pressurization. If it is impractical to isolate the basement from the living space, then basement pressurization will not be practical. Open stairwells between the upstairs and the basement as well as fireplaces or woodstoves in the basement are examples in which basement pressurization would be impractical. If the heating and/or air conditioning (HAC) system is a forced air unit, it will probably not be possible to isolate the basement; hence basement pressurization will not be applicable. A fireplace or woodstove in the living space would make it impractical to pressurize the basement by blowing air from upstairs into the basement. It might be possible in some circumstances to blow outside air into the basement. The most straightforward test for determining the applicability of basement pressurization is a blower door test between the basement and either the upstairs or the outside, whichever is considered the source of air. A rule of thumb is that basement pressurization will not be practical unless a positive pressure of at least 5 Pa can be sustained with a flow rate of not more than 300 cfm under the most challenging conditions. If the test is performed during the winter, the most challenging conditions would presumably be simulated by operating all the air-exhausting appliances in the basement during the test.

6.2 Designing the System

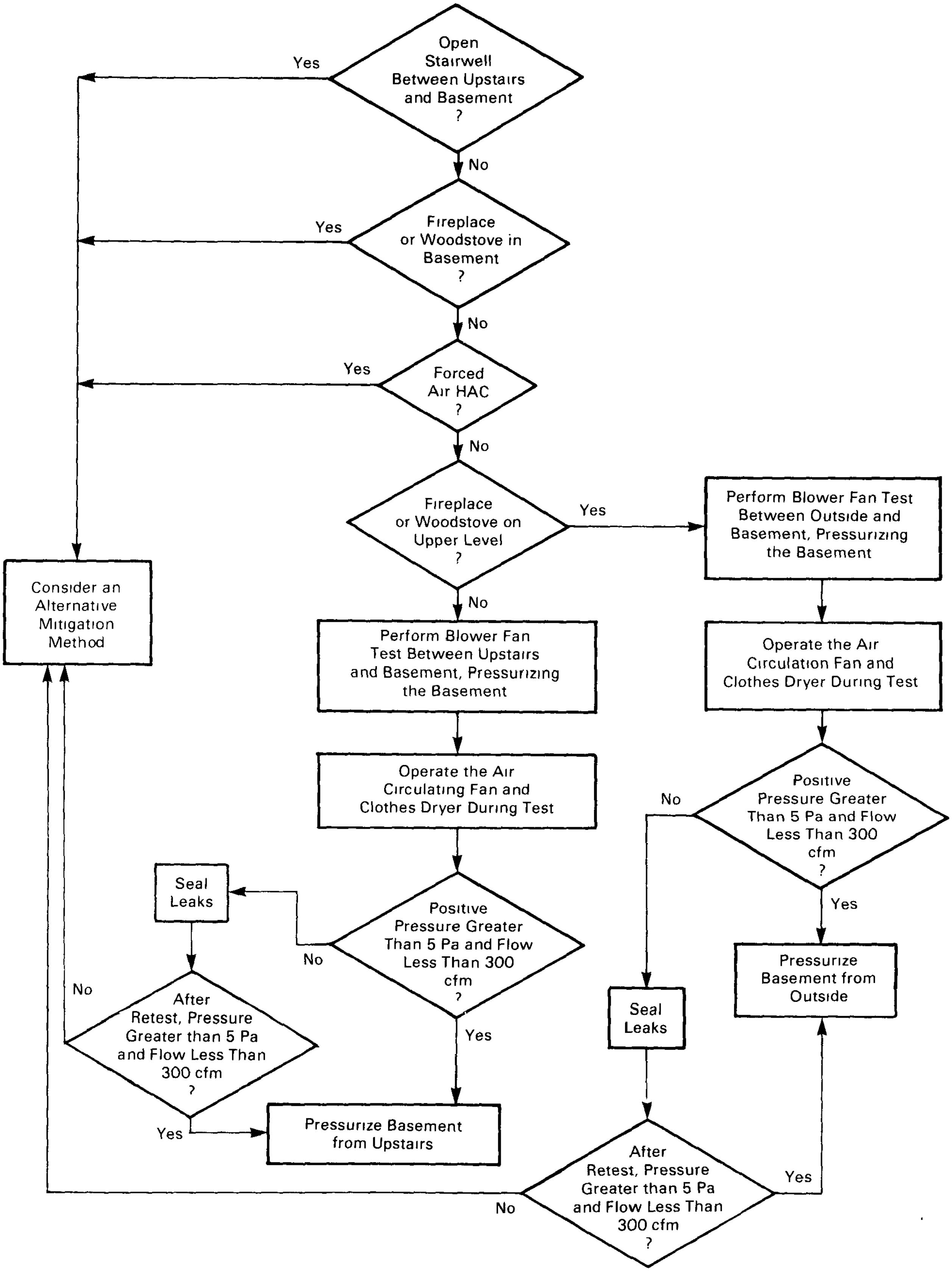
The principles of design are to maximize the performance of the system while minimizing both the installation and the operating costs. For a soil ventilation system, the soil gas is prevented from entering the house either by directing it away from the house by pressurizing the soil under the slab or by collecting it in a ventilation system and exhausting it away from the house (preferably above the eaves). The bulk of EPA's experience has been with the latter type of ventilation system. Limited experience suggests that pressurization works well only in high permeability soils which allow sufficient air flow to dilute the radon under the slab without increasing the pressure to force more soil gas into the basement. The presence of a good aggregate layer may not be sufficient to ensure good movement of soil gas away from the house.

The construction details of the house will nearly always be important to the design of a mitigation system. The location of doors, windows, and other structures inside the house, the location of potential entry routes, the degree of wall and floor finish, the permeability under the slab, and, of course, the substructure type will all influence where the ventilation points can reasonably be located, and where they need to be located in order to maintain adequate sub-slab depressurization at all significant entry routes. Many of these features will also influence the location of the exhaust pipe for a ventilation system. If the house is a slab on grade with a highly finished interior, lack of access from the interior could suggest that the ventilation points be inserted under the slab from outside the house through the foundation wall below slab level rather than penetrating through the slab from inside the house (more studies are planned on this method).

6.2.1 *Primary Considerations*

For a depressurization system to be highly effective, it must treat all the soil gas entry routes in the substructure of the house. The most efficient system

Figure 7. Deciding whether to use basement pressurization (additional considerations are discussed in Section 10.5.2).



would maintain sufficient flow to direct the soil gas away from all the entry routes, but not sufficient flow to extract any excess indoor air through those same entry routes. Extracting excess indoor air adds to the operating costs both in energy to move the excess air and in an energy penalty for removing treated indoor air. Practically, some of these increased operating costs must be accepted in order to obtain an operating margin of safety in the design of the mitigation system. Since the natural driving forces which control the radon entry rate vary significantly from hour to hour and from month to month, the minimum fan speed required to prevent radon entry varies accordingly. At present, a mitigation system has not been developed with sensing and feedback controls to allow the speed of the fan to adjust to the current strengths of the driving forces. It is not currently known whether such a system would be practical or cost-effective. The present philosophy is to design the mitigation system to handle the most challenging set of circumstances that it is likely to experience during the annual cycle of variations.

For U.S. houses, the typical air exchange rate is in the range of 0.5 to 1.0 air changes per hour (ach). For a house with 1500 ft^2 of floor space and exchange rate of 1.0 ach, the infiltration rate is 200 ft^3 per minute (cfm). Some researchers have estimated that as much as 20% (5% is probably more typical) of the infiltrating air in some houses may be soil gas (i.e., infiltration below grade). In that case, the above example would have about 40 cfm of soil gas entering the house. An effective mitigation system would then be expected to handle at least 40 cfm of air flow. However, to treat the entire slab from a central point would probably require a greater flow, because the average pressure difference imposed across the slab to compensate for the naturally occurring driving forces must be higher. The imposed pressure difference decreases significantly from the central ventilation point to the perimeter of the house. In fact, the induced pressure due to the mitigation system must compensate for the natural driving forces at the most remote entry point. Consequently, entry points closer to the ventilation point will experience pressure differences considerably in excess of that required to compensate for the natural driving forces. The amount of excess indoor air extracted through the nearby soil gas entry paths increases with the increased pressure difference imposed along the gas flow paths. Consequently, if the sub-slab is to be ventilated through a single central point, the required fan capacity will probably exceed the rate at which the soil gas initially enters. This emphasizes the importance of sealing all entry routes to minimize the amount of house air that is removed.

6.2.2 *Phased Approach*

Often, it will be cost effective to select and design the radon reduction system for installation in phases. It will sometimes make sense to begin by installing the simplest, least expensive mitigation which offers reasonable potential for achieving the desired radon reductions. The system could then be expanded in a series of pre-designed steps, until the desired degree of reduction is achieved. The alternatives to this phased approach include performing increased diagnostic testing beforehand (at an increased cost) to ensure an improved initial system design, or installing a more extensive (and more expensive) mitigation system to begin with, to ensure that radon levels will be sufficiently reduced on the first try.

The cost effectiveness of the phased approach, versus efforts to reduce phasing by increased diagnostics and/or more extensive initial systems, will have to be determined case by case. This decision will be based on the judgment of the diagnostician/mitigator and the desires of the homeowner. In practice, some phasing will sometimes be unavoidable. Even with increased diagnostics and more extensive initial systems, the initial installation still might not achieve the desired reduction.

Some of the initial, simple steps that homeowners might take can be considered the first phase of mitigation, to the extent that such steps are permanent (e.g., closure of entry routes and airflow bypasses). A more serious effort of sealing entry routes as a reduction technique will often turn into the first phase of the mitigation technique (sealing as a technique is discussed in Section 10.4). A few other specific examples of phasing are suggested below for illustration.

1. A house having slightly elevated radon levels (20 pCi/L or less) has an open sump with substantially elevated levels inside the sump, suggesting that the sump could be the predominant source. Sealing the top of the sump and passively venting the enclosed sump to the outdoors could be implemented prior to any more extensive measures. Additional known entry routes would also be sealed.
2. A house with slightly elevated radon levels has only a partial drain tile system. If the drain tile is easily accessible, ventilation of the partial tile system could be applied readily. This effort would be encouraged if good aggregate were known to exist under the slab. If this installation were not fully successful, sub-slab ventilation points could be added where the drain tile was missing.
3. A house for which sub-slab suction would appear to be the preferred approach has a basement which is partially finished. Unless there is an obvious major source in the finished section,

it might be both cost effective and convenient for the homeowner if an initial sub-slab suction system is installed with ventilation points only in the unfinished portion. If this system turns out to be insufficient, then appropriate ventilation points can be added in the finished section of the basement.

4. A basement house with hollow-block foundation walls and high radon levels might ultimately require ventilation of both the sub-slab and the wall void network. The initial installation might be designed to depressurize the sub-slab, with treatment of the wall voids added later, if needed.

Section 7

Installing a Mitigation System

Some mitigators use local contractors to install the radon reduction system in a house. The installation process should be supervised by the diagnostician/mitigator, or by someone else familiar with the principles of the system being installed. While some steps might seem inconsequential to an installer who is unfamiliar with the principles of the technique, these steps might be very important in the system's ultimate performance. For instance, if an objective is to mortar closed the partially visible open top voids in a block foundation wall, then it is important that the mortar be forced all the way under the sill plate so that the entire void is closed. Mortaring only the exposed part of the void would greatly reduce the effectiveness of the closure. It would be very difficult to check on the completeness of this mortaring job, or to get mortar into any unclosed segment of the void under the sill plate, once the mortar in the visible part of the void had hardened.

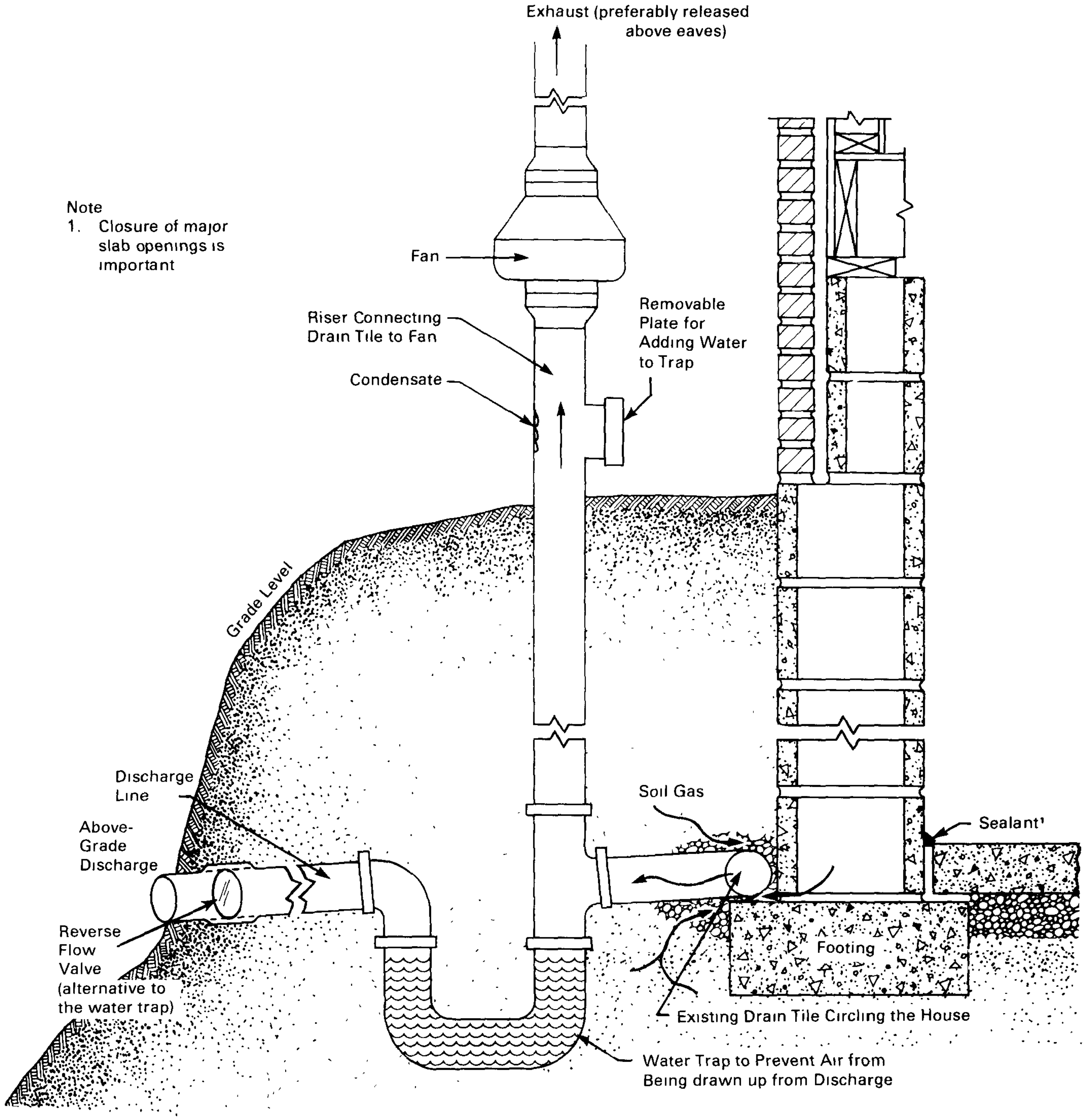
As a practical matter, many detailed decisions regarding the precise configuration of the system will often be made during installation. For example, unanticipated obstacles might be encountered as the installers drill or dig into places the diagnostician could not see during inspection. A run of piping for an active soil ventilation system might not fit around existing features of the house exactly as visualized during initial design. Therefore, the supervisor of the installation crew must ensure that any detailed adjustments made during the installation phase are consistent with the principles of the technique, so that performance is not reduced, and installation is consistent with the desires of the homeowner for a neat, attractive appearance.

