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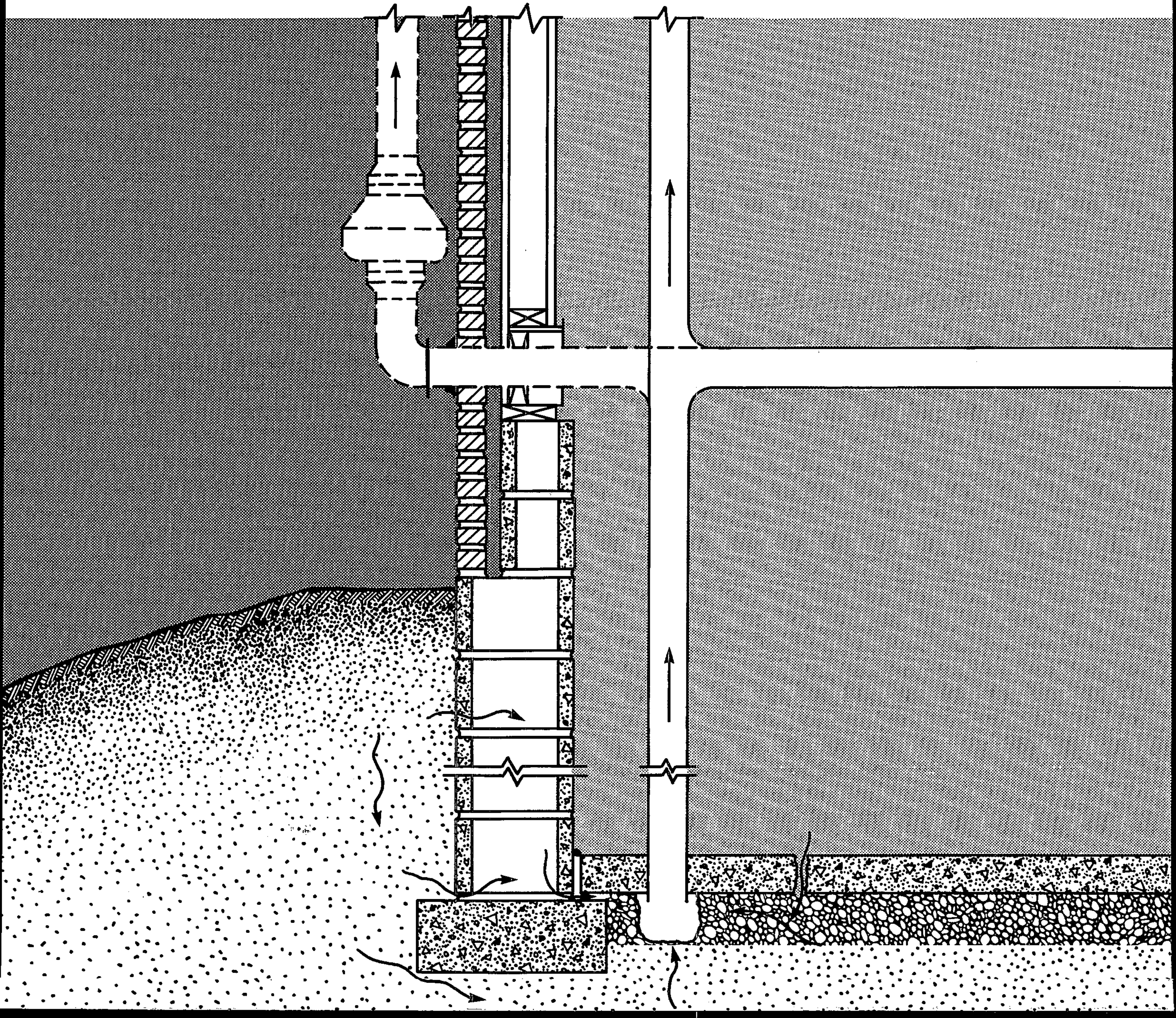
Radon Reduction Techniques for Detached Houses

Technical Guidance
(Second Edition)



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Radon Reduction Techniques for Detached Houses

Technical Guidance

(Second Edition)

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Research Triangle Park, North Carolina 27711

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FOREWORD

This document is intended for use by State officials, radon mitigation contractors, building contractors, concerned homeowners, and other persons as an aid in the selection, design, and operation of radon reduction measurements for houses.

The document is the second edition of EPA's technical guidance for indoor radon reduction techniques. This edition incorporates additional and updated information, reflecting new results and perspectives that have been obtained in this developing field since the first edition was published in June 1986. It is anticipated that future editions will be prepared, as additional experience is gained. New information is continually becoming available through development and demonstration work funded by EPA and others, and through the practical application of these mitigation systems by private mitigators.

A brief overview of the material contained in this document is available in the booklet, "Radon Reduction Methods: A Homeowner's Guide (Second Edition)," OPA-87-010. Copies of that booklet, and additional copies of this more extensive document, can be obtained from the State agencies and the EPA Regional Offices listed in Section 10. Copies can also be obtained from EPA's Center for Environmental Research Information, Distribution, 26 W. St. Clair Street, Cincinnati, OH 45268.