7.1 Drain Tile Ventilation Installed Outside

Drain tiles are pipes intended to collect water and drain it from around the foundation of a house. Because the drain tiles are located near the floor/wall joint, a prominent soil gas entry route, ventilation of these pipes is often very effective in reducing radon levels in the house. Sometimes drain tiles also extend under the slab. If the tiles extend under the slab, or if the communication under the slab is good, tile ventilation can effectively treat the entire sub-slab region. Water collected by the tile system will be drained to a point above grade, to a dry well, or to an interior sump. If an extensive drain-tile network is present, then drain-tile ventilation should be one of the first reduction techniques considered. Even if the drain-tile loop is not complete, this technique can be very effective in reducing the radon levels.

First consider the situation in which the tile system drains to a point above grade. Such an installation is illustrated in Figure 8. The circle beside the footing in Figure 8 represents the cross section of a drain tile which, ideally, forms a continuous loop around the perimeter of the house. The ventilation system, consisting of the trap and riser with the fan, is installed by the mitigator in the discharge line that drains the water from the collection loop. The trap ensures that the fan ventilates the loop near the footings rather than drawing air from the discharge point. The removable plate on the riser allows the homeowner to add water to the trap during dry periods. A water hose connection or even a permanent water line could be installed. The permanent water line should be installed underground to avoid freezing. If the trap becomes dry enough to allow air to pass through, the ventilation system will become ineffective. To decrease the likelihood that the trap will dry out, the vertical arms of the traps should be made as long as practicable. A useful alternative to the water trap is to install a reverse flow valve on the above-grade discharge end of the drain pipe. This reverse valve eliminates the concern over the trap's drying out. Some drain-tile systems have more than one discharge line. All discharge lines must have traps installed. So long as all the tiles are connected, only one fan is required. Note that the trap must always be on the drain discharge side of the fan. In fact, while the traps must be installed in the drain discharge lines, the fan can be installed as shown in Figure 8 or anywhere in the loop. However, it is usually cheaper to install the fan at the same location as the trap. Although one is not shown in the figure, it is advisable to install an alarm to announce if the trap goes dry, if the reverse valve fails, or if the fan becomes ineffective for any other reason.

Figure 8. Drain tile ventilation where tile drains to an above-grade discharge.



After the discharge line is exposed, a section must be removed to allow the trap and riser to be inserted. The trap, riser, and connections must be airtight so that the effectiveness of the fan is not reduced. Consequently, the trap and riser cannot be made of perforated pipe like the drain tiles. The trap can be purchased as a unit or constructed from elbows and tee's cemented together. The longer the vertical arms of the trap, the longer the time required for all the water to evaporate.

The distance from the house to install the trap and fan depends on aesthetics (whether the riser can be hidden by shrubbery, etc.), whether the noise of the fan can be isolated by distance, and the length of electrical cable required to run the fan. Consideration should also be given to whether people will spend much time in the vicinity of the exhaust. If so, the exhaust should be elevated above breathing level to aid in dispersing radon-laden gas or made inaccessible by shubbery, etc. If the exhaust is near the house, it is recommended that it be extended above the eaves. Whether the exhaust is mounted on the roof or away from the house, consideration should be given to the possibility that it could become covered either by debris or by snow and ice. The fan should be durable and resistant to weather conditions, capable of sustaining a pressure differential of 0.5 - 1.0 in. WC (124 - 248 Pa) at a flow rate of 150 - 200 cfm (0.071 - 0.094 cms).

7.2 Drain Tile Ventilation Installed in a Sump

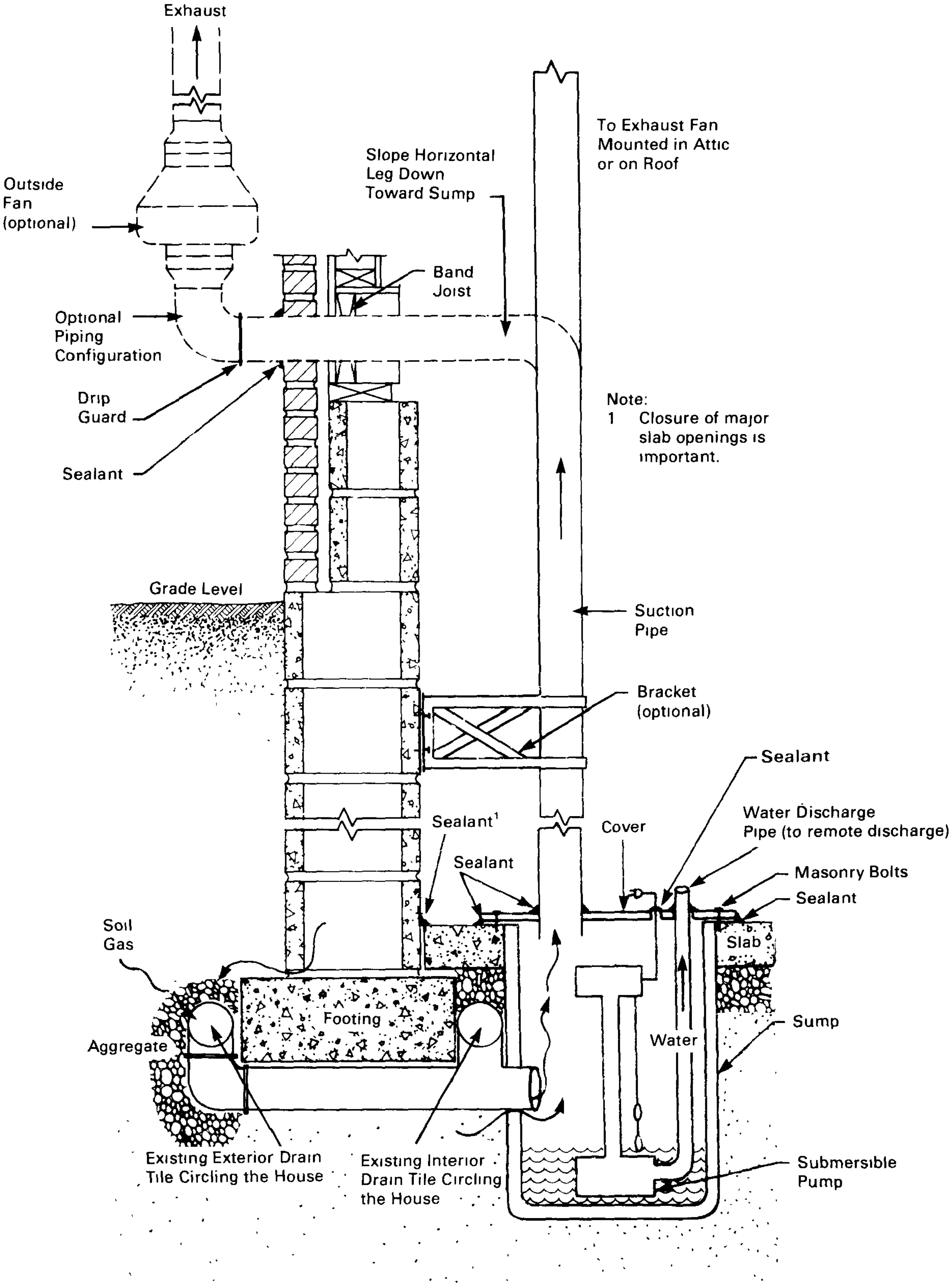
Drain tile ventilation systems are installed somewhat differently when the tiles drain to an interior sump. Figure 9 illustrates such an installation. Although the figure shows the tile loop outside the footings, it may be located on the inside or both. If there is a history of water problems, a sump pump is likely to have been installed already. However, just because a sump is present does not necessarily mean that the exterior tiles drain into the sump. If the homeowner does not know whether the tiles drain into the sump or if additional exterior drain lines exist, their presence can be learned only by observation and conducting tests such as those using tracer gases or a plumber's snake. When the sump is covered, as shown in Figure 9, it is recommended that the existing sump pump be replaced by a submersible pump if such a pump is not already present. The submersible pump is recommended to avoid problems with corrosion of the pump motor and/or for ease of sealing the sump.

For the sump ventilation to be effective, the cover must be sealed airtight. Figure 9 shows a flat cover with penetrations. This cover can be made of sheet metal, plywood, or another suitable material. It will usually be convenient to fabricate the cover in two pieces so it can be fitted around the pipes which penetrate the sump. The possibility of needing to service the sump pump should be taken into consideration when designing the sump cover. Caulk and sealants can be used to ensure an airtight fit. The cover should be secured to the floor with masonry bolts. If water sometimes enters the sump from the top of the slab, then an airtight seal that allows water to drain must be installed. A drain with a water trap can be used for this purpose (EPA88a, Br87, Bro87a, Sc87). While water traps are relatively simple to install, they are effective only so long as they retain water. Alternatively, waterless traps are also available. As an alternative to constructing a sump cover, complete airtight sump units can be purchased to replace leaky, incomplete sumps, or where sump holes have been left for sump installation at a later date.

The ventilation pipe that penetrates the sump cover must extend up through the house shell to exhaust the soil gas extracted through the sump. Figure 9 shows two alternative exits for the exhaust pipe. In one, the pipe penetrates the house shell through the band joist and extends up outside the house. It is recommended that the exhaust be above the eaves of the house and away from windows in such an instance. In the other case, the pipe extends up through the house to the roof and exhausts the soil gas above the roofline. Where the pipe penetrates the roof, the fan should be mounted either in the attic or on the roof. Mounting the fan on the roof is preferable because both noise and the risk of leaking radon back into the house are reduced (no part of the pipe inside the house is under positive pressure). However, the roof-mounted option is more expensive and exposes the fan housing to the elements.

To reduce pressure losses in the pipe, the number of turns and length of pipes should be held to a minimum. Unfortunately, one has limited control over the location of the ventilation point in the sump. Consequently, the least tortuous path acceptable to the homeowner should be chosen. Typically, the homeowner will insist that the exhaust pipe pass through an upstairs closet. The pipe must be supported with mounting brackets either on the basement wall or at the floor penetrations. Horizontal piping runs should be supported by clamps or brackets attached to floor joists. Pipe joints must be completely airtight and should be leak tested. Further, horizontal runs of pipe should be sloped slightly so that condensed water can drain to the ground or to an outside drain. It is imperative that no traps or low points exist in the line. If a natural trap exists in the exhaust line, condensed water can collect and block the air flow.

Figure 9. Drain tile ventilation where tile drains to sump.



7.3 Sub-Slab Ventilation Installed Through the Floor

While drain tile ventilation may be the first choice in some circumstances, sub-slab ventilation is by far the most widely applicable soil ventilation technique. In reality, the two techniques represent variations on the principle of diverting soil gas from entering the substructure by changing the direction of movement of the soil gas. The sub-slab ventilation technique attempts to treat the entire region under the slab, taking particular advantage of the communication in the aggregate bed when one is present. A typical penetration through the slab directly into the aggregate bed is illustrated in Figure 10. Options for exhausting the soil gas above the eaves of the house include either penetrating through the roof from inside the house or extending the exhaust pipe outside the house. The options for installing the exhaust are very similar to those discussed above for sump ventilation (Figure 9).

The greatest concern with sub-slab ventilation arises when the communication under the slab is poor. However, the inability to measure air movement under the slab is no guarantee that sub-slab ventilation will not work. It has been demonstrated on several occasions that sub-slab ventilation can be effective in spite of the failure of an air communication test. A similar instance recently occurred with four slab-on-grade houses in Dayton, Ohio. These houses have heating ducts under the slab which appear to block communication. However, installed sub-slab systems were effective.

If an unused sump is present with openings under the slab and communication under the slab is good, the simplest option is to cover and ventilate the sump. If no sump is present, or communication tests indicate that multiple ventilation points are needed, then it is necessary to make holes in the slab. A number of methods are available to do this. The difficulty of making a hole through the slab is determined by the size of the hole that is needed. In EPA's experience, the ventilation system usually consists of 4-in. PVC pipes.

The easiest way to cut holes of this size is with a coring drill, which removes a core of the proper size for the pipe to fit neatly in the hole. Holes cut this way are perhaps easier to seal around the pipe. Coring drills with diamond bits (and the operators to handle them) can usually be hired from local construction firms. The bits of these drills are usually continuously cooled with water and, consequently, tend to be somewhat messy for use in finished living areas. It is practical in most cases to make a 4-in. hole using small bits. For instance, a circular pattern can be made by drilling small (1/4 to 1/2 in.) holes with a masonry drill and then knocking the center out with a chisel or a rotary hammer (Sa87). If a larger hole (1 to 2 ft^2) is required, a jackhammer may be the proper tool. Although electrically driven hammers can be rented, they may not always be powerful enough to break through the concrete. In some cases a more powerful jackhammer handled by an experienced operator may be required. A jackhammer might be necessary when the sub-slab communication is so poor that an excavated pit around the ventilation point would improve the pressure field extension (EPA88a). This type of installation is illustrated in Figure 11. In this case a 2-ft^2 hole is made in the slab and a large cavity is excavated in the soil. Alternatively, if a core drill and 4-in. bit are available, eight 4-in. adjacent holes forming the outline of a 1-ft square can be quickly opened. The center can then be knocked out to open a 1-ft^2 hole. The pit is covered with plywood and the vent pipe installed with the end extending slightly into the pit. The hole in the slab is then repoured to seal the vent pipe in place. Note that the plywood is supported by aggregate and that the hole in the concrete was jackhammered with a slope around the edge so that the weight of the new concrete will ultimately be supported by the original slab. An alternative to leaving a large open pit would be to fill the pit with coarse aggregate (2-in. stone). The permeability of coarse aggregate is high enough that the pit's effectiveness would not be compromised significantly. If aggregate is used, it should be covered with a material such as polyethylene liner to keep wet concrete from plugging the aggregate. The vent pipe would penetrate the film. The purpose of the pit is to distribute the region of depressurization over a larger surface of the soil resulting in better extension of the pressure field into the surrounding soil. The diagnostician/mitigator and homeowner must weigh the advantages and disadvantages of aesthetics and cost of sub-slab ventilation pits against additional ventilation points installed in holes drilled in the slab. The type of pit excavation just described is expensive because it is labor intensive. If soil and not stone exist under the slab, it is practical to excavate a sizable pit through a 4-in. drill hole. In this case pits are probably less costly than extra ventilation points.

Piping used to construct ventilation systems should be made of plastic such as PVC (thin wall) sewer pipe for durability, as well as for corrosion and leak resistance. Flexible hose such as clothes dryer vent hose is not recommended because it is easily damaged and not conducive to draining water that condenses in the line. It will tend to sag under the weight of condensed water, forming traps which could result in reduced effectiveness of the ventilation system. PVC pipe is readily sealed with the appropriate cement familiar to contractors. It is critical that the joints in the system be airtight. Before a fan is installed in a line, it should be leak checked since the housings of many fans are not designed to be airtight. All the joints in a system including those

Figure 10. **Sub-slab ventilation using pipes inserted down through slab.**

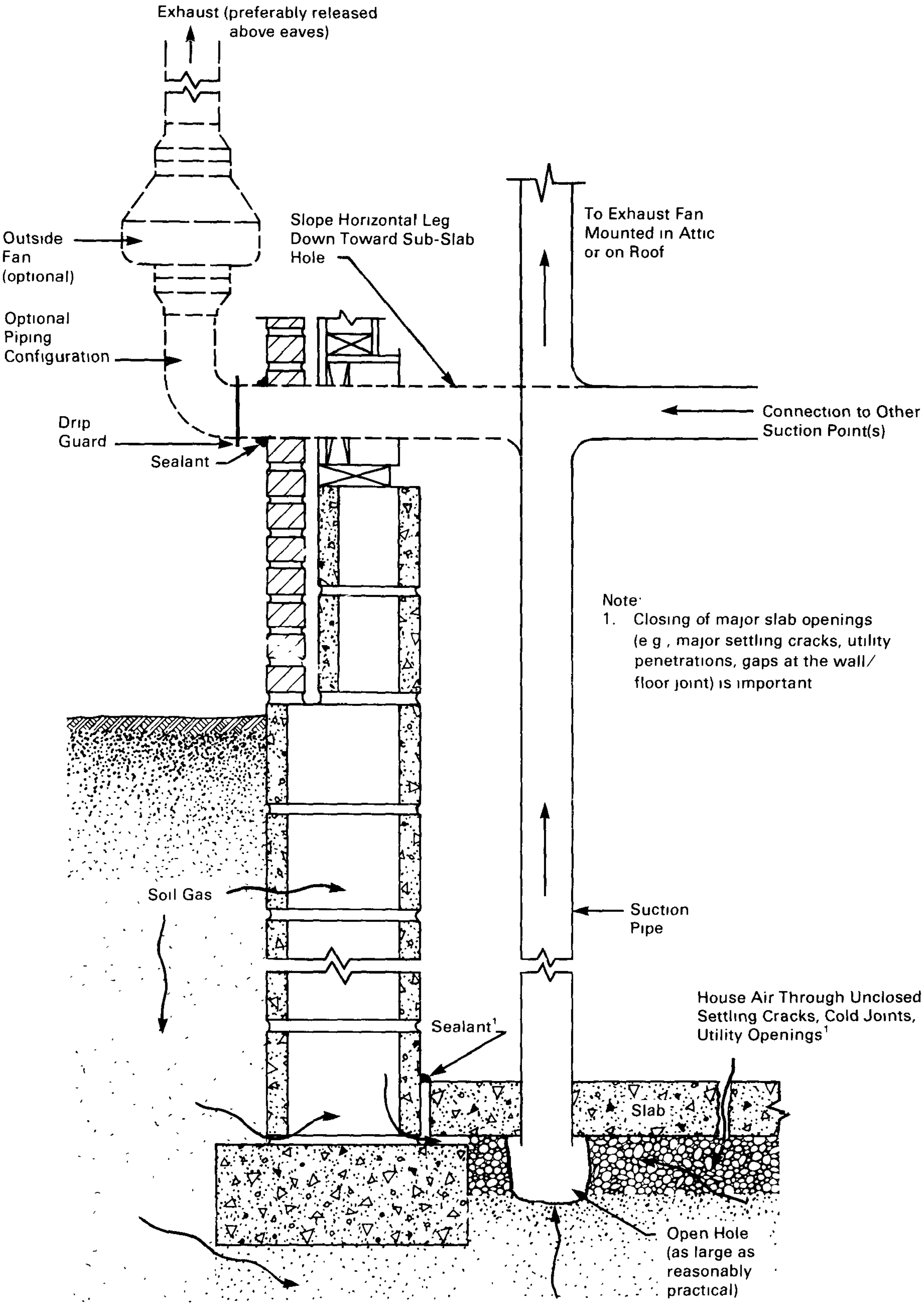
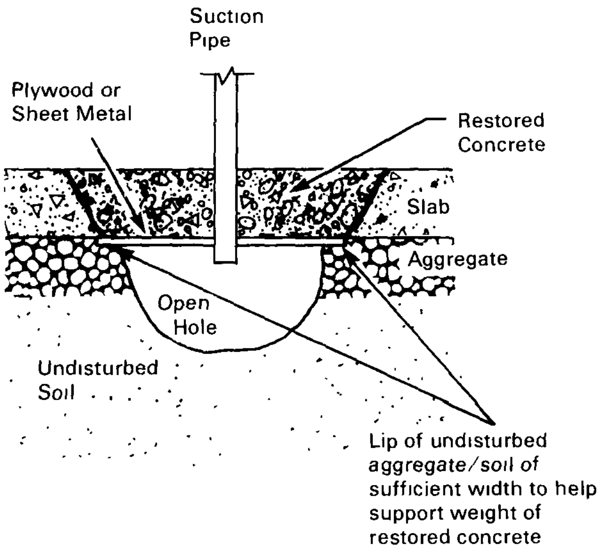


Figure 11. One method for creating open hole under sub-slab depressurization point when slab hole has been created by jackhammer.



where the vent penetrates the slab should be leak tested. If any part of the line on the exhaust side of the fan is indoors, it should be carefully leak tested because it will release radon in the house if it leaks. For this reason, the fan should be mounted in the attic, on the roof, or outside whenever possible. Leaks on the intake side of the fan will reduce the effectiveness of the system by reducing the capacity of the system to depressurize the soil.

The size of the pipe can also influence system performance. If the diameter of the pipe is too small, the fan cannot depressurize the soil because of increased pressure drop in the pipe. Long runs of pipe or turns and elbows have a similar effect. Since small diameter pipe takes up less space and is more easily hidden, it my be desirable to use small pipe in some instances. If using smaller diameter pipe is contemplated, the pressure drop at realistic flow rates should be computed to estimate its effects on system performance. In all cases, care should be taken to ensure adequate support for all pipes and fans installed. All fans should be mounted vertically to prevent water from collecting and all horizontal runs of pipe should be sloped toward the sub-slab vent point so that condensed water can drain back to the soil. If there are any low points in the line that cannot drain properly, a special drain with a water or waterless trap or a reverse valve must be installed to prevent accumulation of water that could impede performance. If the exhaust line penetrates through the band joist, the exterior penetration should be carefully sealed and a drip guard installed to prevent rainwater's running down the pipe and damaging the band joist. Consideration should be given to preventing the exhaust from blockage by birds' nests, bees' nests, or debris. Vents through the roof should be capped with a rain guard that does not impede flow. The possibility that the outlet could be covered by snow accumulation or drifts should also be considered. In cold climates, insulation might be needed on the exhaust pipe to prevent ice from blocking it.

7.4 Wall Ventilation

Although wall ventilation is discussed here as a stand-alone mitigation technique, it finds its widest application as a supplemental aid to methods such as sub-slab ventilation. Wall ventilation would be a preferred technique only in special situations such as no measurable communication under the slab or with the walls, no apparent entry routes in the slab, and high radon levels in the walls. For wall ventilation to be applicable, all major wall openings must be closed and there must be no major slab entry routes away from the wall. There are two types of wall ventilation installations: point-penetration systems and baseboard duct systems. Baseboard duct systems are more expensive and find fewer applications than point-penetrations systems.

Point-penetration systems attempt to ventilate the wall void networks by inserting individual pipes into void cavities at various points. Each block wall, interior or exterior, that rests on a footing should have at least one vent pipe. The fan can be oriented to either pressurize or depressurize the wall void network. Because of their high porosity, untreated block walls often require high flow rates to depressurize the void network, resulting in depressurization of the basement. Problems with backdrafting of combustion appliances and increased radon flow through slab entry routes can occur when the basement is highly depressurized by wall ventilation. There is some concern that pressurization of the wall might increase radon entry through some points. There have been some instances in which sub-slab pressurization increased radon entry (Se87), thus illustrating the potential for adverse effects of pressurization, even in block walls. Concerns also exist that wall or sub-slab pressurization could increase indoor air levels of other contaminants such as termiticides or biological components. Moisture condensation and freezing around footings is another potential concern with wall pressurization. Although the Agency's experience is limited, EPA has had some success in reducing radon levels by both pressurizing and depressurizing block walls (He87a, Sc88).

Usually one block wall does not communicate very well with the wall sharing a common corner. Consequently, at least one ventilation point per wall is recommended. EPA's limited experience with block wall ventilation suggests installing at least two ventilation points in a wall that is longer than about 25 ft (He87a, Sc88). Ventilation points in a wall are typically placed to treat equal surface areas (one point located in the center, two points located a quarter of the way from each end). Walls with fireplaces might need an extra vent point. If diagnostic measurements have identified certain walls as having particularly elevated radon concentrations, additional ventilation points might be advised for those walls. If the wall ventilation system is supplemental to a sub-slab system, only the identified "hot" walls may require a ventilation point. Wall ventilation points should be placed near the bottom of the wall to enhance the treatment there.

For installation, a hole will be drilled or chiseled through one face of a single block into one of the cavities of the block. The ventilation pipe inserted into the block cavity must be well sealed to prevent air leakage around the pipe. Caulk or asphaltic sealant should be worked into the gap to form a good seal. The considerations relating to sizing the pipes are same as those for the other ventilation techniques.

7.5 Methods of Closing the Top Row of Blocks

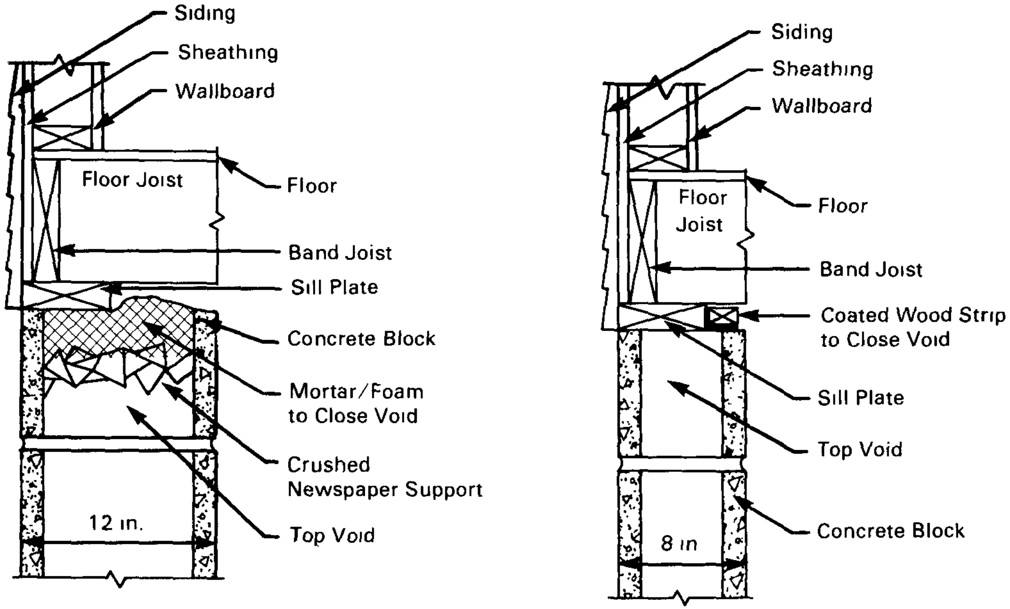
Closure of major openings is important in all soil ventilation systems. It is especially important with wall ventilation because the flow rates through the walls tend to be high anyway. Open voids at the top of the wall make wall ventilation impractical if they cannot be closed. Fortunately, in many areas, the building code requires a row of solid cap blocks. When cap blocks are not present, closing the openings can present quite a challenge.

If the sill plate leaves sufficient access to the openings (perhaps 4 in.), the recommended procedure is to stop each void with crumpled newspaper (or some other suitable support) and fill it with mortar to a depth of at least 2 in. The mortar must be forced under the sill plate and worked to ensure complete sealing of the hole. This procedure is illustrated in Figure 12a.