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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 (Section 11). It is the innovative work of these many persons that has made this document possible.

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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 also, 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.

Backer rod—A rope of compressible plastic foam. Backer rod can be force-fit into wide cracks and similar openings, to serve as a support for caulking material.

Band joist—Also called header joist, header plate, or rim joist. A board (typically 2 x 8 in.*) 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 something through a surface that is to be protected. More specifically, grout, caulk, 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.

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.

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 depressurization, the blower door permits determination of the tightness of the house shell, and an estimation of the natural 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.

Confidence—The degree of trust that a method will achieve the radon reduction estimated.

Contractor—A building trades professional who works for profit to correct radon problems, a remediation expert. At present, training pro-

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*Readers more familiar with metric units may use the equivalents listed at the end of the front matter.

grams 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.

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.

De-gassing—As used here, the release of dissolved radon gas into the house air when radon-containing well water is used in the house.

Depressurization—In houses, a condition that exists when the air pressure inside the house is slightly lower than the air pressure outside or the soil gas pressure. The lower levels of houses are essentially 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.

Exfiltration—The movement of indoor air out of the house.

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.

Equilibrium ratio—As used here, the total concentration of radon progeny present divided by the concentration that would exist if the progeny were in radioactive equilibrium with the radon gas concentration which is present. At equilibrium (i.e., at an equilibrium ratio of 1.0), 1 WL of progeny would be present when the radon concentration was 100 pCi/L. The ratio is never 1.0 in a house; that is, the progeny never reach equilibrium in a house environment, due to ventilation and plate-out. A commonly assumed equilibrium ratio is 0.5 (i.e., the progeny are half-way toward equilibrium), in which case 1 WL corresponds to 200 pCi/L. In practice, equilibrium ratios of 0.3 to 0.7 are commonly observed.

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

French drain (also perimeter drain or channel drain)—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 block wall and the concrete floor slab around the entire perimeter inside the basement.

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

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.

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—Also known as air-to-air heater exchangers or 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), or using ash remaining after combustion of solid fuels (cinder block). Walls constructed using hollow blocks form an interconnected network with their interior hollow cavities.

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 rate. The reverse of exfiltration.

Ionizing radiation—Any type of radiation capable of producing ionization in materials it contacts; includes high energy charged particles such as alpha and beta rays and nonparticulate radiation such as neutrons, gamma rays, and X-rays. In contrast to wave radiation, such as visible light and radio waves, which do not ionize adjacent atoms as they move.

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

Latent heat—Heat that is associated with the change in physical form of a substance (e.g., with the vaporization of liquid water). For example, when an air conditioning unit condenses moisture from humid air, it is said to be removing latent heat. Distinguished from sensible heat.

Load-bearing—A term referring to walls or other structures in a house that contribute to supporting the weight of the house.

Makeup air—In this application, outdoor air supplied into the house to compensate for house air which is exhausted by combustion appliances or other devices such as exhaust fans. Provision of makeup air can reduce the house depressurization that might otherwise result from the use of these appliances.

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.

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 underneath a concrete slab. 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 gas. A picocurie per liter corresponds to 0.037 radioactive disintegrations per second in every liter of air.

Plate-out—As used here, the tendency of radon progeny to adhere to surfaces (such as walls, furniture), as the result of electrostatic charges on these very fine particles.

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.

Sensible heat—Heat which is associated with the change in temperature of a substance. For example, when the temperature of an incoming flow of cold outdoor air is raised by use of a heat recovery ventilator, the outdoor air is said to have gained sensible heat. Distinguished from latent heat.

Sill plate—A horizontal band (typically 2 × 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.

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

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

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. Major constituents of soil gas include nitrogen, water vapor, carbon dioxide, and (near the surface) oxygen. Since radium-226 is essentially always present in the soil or rock, trace levels of radon-222 will exist in the soil gas.

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 in principle 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.

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 × 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 metric units 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*
degree Fahrenheit (°F)	5/9 (°F-32)	degree Centigrade (°C)
inch (in.)	2.54	centimeter (cm)
foot (ft)	30.5	centimeter (cm)
square foot (ft^2)	0.093	square meter (m^2)
cubic foot (ft^3)	28.3	liter (L)
cubic foot per minute (cfm, or ft^3/min)	0.47	liter per second (L/sec)
British Thermal Unit (Btu)	1060	joule
gallon (gal)	3.78	liter (L)
horsepower (hp)	746	watt (W), or joule/sec
atmosphere (atm)	101	kiloPascal (kPa)
inch of water column (in. WC)	248	Pascal (Pa)
picocurie per liter (pCi/L)	37	Becquerel per cubic meter (Bq/m^3)
microrem (μrem)	0.01	microSievert (μSv)
Working Level (WL)	29	microSievert per hour (μSv/hr)

EXECUTIVE SUMMARY

This document is designed to aid in the selection, design, and operation of measures for reducing the levels of naturally occurring radon gas in existing houses. Some of these measures can also be adapted for use in new construction.