If the sill plate allows sufficient space (1 to 3 in.) to force newspapers into the void, but not sufficient working space to ensure that the mortar completely fills the void, an expanding foam such as a single-component urethane foam can be substituted for the mortar. These foams are available in aerosol cans or, for commercial applications, can be extruded through a hose and nozzle. Such a void is also illustrated in Figure 12a.

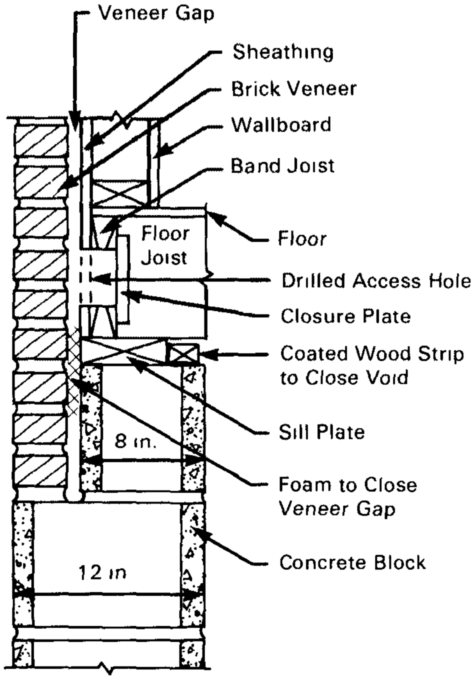
If the top of void is not sufficiently accessible to force newspaper or some equivalent supporting material into the opening, closure becomes much more difficult. A hole could be drilled in the block to inject the foam; however, the foams tested by EPA were not sufficiently self-supporting to remain in the top of the void while they cured. In some cases supports for the foam can be improvised. For instance, it has been suggested that balloons be inserted into the cavity through drilled holes and then inflated to support the foam. It has also been suggested that dowel pins be inserted through a series of small, closely spaced holes to support the expanding foam. Another suggestion was to saw out the first mortar joint to a depth of a few inches, allowing plastic, cardboard, or sheet metal supports to be inserted through the slots. Although some of these techniques could be made to work, they are judged to be too expensive to be practical.

Figure 12. ***Some options for closing major wall openings in conjunction with block wall ventilation.***



a) Closure of top void when void is reasonably accessible.

b) One option for closure of top void when a fraction of an inch of the void is exposed.



c) One option for closing gap between exterior brick veneer and interior block and sheathing.

When the top void was inaccessible, EPA has successfully used the sill plate to close the tops. In cases in which the openings along the edge of the sill plate were sufficiently small, a bead of caulk was used to seal between the sill plate and the block. When the openings along the edge of the sill plate were too large to be caulked, but too small to work mortar into, a wood strip with caulk on two sides was nailed to the edge of the sill plate covering the openings. Both the edge along the block and the crack between the strip and the sill plate were then caulked. This technique is illustrated in Figures 12b and 12c. Although this technique is less effective than using foam (note that the outside edge of the sill plate is not accessible for caulking), it is less expensive and appears to be adequate in many cases (He87a, Sc88).

7.6 Closing the Gap Behind Brick Veneer

In houses with exterior brick veneer, a gap usually exists between the veneer and the sheathing, as well as between the veneer and the block behind it. This situation is illustrated in Figure 12c. This gap could reduce the effectiveness of wall ventilation systems by allowing air to flow into or out of the block void network, thus negating the wall depressurization or pressurization. While it is not clear how often this gap seriously limits the performance of wall ventilation, it is clear that effective wall ventilation can be accomplished in some cases without closing this gap. For at least one house in an EPA study an effort was made to close the veneer gap by drilling through the band joist and extruding urethane foam into the gap. This procedure is illustrated in Figure 12c. There was no clear evidence that the foam improved the performance of the ventilation system.

Obvious holes and cracks in the walls should be closed using grout, caulk, or other sealants. Examples are holes around utility penetrations, chinks in blocks, and mortar joint cracks where pieces of mortar are missing. Pores in the concrete blocks represent a significant amount of air leakage. Coating concrete block walls has not been a standard practice when installing a ventilation system. However, when installing a wall ventilation system on cinder block walls it is advisable to coat the wall to close the pores (pore closure will also help with concrete block walls). Cinder blocks are more porous than concrete blocks. For discussion of the options for closing the pores in a block wall see Reference EPA88a.

Openings in the slab should be closed to assist a wall ventilation system in extending the pressure field under the slab. Of particular concern is the wall/slab joint. Sumps and major cracks should be closed, while floor drains should be either trapped or closed.

Section 8
Post-Installation Diagnostics

Diagnostic measurements should be performed to assess whether the system is performing mechanically the way it is supposed to, and to identify further modifications that might need to be undertaken to improve radon reduction.

Post-mitigation diagnostic tests should also be conducted to ensure that the reduction system is operating properly. While such diagnostic testing will vary from mitigator to mitigator, some key tests are:

- Visual inspection of the system to ensure that it has been installed properly. For active soil ventilation systems, one particularly useful tool is a smoke stick. A smoke stick releases a small stream of smoke which can reveal air movement. The smoke stick can be used, for example, to confirm whether pipe joints and slab/wall closures leak.
- Pressure and flow measurements in the pipes of active soil ventilation systems and heat recovery ventilators. Such measurements can reveal installation and operating problems of various types.
- Sub-slab pressure field measurements, where a sub-slab soil ventilation system has been installed. Such measurements will reveal whether the system is maintaining the desired pressure reduction underneath the entire slab. These measurements can be made with a micromanometer or with a smoke stick.
- Grab sample radon measurements in individual pipes associated with active soil ventilation systems (to identify "hot spots" around the house), and grab measurements to detect the location of soil gas entry routes not being treated by the current system.
- Flow measurements in the flues of existing furnaces, water heaters, and other combustion appliances when an active soil ventilation system has been installed, in order to ensure that house air being removed by the system is not depressurizing the house enough to cause back-drafting of the combustion appliances.

Section 9

Post-Mitigation Monitoring

9.1 Short-Term Monitoring

After the radon reduction system is installed, a several-day measurement of radon gas should be made to give an initial indication of the success of the system. Possible measurement techniques include charcoal canisters, E-PERMs, or continuous monitors. One or a few grab samples, by themselves, are not recommended for the purpose of determining reduction performance, because the 5-minute sampling period is considered to be too brief to provide a meaningful measure. If this initial short-term measurement indicates adequate reductions, then it should be followed up by at least one alpha-track detector measurement. As a minimum, the measurement should be made over 3 months (preferably during the winter) to evaluate sustained system performance. In the event that the mitigation system is installed doing the spring and a 3-month alpha track measurement indicates adequate reductions, it is recommended to begin an annual average, measurement in the form of quarterly alpha track measurements. An effort should be made to have winter months comprise one quarterly measurement. This quarter should represent the most challenging period for the mitigation system.

9.2 Long-Term Monitoring

After all modifications/improvements to the radon reduction system have been completed, a radon measurement of longer duration than that described above is recommended. This longer term measurement will provide a more definitive picture of how the occupants' exposure has been reduced over an extended term by the final installation. Since the EPA guideline of 4 pCi/L is based upon an annual average exposure, this longer duration, post-mitigation measurement would ideally cover a 1-year period. A 12-month alpha-track measurement (or average of four consecutive quarterly tests) would give the most reliable measure of annual average exposure. However, the other methods for making "follow-up" measurements, as described in the EPA protocols (EPA87a), can also be considered. These other methods include charcoal canisters, E-PERMs, or continuous monitors, used once every 3 months during the year. Grab samples are never adequate for final characterization of reduction technique performance.

A disadvantage of a 12-month track-etch measurement is that the level of performance would not become known for a year after installation. This delay is unacceptable. If the technique is not providing adequate performance, corrective action should not be delayed for a year. Therefore, it is recommended that the initial longer duration, post-mitigation measurement be a 3-month alpha-track or E-PERM measurement. Although it is preferred that the test be performed under the challenging conditions of cold weather, it is not recommended that the test be postponed several months. However, it is recommended that measurements be performed during cold weather at the first opportunity. If the results of this winter measurement are below 4 pCi/L, it is probably reasonable to assume that the annual average levels in the house will be below 4 pCi/L. If the results of the winter alpha-track measurement are above 4 pCi/L, then a decision concerning further action is required. If the radon level is sufficiently high, immediate improvements to the mitigation system should be considered. On the other hand, if the radon concentration is only slightly above 4 pCi/L, it is possible that the annual average might be below 4 pCi/L. The objective should be to achieve as low a level as practicable.

The positioning of measurement devices inside the house, and other considerations in the use of the various measurement techniques, should be consistent with EPA's monitoring protocols (EPA86b). Initial, short-term measurements should be made in the basement under closed-house conditions, in accordance with the "screening" protocols (EPA87a). Final, long-term measurements should be made both upstairs and downstairs under normal living conditions, in accordance with the "follow-up" protocols (EPA87a). It is important that both the pre- and post-mitigation measurements be made using the EPA protocols, so that the results will be comparable.

The above discussion addresses measurements made immediately after, or within the first year after, installation of the system, for initial verification of system performance. Homeowners would be well advised to make periodic measurements on a continuing basis, after these initial measurements are completed, to ensure that system performance does not degrade over the years. An ideal approach would be to conduct a single alpha-track measurement each year in the primary living space (or, if preferred, in the lowest livable area of the house). The alpha-track detector could be exposed for the entire 12 months, to provide a measure of the annual average exposure. Some homeowners might consider it more practical to conduct a 1-year alpha-track measurement every third year or so. The more frequent monitoring would be appropriate for houses that initially had high radon levels (greater than 100 pCi/L) and, consequently, the potential for significant health risks over a short period of time should the mitigation system fail.

Section 10
Additional Radon Reduction Techniques

The preceding discussion addressed the overall approach for implementing radon reduction measures in houses as well as detailed descriptions of the most frequently used reduction techniques. The following discussion summarizes some of the key features regarding a few of these techniques, but mainly describes additional reduction techniques that are less frequently applied. Passive soil ventilation is an attractive technique whose practicality remains to be demonstrated. Crawl-space ventiliation, house ventilation, and sealing are further developed because of their growing importance as mitigation techniques. The topics of house pressure adjustments, air cleaning, removal of radon from well water, and radon reduction in new construction are discussed to form a complete list of techniques.

10.1 Passive Soil Ventilation

The active (fan-assisted) soil ventilation approaches discussed previously might also be considered for operation as passive soil ventilation systems. This would dictate that the system be designed to take full advantage of natural driving forces to create a draft in the exhaust pipe in the absence of the fan. This application could represent an example of the phased approach to design in which a system is first designed to operate in the passive mode with the option to add a fan later if needed. Since passive systems do not use fans, they avoid the maintenance requirements, noise, and operating costs associated with fans. These systems rely upon wind-related depressurization near the house roofline, and the thermal stack effect (during cold weather) to create a natural draft in the passive vent stack. Further work is needed to develop and adapt solar energy techniques to enhance the natural thermal stack effect as a driving force for passive ventilation. The depressurization which can thus be established is very small, relative to that possible with a fan, and a very effective network for distributing this depressurization is needed if a passive system is to be able to maintain sufficient depressurization in the soil. Installation of such an effective network (e.g., a network of perforated pipe under the slab with a good layer of crushed rock) can be expensive if it is not already in place (e.g., in the form of sub-slab drain tiles installed when the house was built). In addition, since depressurization levels are so low, a passive system would be more likely to be overwhelmed when the house is depressurized by weather or occupant activities. The performance of passive systems could thus be more variable over time than that of active systems. In addition, passive systems can rarely if ever reduce radon levels to as low values as can active systems.

Insufficient data exist to permit a reliable assessment of the long-term performance and cost-effectiveness of passive systems. Thus, although the potential benefits of maintenance-free passive systems are apparent, their performance is too uncertain for them to be recommended until more information becomes available. If a fairly substantial piping network is already in place (such as sub-slab drain tiles), the ventilation system that is installed connecting to these tiles might initially be designed and operated in a passive mode to determine if passive operation is sufficient. However, performance should be monitored closely, and conversion to an active system undertaken if passive operation proves to be insufficient.

10.2 Crawl-Space Ventilation

Crawl spaces are a major type of substructure. Crawl-space houses have living space built over an enclosed area that is usually exposed earth. Even if the living space appears to be well separated from soil gas by the crawl-space volume, these houses often have elevated radon levels. In some cases the radon-laden soil gas is transported through the foundation wall into the house. More often, however, the crawl-space air contains high concentrations of radon, which enters the house through leaks in the floor. When the air circulation system has return ducts in the crawl space, this system can be a major transporter of radon into the house. This happens because the return ducts are often very leaky. When the return ducts are depressurized by the operation of the circulation fan, crawl-space air containing high radon concentrations flows into the return plenum and is transported to the outlet vents. This effect is especially pronounced when a part of the return duct and plenum has been formed by enclosing the floor joist with sheet metal. Much air can leak into these pan ducts. Although it is very difficult, if not impossible, to seal these leaky return ducts once they are in place, tape and caulking can be used to close those major leaks that are accessible.

The general strategy for reducing the radon levels in a crawl-space house is to isolate and ventilate. Isolation is accomplished either by sealing the interface between the living space and the crawl space, or by separating the soil from the crawl space using an impermeable film such as polyethylene. Ventilation is accomplished either by increasing the air exchange rate in the crawl space or by ventilating underneath the film.

In some cases, crawl-space air can be diluted adequately by opening the foundation vents. Even if the resulting natural (passive) ventilation is not sufficient, it may be possible to obtain the required radon reduction by actively blowing air from inside the crawl space to the outside using a fan. The foundation vents should remain open to provide adequate dilution. The primary drawback to this type of ventilation occurs when the crawl space cannot be allowed to freeze. In cold climates, the subfloor, water lines, and fuel lines passing through the crawl space have to be adequately insulated and, if necessary, heat traced. In some cases, the increased costs of heating might make this type of ventilation impractical. In other cases, the foundation vents may have to be closed and the crawl space depressurized by a fan. Even if the radon concentration in the living space were reduced significantly, the concentration in the crawl space would increase as a result of the depressurization. Therefore, this may not be an acceptable solution. An alternative approach would be to pressurize the crawl space by blowing outside air in. If the crawl space is well isolated from the living space, this pressurization can prevent radon from entering the crawl space. In practice, this technique appears to be another example of radon reduction by dilution. There is a danger that if the living space is not well isolated higher levels of radon will be forced into the living space.

For sub-film ventilation, the increased infiltration should be much less than when the foundation vents are open with no sub-film ventilation. Ventilation under a polyethylene film uses an approach similar to sub-slab ventilation. The intent is to collect and exhaust to the outside all the soil gas that might otherwise find its way into the crawl space or the house. In order to completely isolate the soil from the crawl space, it is necessary to either tape or bond the overlapped edges of the impermeable film, and to seal the edges of the film to the foundation walls. One method of attaching the film to the wall is to wrap the edges around wood furring strips and nail the strips either to the sill plate or to the foundation wall. The point of contact between the wall and plastic can then be caulked. Penetrations through the plastic film such as sewer, water, and fuel lines, as well as foundation piers must also be sealed by taping and caulking. The better the film is sealed, the less crawl-space air will be exhausted through the fan, resulting in increased infiltration of outside air and increased heating costs. In milder climates, effective sealing of the film may be less critical. Subliner ventilation has been tested on a number of occasions (Br87, Bro87b, He87b, Os87, Sc88, Si87). In many of these installations, perforated pipe networks were placed between the soil and the plastic film and depressurized. Although these systems appeared to work well in most cases, interpretation of the results was complicated by the fact that most of the houses had combinations of crawl spaces with other substructure types. Consequently, more than one radon reduction method was operating. More recently, in EPA's Tennessee Project (Py88) purely crawl-space houses have been successfully mitigated using subliner ventilation.

10.3 House Ventilation

Natural ventilation (opening of windows, doors, and vents) is a very effective, universally applicable radon reduction technique that can be readily implemented by the homeowner. During mild weather, there is essentially no cost for implementing this technique. If done properly, natural ventilation is consistently capable of high reductions, probably above 90% if a sufficient number of windows or vents are opened. The high reductions result because natural ventilation both reduces the flow of soil gas into the house (by facilitating the infiltration of outdoor air to compensate for temperature- and wind-induced exfiltration) and dilutes any radon in the house air with outdoor air which is almost radon-free. Proper implementation of natural ventilation involves ensuring that windows are open on the lower level of the house; opening windows on only the upper level might make radon problems worse by increasing the depressurization in the lower level. Also, windows should be opened on more than one side of the house, preferably on all sides, to provide proper cross-ventilation; under some conditions, radon levels might be made worse by wind-induced depressurization if windows are opened only on the downwind side. Windows and vents must remain open essentially all the time for continuous effectiveness. A special case is natural ventilation of the crawl-space house by opening crawl-space vents on all sides of the house, creating a pressure-neutralized buffer zone between the soil and the living area.

The primary shortcoming of natural ventilation is that extreme temperatures could make this technique impractical to use 365 days a year in most parts of the country, due to discomfort and/or increased heating (and cooling) costs during winter (and summer). Open windows can also compromise the security of the house. One possible way to reduce the discomfort and energy penalty would be to leave windows open only an inch or two during extreme weather, which would reduce the radon reduction effectiveness. In the case of crawl-space houses, the crawl-space vents could be left open all year if water pipes and the subflooring under the living area were adequately insulated.

If natural ventilation is used during the winter, heating costs might increase by as little as 10% (if windows are left open only slightly, or if a crawl space is ventilated), or by more than 300% if windows in heated living space are left wide open, which is generally not practical from a comfort standpoint. There would be a comparable increase in air conditioning costs in the summer. In view of the effectiveness and ease of implementation of natural ventilation, it is recommended that a homeowner whose house has elevated radon levels seriously consider this approach for as much of the year as possible, at least until some other radon reduction approach is implemented. Natural ventilation can also be used in conjunction with some of the other mitigation approaches.

Rather than relying upon natural air movement, forced-air fans can be used to provide a controlled amount of forced ventilation. For example, a fan could be installed to blow fresh air into the house continuously through the existing central forced-air heating ducts and supply registers, with windows and doors remaining closed. Alternatively, fans could blow air into the house through protected intakes through the side of the house, or could be mounted in windows. A fan could also be installed to blow outdoor air into a crawl space. Advantages of forced-air ventilation relative to natural ventilation include reduction or elimination of house security concerns that can arise when windows are left open. Also, the amount of fresh air entering the house could be controlled. However, a fan system will involve some initial capital cost, and a continuing cost for electricity to run the fan(s), which natural ventilation does not require. Forced-air ventilation can also result in the condensation and freezing of moisture inside exterior walls of humidified houses during cold weather. For a given increase in the ventilation rate, the increase in the heating and cooling costs will be the same for either natural ventilation or forced-air ventilation (without heat recovery).

Natural and forced-air ventilation would be expected to provide similar radon reductions for a given increase in ventilation rate, if the forced-air system effectively distributes the air (including sufficient air delivery to the lower levels of the house). The same reduction mechanisms would come into play in both cases; i.e., reduction of soil gas influx, and dilution. However, to achieve a comparable increase in ventilation using fans to match the natural flows which produce 90% radon reductions, the fans will probably have to provide at least 750 to 1,000 cfm of fresh air, and perhaps more, in a house of typical size and natural infiltration rate. By comparison, an individual window fan might move about 500 cfm, and a central furnace fan about 2,000 cfm. If the house shell is sufficiently tight, inward-blowing forced-air systems might slightly pressurize the house (or the basement), providing reductions above those with comparable natural ventilation.

With forced-air systems, it is crucial that the fan be oriented to blow outdoor air into the house, because fans operating to exhaust indoor air could depressurize the house and possibly increase radon entry rates. Typical ceiling-mounted whole-house fans on the market are designed to operate in the exhaust mode, exhausting house air into the attic. Whole-house fans are thus not currently recommended for radon reduction.

Heat recovery ventilators (HRVs)--also known as air-to-air heat exchangers--are forced-air ventilation systems intended to reduce the energy penalty and the comfort penalty associated with ventilation. The heated (or air-conditioned) house air--which would otherwise exfiltrate without any energy recovery when outdoor air is simply blown into the house--is exhausted through the HRV, transferring between 50 and 80% of its heat to the incoming fresh air. HRVs provide no greater radon reduction than a comparably sized ventilation fan without heat recovery. HRVs can be fully ducted, with supply and return ducts leading to different parts of the house, analogous to central forced-air furnace ducting. Alternatively, wall-mounted HRVs are analogous to wall-mounted air conditioners, without external ducting.

The applicability of HRVs for radon reduction will likely be limited to situations where only moderate reductions are needed. Due to the cost and commercially available capacities for residential HRVs, it is believed that no more than 200 to 400 cfm of HRV ventilation capacity might be installed practically in a house of typical size. This amount of ventilation is low relative to what might be achieved with increased natural ventilation, and could typically produce radon reductions of 50 to 75%. Thus, if an HRV were intended to serve as a stand-alone measure to achieve 4 pCi/L in a house of typical size and infiltration rate, the initial radon level in the house could be no greater than 10 to 15 pCi/L. Greater reductions can sometimes be achieved in tight houses (i.e., low natural infiltration rates).

HRVs will most likely be cost-effective, relative to comparable ventilation without heat recovery, only in areas with cold winters and/or hot, humid summers. High fuel costs and high HRV heat recovery efficiencies could also improve HRV cost effectiveness. For the HRV to be cost effective, the operating cost savings resulting from the reduced energy penalty must more than offset the initial capital cost of the HRV (and the cost of electricity to run the two fans). Where winters are not particularly cold, or summers particularly hot, it can prove less expensive to achieve the desired degree of ventilation simply by opening windows. It is recommended that, before a decision is made to install an HRV, the cost effectiveness of the unit for that part of the country be determined.

While the overall radon reduction performance of fully ducted HRVs is usually consistent with the increase in ventilation rate, the performance in different parts of the house cannot always be reliably predicted prior to installation based solely upon the anticipated increase in ventilation. Air and soil gas flows throughout the house apparently can sometimes be affected in a complex manner. Also, performance can be sensitive to proper balancing of fresh air inlet versus stale air exhaust flows. This balance can vary over time (due to dirt or ice buildup in the HRV core, to changes in wind velocity, or to changes in occupancy habits such as opening doors). The homeowner must conduct the maintenance that is required (e.g., cleaning or replacing air filters, cleaning the core, annual rebalancing of flows). A word of caution is in order; balancing HRVs is tricky, and only individuals thoroughly familiar with their operation should attempt balancing them.

HRVs are typically balanced such that the inlet and outlet flows are equal, which is the condition providing the best heat recovery performance. Under these conditions, the HRV will generally not reduce the influx of soil gas, an important mechanism for radon reduction in the cases of natural ventilation and forced-air ventilation without heat recovery. Balanced HRVs reduce radon by the dilution mechanism only. If the HRV is deliberately operated in an unbalanced mode, with the inlet flow being greater than the exhaust, it could contribute to neutralization of the pressure between indoors and outdoors (or perhaps even to pressurization of the house), reducing soil gas influx. Unbalanced operation would reduce the energy efficiency of the system. There are not sufficient data to confirm whether such unbalanced HRV operation--or whether HRV ducting configurations designed to pressurize a basement--can consistently improve HRV radon reduction performance.

10.4 Sealing

The term "sealing," as commonly used, can have two different meanings from the standpoint of this document. In the first meaning, sealing refers to the treatment of a soil gas entry route into the house in a manner which provides a true gastight physical barrier to soil gas. Such a barrier is intended to prevent the convective movement (and sometimes the diffusive movement) of soil gas containing radon from the soil into the house through the treated entry route. In the second meaning, the term is used to refer to treatment of entry routes in a manner which prevents most gas flow through the route, but is not truly gastight. Such treatment is referred to in this manual as "closure" of the entry route, rather than true sealing. As discussed later, the purpose of the entry route treatment determines whether true sealing is required, or whether simple closure is sufficient. True gastight seals are difficult to establish and maintain.

Sealing of all soil gas entry routes is difficult and challenging. Many different sealants with different properties are required for the numerous surfaces through which entry routes may penetrate. A thorough job of sealing entry routes will typically result in a 50-70% reduction in radon. However, greater than 90% reduction has been achieved occasionally.

For the purposes of this discussion, soil gas entry routes are divided into major and minor categories. Major routes are usually relatively large, distinct openings between the house and the soil. Major routes include areas of exposed soil inside the house, sumps, floor-to-wall cracks, floor drains, French drains, large cracks, and uncapped top blocks in hollow-block foundation walls. Minor routes are small, but can be distributed over broad areas. Examples of minor routes include small cracks and the pores in block walls. Because they are often numerous and widespread, minor routes collectively can be very important sources of radon entry in the house.

Accessible major entry routes should always be closed as a matter of course to reduce soil gas entry with or without additional mitigation. A reasonable effort should be made to ensure that these closures are true gastight seals. However, the openings associated with these entry routes are generally so large that some meaningful radon reduction will be achieved even if it is not practical to establish a gastight seal. Closure methods generally involve cementing shut holes in slabs and walls, and covering and/or installing traps in water collection systems. In addition to these large routes, intermediate-sized holes and cracks in slabs and walls should be closed with mortar, caulk, or other sealant. Intermediate holes and cracks include those where there is a distinct opening amenable to closure, and exclude minor entry routes such as hairline cracks and the pores in block walls. The degree of radon reduction which can be achieved through closure of major and intermediate-sized entry routes will vary from house to house, and will probably not often be sufficient by itself to reduce high-radon houses below 4 pCi/L if the initial level is above 10 pCi/L. However, some degree of reduction will generally be achieved, depending upon the relative importance of the entry routes which are closed, the nature of the remaining unclosed entry routes, and the effectiveness of the closures (i.e., whether they are gastight seals). In some cases, the reduction can be significant. Because these closures can often be implemented relatively easily by the homeowner at relatively little cost, the homeowner is well advised to take these steps. These closures would also be needed if a soil ventilation system were subsequently installed in the house.

Simple closure of major and intermediate routes is generally sufficient when the purpose is to prevent house air from flowing out through the entry route when suction is being applied by an active soil ventilation system. Large amounts of house air leakage into the soil ventilation system might reduce the effectiveness of the system. However, small amounts of leakage can be handled by the soil ventilation system, so that gastight sealing is not required. Even if a gastight seal were established for a given entry route, the soil ventilation system would probably still receive comparable degrees of air leakage from the numerous other small entry routes which were not sealed. Thus, the expense and effort involved in true sealing of entry routes may not be justified for reducing leakage into active soil ventilation systems.

If an attempt were to be made to reduce high radon levels in a house below 4 pCi/L using sealing techniques alone, it would be necessary to apply a permanent, true gastight seal over essentially every soil gas entry route. Special care would be required to ensure that the major and intermediate routes were sealed gastight. Also, the minor routes such as small cracks and block pores would have to be sealed, requiring special surface preparation (such as routing of the cracks prior to sealing) and materials (such as coatings or membranes to seal the pores in block walls). Inaccessible entry routes (such as those concealed within block fireplace structures) would have to be sealed, possibly requiring partial dismantling of the structure. Because entry routes are often numerous, with some concealed and inaccessible, because gastight seals are often difficult to ensure, and because sealed routes can reopen (and new routes can be created) as the house settles over the years, sealing alone is not felt to be a viable technique for treating houses with high radon levels. At present, it appears that homeowners will be best served simply by executing reasonable closure or sealing of the accessible major and intermediate entry routes--and by then moving on to some other approach if that level of sealing does not give adequate reductions.

The pores in a block wall can be significant radon entry routes. This is especially true with cinder blocks. Paints and other pore-filling coatings can be effective in reducing air flow through these porous surfaces; however, cracks should first be filled with caulk or another sealant. Latex paints may require three or more coats (a minimum of three is recommended) to be highly effective in stopping air flow through a hollow-block concrete wall. Waterproof and epoxy paints may be as effective with only one or two coats. Further studies of block wall sealing are under way.

If openings are to be closed using sealants, the first step is to choose the appropriate material. Table 4 gives a partial listing by category of the available sealants, along with some suggestions for applicability. The information in this table was obtained from sources including manufacturers' literature, laboratory research study reports, and field study reports. This information does not constitute an exhaustive list of sealants or of pertinent information relating to these particular products. Particular attention should be paid to information relating to safety concerns. If there is any suspicion that the safety precautions supplied with a particular product are inadequate, the manufacturer should be contacted for further advice. Manufacturers' addresses could be obtained from reference books (such as the Thomas Register) in the local library. Since many sealants are designed to bond to specific surfaces, more than one type of sealant may be required to close all the entry routes in a particular house. Table 4 compares the properties and applicability of several products. Listing of a product in this table does not imply EPA approval or recommendation. Further information on new products may be available from the manufacturers.

10.5 House Pressure Adjustments

10.5.1 Reduce Depressurization

Depressurization of the lower levels of the house (relative to the surrounding soil) is a primary factor contributing to the flow of soil gas into the house. Some steps can be taken to reduce the effects of some of the contributors to this depressurization. In addition, steps can be taken to reduce flow of house air up through, and out of, the house as a consequence of depressurization. Reduction in air outflow should reduce soil gas inflow.

There are currently insufficient data to estimate the contributions of the various sources of depressurization to the radon levels in the house. Their effects will vary from house to house. Therefore, the radon reductions that might generally be achieved by addressing these sources cannot now be predicted. Moreover, since some of these sources exert only intermittent influence (such as fireplaces and exhaust fans), any radon reductions that are achieved by controlling these sources will apply only over short time periods. However, it is known that such sources can sometimes be significant contributors to indoor radon, and that the benefits of addressing them can be significant. Therefore, it

Table 4. Sealant Information

Sealant Name	Sealant Type	Safety Concerns	Application Effectiveness (%)	Cost	Sealant Manufacturer
Small Cracks					
Fomofill	One component, caulk bead	________	________	$11/cf	Fomo Products, Inc.
Geocel Construction 1200	Caulk, silicone	Nontoxic, water-based solvent	________	$2/tube	Geocel Corp.
Geocel Construction 2000	Copolymer caulk	Ventilation required during installation	________	$2.50/tube	Geocel Corp.
Geocel SPEC 3000	Caulk, urethane	Use respirators w/organic vapor cartridges	________	$3/tube	Geocel Corp.
Sikatop	Nonshrink grout w/binder	________	________	________	Sika Chemical Corp
Sikadur	Nonshrink grout w/binder	________	________	________	Sika Chemical Corp.
Silastic	Caulk, silicone	________	________	________	Wright/Dow Corning
Insta-Seal Kit, I-S 550	One component, caulk bead	Ventilation required during installation		$79/2.2cf	Insta-Foam Products, Inc.
Handi-Foam, Model I-160	One component, caulk bead	________	________	$89/2.2cf	Fomo Products, Inc.
Large Cracks					
Versi-foam 1	Two component urethane foams	Ventilation required during installation	________	$22/1cf	Universal Foam System, Inc.
Versi-foam 15	Two component urethane foams	Ventilation required during installation	________	$220/15cf	Universal Foam System, Inc.
Froth Pak FP-180	Two component urethane foams	Ventilation required during installation		$254/15cf	Insta-Foam Products, Inc.
Dow Corning Fire Stop Foam Kit #2001	Two component silicone liquid	________	________	1-2lb. kit:$12.75/1cf	Insta-Foam Products, Inc.
Insta-Seal Kit, I-S 550	One component, caulk bead	Ventilation required during installation	________	$78/2.2cf	Insta-Foam Products, Inc.
Handi-Foam, Model 1-160	One component, caulk bead	________	________	$89/2.2cf	Fomo Products, Inc.

(continued)

Table 4. Continued

Sealant Name	Sealant Type	Safety Concerns	Application Effectiveness (%)	Cost	Sealant Manufacturer
Large Cracks (continued)					
Froth Pak Kit FP-9.5	Two component, spray foam	—	—	—	Insta-Foam Products, Inc.
Fomofill	One component, caulk bead	—	—	$11/1cf	Fomo Products, Inc.
Geocel Construction 1200	Caulk, silicone	Nontoxic, water-based solvent	—	$2/tube	Geocel Corp.
Geocel Construction 2000	Copolymer caulk	Ventilation required during installation	—	$2.50/tube	Geocel Corp.
Geocel SPEC 3000	Caulk, urethane	Use respirators w/organic vapor cartridges	—	$3/tube	Geocel Corp.
Tremco THC-900	Flowable urethane, two-part	Ventilation required during installation	—	$49/1.5 gal.	Tremco
Zonolite 3300	Spray foam and fire proofing	Check ventilation requirements	—	—	W. R. Grace and Co.
Polycel One	Expanding foam, polyurethane	Not used in living space; may cause allergic reactions on skin	—	$80/16 lb. tank	W. R. Grace and Co.
Pores					
Foil-Ray	Reflective insulation	Flammable, non-toxic	99	$0.36/sq.ft tape-$8.50/roll)	—
Thiocol WD-6	Alkylpolysulfide copolymer (0.102 cm thickness)	Non-hazardous; choking fumes when burned; wear masks, gloves, shield; avoid inhalation	90	—	Thiokol Corp.
Rock Coat 82-3	P.V.C. copolymer solution (0.127 cm thickness)	Fire hazard, exhaust; wear goggles, gloves	26	—	Halltech, Inc.
Resitron II	Two component furan	—	97	$6.75/gal. ($0.33/sq.ft)	Ventron Corp.
HydrEpoxy 156	—	—	94	$7.30/gal. ($0.19/sq.ft)	Acme Chemicals & Insulation Co.
HydrEpoxy 300	Two component, water-based epoxy	Self-extinguishing	85	$6.37/gal. ($0.31/sq.ft)	Acme Chemicals & Insulation Co.
Aerospray 70	One component	Self-extinguishing	99	$2.96/gal.	American Cyanamid

(continued)

Table 4. **Continued**

Sealant Name	Sealant Type	Safety Concerns	Application Effectiveness (%)	Cost	Sealant Manufacturer
Pores (continued)					
Blockbond	Surface bonding cement w/binder	Check ventilation requirements	—	—	—
Shurewall	Surface bonding cement w/binder	Check ventilation requirements	—	—	—
Acryl 60	Surface bonding cement w/binder	Check ventilation requirements	—	—	Standard Dry Wall Products
Trocal, etc.	Sheeting: polymer,Al-mylar, PVC, polyethylene	—	—	—	Dynamit Nobel of America, Inc.
—	Polyethylene terephthalate (0.009 cm thickness)	—	99	—	—
Polyester	One component, medium viscosity, unsaturated polyester	Self-extinguishing	95	$2.11/gal. ($0.13/sq. ft.)	Essex Chemical Corp.
Saran Latex XD4624	Experimental Saran Latex	—	89	$2.72/gal. ($0.12/sq.ft)	Dow Chemical Co.
Design Openings					
Versi-foam 1	Two component urethane foams	Ventilation required during installation	—	$22/cf	Universal Foam System, Inc.
Versi-foam 15	Two component urethane foams	Ventilation required during installation	—	$220/15cf	Universal Foam System, Inc.
Froth Pak FP-180	Two component urethane foams	Ventilation required during installation	—	$254/15cf	Insta-Foam Products, Inc
Froth Pak Kit FP-9.5	Two component, spray foam	—	—	—	Insta-Foam Products, Inc.
Vulkem	Flowable urethane, 1 part	Ventilation required during installation	—	$10/qt. tube	
Zonolite 3300	Spray foam and fire proofing	Check ventilation requirements	—	—	W. R. Grace and Co.

NOTE: Inclusion of a sealant in this table should not be construed as an endorsement by EPA of the product or its manufacturer. This table is not represented as a complete listing of suitable products or manufacturers. This table is intended only as a partial listing of some of the sealants known to be commercially available.

serves the homeowner well to take whatever steps are possible to reduce depressurization.

Some steps which homeowners might easily and inexpensively implement include:

- Slightly opening windows near exhaust fans and combustion appliances when these appliances are in use to facilitate the inflow of outdoor air to make up for the house air exhausted by these devices;
- Sealing off cold-air return registers in the basement for central forced-air heating and cooling systems and sealing around the return ducting in the basement to reduce the extent to which the basement is depressurized; and
- Closing accessible airflow bypasses (between stories) and accessible openings through the house shell on the upper levels to reduce air movement up through, and out of, the house as the result of the thermal stack effect.

Before considering more expensive measures for addressing a depressurization source (e.g., installation of a permanent source of outdoor combustion air for a fireplace), the homeowner might wish to make radon measurements with and without the fireplace in operation. Such measurements would suggest whether that source is a sufficiently important contributor to indoor radon levels to make the investment worthwhile.

10.5.2 House Pressurization

If the pressure difference between the house and the soil can be reversed so that the house is higher in pressure than is the soil, the convective flow of soil gas inward will be stopped altogether. House pressurization is a developing reduction technique which has been tested in only a few basement houses to date. Radon reductions as high as 90% have sometimes been observed using this approach. For houses with basements (or with heated crawl spaces) it might be possible to isolate the basement (crawl space) from the remainder of the house, and to pressurize it by blowing air into the basement (crawl space) from the other parts of the house.

The ability to isolate and tighten that portion of the house in contact with the soil is a key consideration. If the portion in contact with the soil could not be isolated, it would be necessary to pressurize the entire house, by blowing in outdoor air--a potentially impractical approach which would have a large heating penalty. Even with the isolation and tightening, the heating penalty could be significant, because of increased infiltration upstairs when large amounts of upstairs air are blown into the basement. While basement pressurization appears to offer potential, the technique requires further testing before it can be designed and operated with confidence. One concern that has been expressed about this technique is the collection of moisture in the walls as a result condensation as warm moist air contacts the colder surfaces of the outer parts of the wall. Increased moisture could damage wood components and freezing might damage concrete blocks.

10.6 Air Cleaning

Since radon decay products are solid particles, they can be removed from the air, after the entry of the radon gas into the house, by continuously circulating the house air through a device which removes particles. Such air cleaning devices have been available for residential use for many years. These devices include mechanical filters and electrostatic devices which can be incorporated into the air handling system associated with a central forced-air heating and cooling system, or which can stand alone inside the house.

Radon decay products will rapidly attach to other, larger dust particles in the house air. If no air cleaner is in use, the concentration of dust particles will be sufficient such that only a small fraction of the decay products will not be thus attached. Air cleaners remove the dust particles so that newly created decay products, which are continuously being generated by the radon gas throughout the house, find many fewer dust particles to adhere to. Therefore, while air cleaners can reduce the total concentration of radon decay products, they can actually increase the concentration of unattached decay products.

At present, particle-removal air cleaners cannot be recommended for the purpose of reducing the health risk due to radon and its decay products. Unattached decay products may result in a greater health risk than those attached to dust particles, because the unattached progeny could deposit selectively in a fairly small portion of the lung, giving that portion a high dosage of alpha particle bombardment. The health data currently available are not sufficient to confirm whether the potential increase in unattached progeny caused by an air cleaner, combined with the net decrease in total progeny, would typically cause an increase or a decrease in the lung cancer risk to the homeowner. While the use of air cleaners cannot currently be recommended for radon progeny reduction due to this uncertainty, neither can it be recommended that air cleaners be turned off in cases where they are being used for reasons other than radon (e.g., to reduce allergy problems).

Air cleaners, if designed for high efficiency, can be highly effective in removing the radon progeny (both attached and unattached) which pass through them. However, a difficulty arises in circulating the house air through the devices fast enough to provide high house-wide reductions. Progeny are constantly being generated by radon decay in every corner of the house. The challenge is to remove these progeny in the air cleaner before they can be inhaled. To achieve 90% reduction of the total decay products in a house of typical size and infiltration rate, the air would have to circulate through a highly efficient air cleaner at a rate of about 2000 cfm. This is approximately the capacity of a central forced-air furnace fan for a house of typical size. Thus, to achieve 90% total reduction, an efficient air cleaner could be installed in the central furnace ducting and the furnace fan operated continuously (not being allowed to cycle off). The alternative of installing stand-alone air cleaners in individual rooms to achieve 90% reduction is considered impractical; about eight such units would be needed (almost one in every room), if each air cleaner handles 250 cfm. A more realistic number of one or two 250-cfm units in the entire house could give 50 to 70% reduction in the total progeny concentration, if the total house air could be effectively circulated through such localized units (e.g., via ducting). Many stand-alone air cleaners on the market are much smaller than 250 cfm, some treating only a few cubic feet per minute. Such small units would provide no meaningful reduction of the total progeny.

The percentage reductions discussed in the preceding paragraph are the reductions in the total decay product concentration. The effects of those air cleaners on the concentration of the unattached progeny would depend on a number of factors and are difficult to predict. With a 2,000-cfm unit, it is possible that the concentration of unattached progeny would not decrease at all as a result of air cleaner operation, and might even increase. With one or two 250-cfm units, the unattached concentration would very likely be increased by the air cleaner(s). The smaller units could circulate the house air fast enough to reduce the dust particle concentration (thus increasing the fraction of unattached progeny), but not fast enough to remove the unattached progeny which are being generated.

The above discussion has focused on air cleaners which remove particles (and hence radon decay products). Air cleaners which might remove radon gas are in a developmental stage and are not considered here.

10.7 Radon Removal from Well Water

Radon gas from the surrounding soil can dissolve in groundwater. If the groundwater is drawn directly into a house from an individual well (or perhaps from a small community well), the dissolved radon can escape into the air, contributing to airborne radon levels. Houses receiving water from a municipal water treatment plant will not have this potential problem, because any radon in the water supply will have been released during treatment and handling before the water reaches the house. As a rule of thumb, 10,000 pCi/L of radon in well water will contribute roughly 1 pCi/L of airborne radon to the house air on the average, although localized airborne levels can be much higher. If water concentrations are sufficiently high (above perhaps 40,000 pCi/L), some effort to address the water source of radon would be advisable, in addition to efforts addressing the soil gas source.

One option for addressing the radon in water is to ventilate the house near the point of usage whenever water is used. A second option-- more practical as a long-term solution--is to treat the well water before it is used in the house.

One approach for treating the water is to install a granular activated carbon (GAC) treatment unit on the water line entering the house from the well, following the pressure tank. These GAC units have been used in residential applications for removing water contaminants other than radon (for example, organics). A number of GAC units have been installed over the past 6 years specifically for radon removal. If the unit is properly sized and contains a brand of carbon specifically selected for radon removal, radon removals of over 99% have sometimes been obtained. The reported performance of those carbon units which have been in operation for several years suggests that the units can operate with no degradation in radon reduction performance for at least several years, with minimal maintenance. One major consideration with GAC units is that they must be properly shielded (or else located remote from the house), in order to protect the occupants from gamma radiation resulting from radon and radon decay products accumulated on the carbon bed. Another consideration is that, depending upon State regulations, the spent carbon might in some cases have to be disposed of as a low-level radioactive waste. An additional concern which will not be discussed here is the possible bacterial growth that has been reported to occur in the carbon bed.

Aeration of the well water is another treatment option, to release and vent the dissolved radon before the water is used in the house. Several aerator designs have been tested for residential use, and reductions above 90% have been reported with some of them. Aerators will avoid the need for gamma shielding that carbon units have, and will avoid concerns regarding the disposal of waste carbon. However, aeration units are more expensive to install and operate than are GAC units, and the radon removal capabilities of the aerators that are currently being marketed are generally lower than the 99+% that has sometimes been reported for GAC. Although home aeration units are commercially available, experience with aerators for residential use is limited to date. In addition, aerators will be more complex than GAC units, generally requiring at least one additional water pump (to boost the low-radon water from the aerator back up to the pressure needed to move it through the house plumbing) and a fan or air compressor (to provide the stripping air).

10.8 Radon Reduction in New Construction

When a house is under construction, steps can be taken to reduce the risk that the house will have elevated radon levels. In addition, measures can be installed that will facilitate the activation of an effective radon reduction system if levels do turn out to be elevated after the house is built. The actual effectiveness of these individual steps has not yet been demonstrated in new construction; the necessary demonstration is being initiated now. However, these techniques are logical extensions of current knowledge and of the experience to date in existing houses. These steps can be implemented with less expense, and with greater effectiveness, during the construction stage than they can after the house is completed. Therefore, persons who are concerned about a potential for elevated radon levels in houses they are building should consider these steps.

Steps that can be taken to reduce the risk of elevated radon levels in a new house are:

- Efforts to reduce soil gas entry routes, including, for example, avoiding cracks in the concrete floor slab, sealing around utility penetrations through the slab and foundation walls, capping the top of hollow-block foundation walls, and sealing the top of sumps.
- Efforts to reduce the house depressurization and house air exfiltration that can increase soil gas influx, including, for example, avoiding thermal bypasses throughout the house, providing an external air supply for certain combustion appliances, and ensuring the presence of adequate vents in crawl spaces. These steps are discussed in EPA's "Radon-Resistant Residential New Construction" (EPA88b) and "Radon Reduction in New Construction, an Interim Guide" (EPA87d).

As a further precaution, provisions can be made during construction that will enable effective sub-slab suction after the house is built, if radon levels turn out to be elevated despite the preventive steps mentioned above. These provisions include a 4-in. deep layer of clean, crushed rock under the slab, with an exterior or interior drain tile loop which drains into a sump or which is stubbed-up and capped outside the house or through the slab. Alternatively, one or more 1-ft lengths of PVC pipe can be embedded into the aggregate through the slab and capped at the top. These standpipes can later be uncapped and connected to a fan in suction (or to a passive convection stack) if needed.

Section 11

Sources of Information

The first point of contact for information concerning indoor radon and radon reduction measures should be the appropriate state agency. In most states these agencies have copies of EPA publications for distribution. They can also provide information about any state radon programs that may exist. They are the best source of information about radon occurrence in an individual state. Table 5 lists the agency to contact for each of the states.

If you desire further information, additional assistance and contacts can be provided by the EPA Regional Office for the region that includes your state. Table 6 lists the address and telephone number of the radiation staff for each of EPA's 10 Regional Offices. The table also includes the appropriate Regional Office to contact for each state.

Table 5. Radon Contacts for Individual States

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

Alaska
Alaska Department of Health and Social Services
P.O. Box H
Juneau, AK 99811-0613
(907) 465-3019

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

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

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

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

Connecticut
Connecticut Department of Health Services
Toxic Hazards Section
150 Washington Street
Hartford, CT 06106
(203) 566-8167

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

(continued)

Table 5. Continued

District of Columbia
DC Department of Consumer and Regulatory Affairs
614 H Street, NW, Room 1014
Washington, DC 20001
(202) 727-7728 or (202) 727-7722

Florida
Florida Office of Radiation Control
Building 18, Sunland Center
P.O. Box 15490
Orlando, FL 32858
(305) 297-2095

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

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

Idaho
Radiation Control Section
Idaho Department of Health and Welfare
Statehouse Mail
Boise, ID 83720
(208) 334-5879

Illinois
Illinois Department of Nuclear Safety
Office of Environmental Safety
1035 Outer Park Drive
Springfield, IL 62704
(217) 785-9900

Indiana
Division of Industrial Hygiene and Radiological Health
Indiana State Board of Health
1330 W. Michigan Street
P.O. Box 1964
Indianapolis, IN 46206-1964
(317) 633-0153

Iowa
Bureau of Radiological Health
Iowa Department of Public Health
Lucas State Office Building
Des Moines, IA 50319-0075
(515) 281-7781

(continued)

Table 5. Continued

Kansas
Bureau of Air Quality and Radiation Control
Attention: Radon
Forbes Field, Building 321
Topeka, KS 66620-0110
(913) 296-1560, 296-1568

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

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

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

Maryland
Division of Radiation Control
Maryland Department of Health and Mental Hygiene
201 W. Preston Street
Baltimore, MD 21201
(301) 333-3130 or (800) 872-3666

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

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

Minnesota
Section of Radiation Control
Minnesota Department of Health
P.O. Box 9441
717 SE Delaware Street
Minneapolis, MN 55440
(612) 623-5350 or (800) 652-9747

(continued)

Table 5. Continued

Mississippi
Division of Radiological Health
Mississippi Department of Health
P.O. Box 1700
Jackson, MS 39215-1700
(601) 354-6657

Missouri
Bureau of Radiological Health
Missouri Department of Health
1730 E. Elm, P. O. Box 570
Jefferson City, MO 65102
(314) 751-6083

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

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

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

New Hampshire
New Hampshire Radiological Health Program
Health and Welfare Building
6 Hazen Drive
Concord, NH 03301-6527
(603) 271-4588

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

(continued)

Table 5. Continued

New Mexico
Dr. Margo Keele, Radon Project Manager
New Mexico Environmental Improvement Division
Community Services Bureau
P.O. Box 968
Santa Fe, NM 87504-0968
(505) 827-2957

New York
Bureau of Environmental Radiation Protection
New York State Health Department
2 University Place
Albany, NY 12203
(518) 458-6461 or (800) 458-1158 (in State) or
(800) 342-3722 (New York State *Energy Office*)

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

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

Ohio
Robert M. Quillin, Program Administrator
Radiological Health Program
Ohio Department of Health
1224 Kinnear Road, Suite 120
Columbus, OH 43212
(614) 644-2727 or (800) 523-4439 (in State only)

Oklahoma
Radiation and Special Hazards Service
Oklahoma State Department of Health
P.O. Box 53551
Oklahoma City, OK 73152
(405) 271-5221

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

(continued)

Table 5. Continued

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

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

Rhode Island
Division of Occupational Health and Radiation Control
Rhode Island Department of Health
206 Cannon Building
75 Davis Street
Providence, RI 02908

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

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

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

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

(continued)

Table 5. **Continued**

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

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

Virginia
Bureau of Radiological Health
Department of Health
109 Governor Street
Richmond, VA 23219
(804) 786-5932 or (800) 468-0138 (in State)

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

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

Wisconsin
Division of Health
Section of Radiation Protection
Wisconsin Department of Health and Social Services
5708 Odana Road
Madison, WI 53719
(608) 273-5180

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

Table 6. Radiation Contacts for EPA Regional Offices

Address and Telephone	States in EPA Region
Region 1 U.S. Environmental Protection Agency APT-2311 John F. Kennedy Federal Building Boston, MA 02203 (617) 565-3234	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont
Region 2 2AWM:RAD U.S. Environmental Protection Agency 26 Federal Plaza New York, NY 10278 (212) 264-4418	New Jersey, New York, Puerto Rico, Virgin Islands
Region 3 3AM12 U.S. Environmental Protection Agency 841 Chestnut Street Philadelphia, PA 19107 (215) 597-8320	Delaware, District of Columbia, Maryland, Pennsylvania, Virginia, West Virginia
Region 4 U.S. Environmental Protection Agency 345 Courtland Street, N.E. Atlanta, GA 30365 (404) 347-2904	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee
Region 5 5AR-26 U.S. Environmental Protection Agency 230 South Dearborn Street Chicago, IL 60604 (312) 886-6175	Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin
Region 6 6T-AS U.S. Environmental Protection Agency 1445 Ross Avenue Dallas, TX 75202-2733 (214) 655-7208	Arkansas, Louisiana, New Mexico, Oklahoma, Texas
Region 7 U.S. Environmental Protection Agency 726 Minnesota Avenue Kansas City, KS 66101 (913) 236-2893	Iowa, Kansas, Missouri, Nebraska
Region 8 8HWM-RP U.S. Environmental Protection Agency 999-18th Street, Suite 500 Denver, CO 80202-2405 (303) 293-1709	Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming
Region 9 A-1-1 U.S. Environmental Protection Agency 215 Fremont Street San Francisco, CA 94105 (415) 974-8378	American Samoa, Arizona, California, Guam, Hawaii, Nevada
Region 10 AT-082 U.S. Environmental Protection Agency 1200 Sixth Avenue Seattle, WA 98101 (206) 442-7660	Alaska, Idaho, Oregon, Washington

(continued)

Correspondence should be addressed to the EPA Radiation Representative at each address.

Table 6. **Continued**

	EPA Region		EPA Region
Alabama	4	Montana	8
Alaska	10	Nebraska	7
American Samoa	9	Nevada	9
Arizona	9	New Hampshire	1
Arkansas	6	New Jersey	2
California	9	New Mexico	6
Colorado	8	New York	2
Connecticut	1	North Carolina	4
Delaware	3	North Dakota	8
District of Columbia	3	Ohio	5
Florida	4	Oklahoma	6
Georgia	4	Oregon	10
Guam	9	Pennsylvania	3
Hawaii	9	Puerto Rico	2
Idaho	10	Rhode Island	1
Illinois	5	South Carolina	4
Indiana	5	South Dakota	8
Iowa	7	Tennessee	4
Kansas	7	Texas	6
Kentucky	4	Utah	8
Louisiana	6	Vermont	1
Maine	1	Virginia	3
Maryland	3	Virgin Islands	2
Massachusetts	1	Washington	10
Michigan	5	West Virginia	3
Minnesota	5	Wisconsin	5
Mississippi	4	Wyoming	8
Missouri	7		

Section 12

References

Br87 - Brennan, T., Camroden Associates, Inc., Rome, NY, private communication, July 1987.

Br88a - Brennan, T., W. Brodhead, S. Galbraith, W. Makafske, C. Silver, and V. Edward. Reducing Indoor Radon: Training Manual, New York State Energy Office, Albany, NY, 1988.

Br88b - Brennan, T., and S. Galbraith. Practical Radon Control for Homes, Cutter Information Corp., Arlington, MA. 1988.

Bro87a - Brodhead, W., Mitigation Quality Control Checklist in Reducing Radon in Structures: Student Manual, prepared for U.S. Environmental Protection Agency Radon Reduction Training Course under contract number 68-01-7030, January 1987. (An updated EPA report is in preparation.)

Bro87b - Brodhead, W., Buffalo Homes, Riegelsville, PA, private communication, July 1987.

EPA86a - U.S. Environmental Protection Agency, A Citizen's Guide to Radon, OPA-86-004, Washington, DC, August 1986.

EPA86b - Ronca-Battista, M., P. Magno, S. Windham, and E. Sensintaffer, Interim Indoor Radon and Radon Decay Product Measurement Protocols, U.S. Environmental Protection Agency, EPA-520/1-86-04 (NTIS PB86-215258), Washington, DC, February 1986.

EPA86c - Singletary, H. M., K. Starner, and C. E. Howard, Implementation Strategy for the Radon/Radon Progeny Measurement Proficiency Evaluation and Quality Assurance Program, U. S. Environmental Protection Agency, EPA-520/1-86-03, Washington, DC, February 1986.

EPA87a - Ronca-Battista, M., P. Magno, and P. Nyberg, Interim Protocols for Screening and Follow-Up Radon and Radon Decay Product Measurements,U.S. Environmental Protection Agency, EPA-520/1-86-014, Washington, DC, February 1987.

EPA87b - U. S. Environmental Protection Agency, Radon/Radon Progeny Cumulative Proficiency Report, EPA-520/1-87-002, January 1987.

EPA87c - U.S. Environmental Protection Agency, Removal of Radon from Household Water, OPA-87-009, August 1987.

EPA87d - U.S. Environmental Protection Agency, Radon Reduction in New Construction, An Interim Guide, OPA-87-009, August 1987.

EPA88a - Henschel, D. B., Radon Reduction Techniques for Detached Houses, Technical Guidance (Second Edition), U.S. Environmental Protection Agency, EPA/625/5-87-019, Research Triangle Park, NC, January 1988.

EPA88b - Osborne, M.C., Radon-Resistant Residential New Construction, U.S. Environmental Protection Agency, EPA-600/8-88-087, Research Triangle Park, NC, July 1988.

EPA88c - U.S. Environmental Protection Agency, Protocols for Screening and Followup Radon and Radon Decay Product Measurements (in preparation).

Ha87 - Harrje, D. T., Hubbard, L. M., and Sanchez, D.C."Proceedings of the Radon Diagnostics Workshop, April 13-14, 1987," PU/CEES Report No. 223, 1987. (EPA report is in preparation.)

He87a - Henschel, D.B., and A. G. Scott, Testing of Indoor Radon Reduction Techniques in Eastern Pennsylvania: An Update, in *Indoor Radon II: Proceedings of the Second APCA International Specialty Conference on Indoor Radon*, pp. 146-159, Cherry Hill, NJ, April 1987.

He87b - Henschel, D. B., and A. G. Scott, Some Results from the Demonstration of Indoor Radon Reduction Measures in Block Basement Houses, in *Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate*, Vol. 2, pp. 340-346, Berlin, West Germany, August 1987.

Ma87 - Matthew, T. G. et al. from Oak Ridge National Laboratory, and Hubbard, L. M. et al. from Princeton University, "Investigation of Radon Entry and Effectiveness of Mitigation Measures in Seven Houses in New Jersey: Midproject Report," ORNL/TM-10544, 1987.

Mar88 - Marynowski, J. M., "Measurement and Reduction Methods of Cinder Block Wall Permeabilities," Senior Thesis in Chemical Engineering, Princeton University, 1988.

Na85 - Nazaroff, W. W., S. M. Doyle, A. V. Nero, and R. G. Sextro, Potable Water as a Source of Airborne Radon-222 in *U.S. Dwellings: A Review and Assessment*, Lawrence Berkeley Laboratory, Report LBL-18154, December 1985.

Os87 - Osborne, M. C., Resolving the Radon Problem in Clinton, NJ, Houses, presented at the 4th International Conference on Indoor Air Quality and Climate, Berlin, West Germany, August 1987.

Py88 - Pyle, B. E., A. D. Williamson, C. S. Fowler, F. E. Belzer III, M. C. Osborne, and T. Brennan, Radon Mitigation in Crawl Space Houses in Nashville, Tennessee, presented at the 81st Annual Meeting of APCA, Dallas, TX, June 19-24, 1988.

Sa87 - Saum, D., INFILTEC Radon Control Services, Falls Church, VA, private communication, June 1987.

Sc87 - Scott, A. G., American ATCON, Wilmington, DE, private communication, July 1987.

Sc88 - Scott, A. G., A. Robertson, and W. O Findlay, "Installation and Testing of Indoor Radon Reduction Techniques in 40 Eastern Pennsylvania Houses," EPA-600/8-88-002 (NTIS PB88-156 617). Research Triangle Park, NC, January 1988.

Se87 - Sextro, R. G. et al., "An Intensive Study of Radon and Remedial Measures in New Jersey Homes: Preliminary Results," Lawrence Berkeley Laboratory, University of California, LBL-23128, 1987. (EPA report in preparation under interagency agreement DW89931876-01 with the U.S. Department of Energy.)

Si87 - Simon, R., Barto, PA, private communication, April 13, 1987.

Tu87 - Turk, B. H., J. Harrison, R. J. Prill, and R. G. Sextro, "Preliminary Diagnostic Procedures for Radon Control," EPA-600/8-88-084 (NTIS PB88-225 115), June 1988.

Appendix

The following house inspection form is to be used in conjunction with the visual inspection. It is quite detailed, but not all entries are pertinent to all houses. The form is designed to be fairly complete and, consequently,may call for information that is not always needed. Experience shows that collecting too much information is preferable to collecting too little, since the latter may require a second visit to the house. Survey type information is quickly obtained and, therefore, should be collected as completely as possible on the first visit. This form is organized to facilitate incorporating the information into a report.

EXAMPLE OF A HOUSE INSPECTION FORM THAT CAN BE USED DURING A VISUAL SURVEY (from Reference Tu87)

RADON SOURCE DIAGNOSIS
BUILDING SURVEY

NAME: ____________________

ADDRESS: ____________________

____

____

PHONE NO. ____________________

HOUSE INSPECTED: (i.d.) ____________________

DATE: ____________________

ARRIVAL TIME: ____________________

DEPARTURE TIME: ____________________

SURVEY TECHNICIANS: ____________________

____

____

____

I. BASIC CHARACTERIZATION OF BUILDING AND SUBSTRUCTURE

Site

1. Age of house ____________________

2. Basic building construction:
   Exterior materials ____________________
   ____
   Interior materials ____________________
   ____

3. Earth-based building materials in the building - describe:
   ____
   ____

4. Domestic water source:
   a. municipal surface
   b. municipal well
   c. on-site well
   d. other ____________________

5. Building infiltration or mechanical ventilation rate:
   a. building shell - leaky, moderate, tight
   b. weatherization - caulk, weatherstrip, etc.
   c. building exposure: (1) heavy forest ____________________
      (2) lightly wooded or other nearby buildings ____________________
      (3) open terrain, no buildings nearby ____________________
   exhaust fans: (1) whole house attic fans ____________________
      (2) kitchen fans ____________________
      (3) bath fans ____________________
      (4) others ____________________
      (5) frequency of use ____________________
   other mechanical ventilation ____________________

(continued)

HOUSE INSPECTION FORM (Continued)

6. Existing radon mitigation measures
   Type ____________________
   Where ____________________
   When ____________________

7. Locale - description: ____________________

8. Unusual outdoor activities:
   farm ____________________
   construction ____________________
   factories ____________________
   heavy traffic ____________________

Substructure

1. Full basement (basement extends beneath entire house)
2. Full crawl space (crawl space extends beneath entire house)
3. Full slab on grade (slab extends beneath entire house)
4. House elevated above ground on piers
5. Combination basement and crawl space (% of each)
6. Combination basement and slab on grade (% of each)
7. Combination crawl space and slab on grade (% of each)
8. Combination crawl space, basement, and slab on grade (% of each)
9. Other - specify

Occupants

1. Number of occupants ____________________ Number of children ____________________
2. Number of smokers ____________________ Type of smoking ____________________
   Frequency ____________________

Air quality

1 Complaints about the air (stuffiness, odors, respiratory problems, watery eyes, dampness, etc.)

2. Are there any indications of moisture problems, humidity or condensation (water marks, molds, condensation , etc.)? __________
   When ____________________

   Note: Complete floor plan with approximate dimensions and attach.

II. BUILDINGS WITH FULL OR PARTIAL BASEMENTS

1. Basement use: occupied, recreation, storage, other ____________________

2. Basement walls constructed of:
   a. hollow block: concrete, cinder
   b. block plenums: filled, unfilled,
      top block filled or solid: yes, no
   c. solid block: concrete, cinder
   d. condition of block mortar joints: good, medium, poor
   e. poured concrete
   f. other materials - specify: ____________________
   g. estimate length and width of unplanned cracks: ____________________
   h. interior wall coatings: paint, sealant, other ____________________
   i. exterior wall coatings: parget, sealant, insulation (type ____________________)

(continued)

HOME INSPECTION FORM (Continued)

3. Basement finish:
   a. completely unfinished basement, walls and floor have not been covered with paneling, carpet, tile, etc.: ________________
   b. fully finished basement - specify finish materials: ________________
   c. partially finished basement - specify: ________________

4. Basement floor materials:
   a. contains unpaved section (i.e., exposed soil) - specify site and location of unpaved area(s): ________________
   b. poured concrete, gravel layer underneath
   c. block, brick, or stone - specify ________________
   d. other materials - specify ________________
   e. describe floor cracks and holes through basement floor ________________
   f. floor covering - specify ________________

5, Basement floor depth below grade - front__________ rear________
side 1 ________ side 2 ________

6. Basement access:
   a. door to first floor of house
   b. door to garage
   c. door to outside
   d. other - specify________________

7. Door between basement and first floor is:
   a. normally or frequently open
   b. normally closed

8. Condition of door seal between basement and first floor - describe (leaky, tight, etc.): ________________

9. Basement window(s) - specify:
   a. number of windows ________________
   b. type ________________
   c. condition________________
   d. total area:________________

10. Basement wall-to-floor joint:
    a. estimate total length and average width of joint:________________
    b. indicate if filled or sealed with a gasket of rubber, polystyrene, or other materials - specify materials:________________
    c. accessibility - describe:________________

11. Basement floor drain:
    a. standard drain(s) - location:________________
    b. French drain - describe length, width, depth:________________
    c. other - specify:________________

(continued)

HOUSE INSPECTION FORM (Continued)

d. connects to a weeping (drainage) tile system beneath floor - specify source of information (visual inspection, homeowner comment, building plan, other):______________________________
e. connects to a sump
f. connects to a sanitary sewer
g. contains a water trap or waterless trap
h. floor drain water trap is full of water:
  (1) at time of inspection
  (2) always
  (3) usually
  (4) infrequently
  (5) insufficient information for answer
  (6) specify source of information______________________________

12. Basement sump(s) (other than above) - location:______________________________
a. connected to weeping (drainage) tile system beneath basement floor - specify source of information:
____
b. water trap is present between sump and weeping (drainage) tile system - specific source of information:____________
c. wall or floor of sump contains no bottom, cracks, or other penetrations to soil - describe:
____
e. sump contains water:
  (1) at time of inspection
  (2) always
  (3) usually
  (4) infrequently
  (5) insufficient information for answer
  (6) specify source of information:______________________________
  (7) pipe or opening through which water enters sump is occluded by water:
    (a) at time of inspection
    (b) always
    (c) usually
    (d) infrequently
    (e) insufficient information for answer
    (f) specify source of information
f. contains functioning sump pump:______________________________

13. Forced air heating system ductwork: condition of seal - describe:
supply air:______________________________
return air______________________________
- basement heated: a. intentionally
  b. incidentally

14. Basement electrical service:
a. electrical outlets - number ____________________ (surface or recessed)
b. breaker/fuse box - location ______________________________

15. Penetrations between basement and first floor:
a. plumbing: ______________________________
b. electrical: ______________________________
c. ductwork: ______________________________
d. other: ______________________________

16. Bypasses or chases to attic (describe location and size):
____

17. Floor material type, accessibility to flooring, etc.: ______________________________

18. Is caulking or sealing of holes and openings between substructure and upper floors possible from:
a. basement?
b. living area?

(continued)

HOUSE INSPECTION FORM (Continued)

III. BUILDINGS WITH FULL OR PARTIAL CRAWL SPACES

1. Crawl space use: storage, other

2. Crawl space walls constructed of:
   a. hollow block: concrete, cinder
   b. block plenums: filled, unfilled
      top block filled or solid: yes, no
   c. solid block: concrete, cinder
   d. condition of mortar joints: good, medium, poor
   e. poured concrete
   f. other materials - specify:
   g. estimate length and width of unplanned cracks:
   h. interior wall coatings: paint, sealant, other
   i. exterior wall coatings: parget, sealant, insulation (type)

3. Crawl space floor materials:
   a. open soil
   b. poured concrete, gravel layer underneath:
   c. block, brick, or stone - specify:
   d. plastic sheet condition:
   e. other materials - specify:
   f. describe floor cracks and holes through crawl space floor:
   g. floor covering - specify:

4. Crawl space floor depth below grade:

5. Describe crawl space access:
   condition:

6. Crawl space vents:
   a. number
   b. location
   c. cross-sectional area
   d. obstruction of vents (soil, plants, snow, intentional)

7. Crawl space wall-to-floor joint:
   a. estimate length and width of crack
   b. indicate if sealed with gaskets of rubber, polystyrene, other - specify
   c. accessibility - describe

8. Crawl space contains:
   a. standard drain(s) - location
   b. French drain - describe length, width, depth
   c. sump
   d. connect to: weeping tile system
      (1) sanitary sewer
      (2) water trap (trap filled, empty)

9. Forced air heating system ductwork: condition and seal - describe

10. Crawl space heated: a. intentionally
    b. incidentally

11. Crawl space electrical service:
    a. electrical outlets - number
    b. breaker/fuse box - location

12. Describe the interface between crawl space, basement, and slab:

(continued)

HOUSE INSPECTION FORM (Continued)

13. Penetrations between crawl space and first floor:
    a. plumbing ________________
    b. electrical ________________
    c. ductwork: ________________
    d. other: ________________

14. Number and locations of bypasses or chases to attic ________________

15. Caulking feasible from: a. basement
    b. living room

IV. BUILDINGS WITH FULL OR PARTIAL SLAB FLOORS

1. Slab use: occupied, recreation, storage, other: ________________

2. Slab room(s) finish:
    a. completely unfinished, walls and floor have not been covered with paneling, carpet, tile, etc.
    ____
    b. fully finished - specify finish materials ________________
    c. partially finished - specify ________________

3. Slab floor materials:
    a. poured concrete
    b. block, brick, or stone - specify ________________
    c. other materials - specify ________________
    d. fill materials under slab: sand, gravel, packed soil, unknown
    - source of information________________
    e. describe floor cracks and holes through slab floor ________________
    f. floor covering - specify ________________

4. Elevation of slab relative to surrounding solid (e.g., on grade, 6 in. above grade): ________________
    - is slab perimeter insulated or covered? yes, no

5. Slab area access to remainder of house - describe: ________________
    - normally: open, closed

6. Slab wall-to-floor joint (describe accessibility):
    a. estimate length and width of crack ________________
    b. indicate if sealed with gasket of rubber, polystyrene, other - specify ________________
    c. accessibility - describe ________________

7. Slab drainage:
    a. floor drain - describe ________________
    b. drain tile system beneath slab or around perimeter - describe ________________
    c. source of information ________________

(continued)

HOUSE INSPECTION FORM (Continued)

8. Forced air heating system ductwork:
    a. above slab condition and seal - describe ____________________
    b. below slab: ____________________
        (1) length and location ____________________
        (2) materials ____________________

9. Slab area electrical service:
    a. electrical outlets - number ____________________
    b. breaker/fuse box - location ____________________

10. Describe the interface between slab, basement, and crawl space:

____

11. Penetrations between slab area and occupied zones:
    a. plumbing ____________________
    b. electrical ____________________
    c. ductwork ____________________
    d. other ____________________

12. Bypasses or chases to attic: ____________________

(continued)

HOUSE INSPECTION FORM (Continued)

V. SUBSTRUCTURE SERVICE HOLES AND PENETRATIONS

(Note on Floor Plan)

Complete table to describe all service penetrations (i.e., pipes or conduit for water, gas, electricity, or sewer) through subfloors and walls. Indicate on floor plan.

Description of service, size, location, accessibility	Size of crack or gap around service and type and condition of seal
Example: water, 3/4-in. cooper pipe, through floor, accessible.	Example: Approx. 1/8-in. gap around circumference of pipe with sealing polystyrene gasket.

(continued)

HOUSE INSPECTION FORM (Continued)

VI. APPLIANCES

MAJOR APPLIANCES LOCATED IN SUBSTRUCTURE (CRAWL SPACE, SLAB ON GRADE, BASEMENT)

Appliance	Location (Crawl, slab, base)	Description (Fuel type, style, operation)
Furnace		
Water heater		
Water conditioners		
Air conditioner		
Clothes dryer		
Exhaust fans		
Other:		

Forced air duct/plenum seals - describe

Combustion appliances: combustion air supplied (yes, no)

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