Radon-222 is a colorless, odorless radioactive gas which is created by 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 essentially everywhere, becoming a trace constituent of the "soil gas" which exists in the soil, and also dissolving in underground water. Radon-containing soil gas 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 is drawn into the house. 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 soil, 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 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 gas being released from water used in the house. However, well water is usually only a secondary radon source compared to soil gas.

Radon gas at sufficient concentrations is a health concern because it decays into other radioactive elements ("radon progeny") which 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 progeny exceed roughly 0.02 "working levels" (0.02 WL). By some estimates, 12 percent of U. S. houses might have radon concentrations exceeding this guideline.

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 pre-reduction radon concentration and a variety of house design and construction details.

This document is intended for use as a handbook by State officials, radon mitigation contractors, building contractors, concerned homeowners, and other persons to aid in the selection and design process, and to aid in evaluating the operation of the installed system. Section 2 of the document describes the overall approach for reducing indoor radon levels. Sections 3 through 8 provide guidance on the selection, design, and operation of specific reduction techniques.

Residential radon reduction is a relatively new field. While substantial radon reductions can be achieved in essentially any house having elevated levels, it is not currently possible to guarantee that levels will always be reduced below an annual average of 4 pCi/L. The performance of a given system in a given house—and/or the ultimate costs that will be incurred in modifying the system to achieve the desired performance—cannot always be reliably predicted before installation.

The following section (E.1) discusses the overall approach that can be followed in the implementation of a radon reduction measure, summarizing Section 2 of this document. Section E.1 begins with the initial determination that a radon problem exists in a house, and proceeds through the various steps, ending with the testing to verify that an installed reduction measure is in fact functioning properly. The next section (E.2) provides an overview of the various radon reduction measures that can be considered, summarizing Sections 3 through 8.

E.1 Approach for Radon Reduction

E.1.1 Measurement of Radon Levels

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. As discussed in Section 2.1, 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 themselves. 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). This time integration averages out the inherent hour-to-hour variation in indoor radon levels, and thus provides a meaningful measure of the concentration to which homeowners are exposed.

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. 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.

More details on measurement methods and protocols are provided in Section 2.1.

E.1.2 Identification of Radon Entry Routes and Driving Forces

If elevated indoor radon levels are discovered, a logical next step is to identify where the radon might be entering, and the features possibly contributing to the driving force causing soil gas to enter.

Radon-containing soil gas can enter a house anywhere that it can find an opening where the house contacts the soil. Such openings will always be present, even in well-built houses. A checklist of possible entry routes for various house substructure types is presented as Table 4 in Section 2.2; these entry routes are illustrated in Figure 1. 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 poured concrete walls);
- openings in concrete slabs (such as any holes through the slabs, sumps, untrapped floor drains which connect to the soil, the joint between the slab and the foundation wall, and settling cracks and cold joints);
- for crawl-space houses, any openings between the crawl space and the living area (such as utility penetrations through the subflooring);
- for crawl-space houses any leakage of crawl-space air into the low-pressure return ducting of a central forced-air furnace located in the crawl space.

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.

Factors which can contribute to the driving force for soil gas entry are listed in Table 5 in Section 2.2. These factors include:

- weather-related factors (specifically, temperature and wind velocity), which cause portions of the house to become depressurized;
- house design factors including the tightness of the house shell and thermal bypasses between stories, as discussed in Section 2.2. These factors can facilitate air movement up through the house, and soil gas flow into the house, under the temperature-induced depressurization.
- homeowner activities, such as the use of combustion appliances and exhaust fans, which can contribute to depressurization.

E.1.3 Immediate Radon Reduction Steps by Homeowner

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. As discussed in Section 2.3, such steps include:

- increased 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 living areas). 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.
- closure of 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.

- taking 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.

E.1.4 Diagnostic Testing to Aid in Selection and Design of Radon Reduction Measures

A variety 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 measure for a particular house. A number of candidate diagnostic tests are described in Section 2.4. While various diagnostic tests are used by various mitigators, some of the more important ones are:

- visual survey of possible soil gas entry routes, of features possibly contributing to the driving force, and of structural features which could influence mitigation selection and design. Such a survey is an essential component of any good diagnosis.
- measurement of the permeability (the ease of gas movement) underneath the concrete slab, whenever sub-slab soil ventilation is being considered as a control technique. Such measurements can provide substantial information to aid in the selection of sub-slab ventilation pipe location, fan capability, and piping diameter.
- measurement of the natural infiltration rate (or the effective leakage area through the house shell). This measurement is useful only when the reduction techniques which increase the ventilation rate are being considered (such as a heat recovery ventilator). The performance of ventilation techniques in reducing radon will depend upon what the infiltration rate is before the system is installed.

Some of the other diagnostic tests which are commonly considered are: a) radon measurements at potential soil gas entry routes, to assess whether some routes are relatively more important than others, thus warranting some priority in the design of the mitigation system; and b) measurements of radon levels in well water and of gamma levels inside and outside the house, as indicators of whether water or building materials (in addition to soil gas) might be important contributors to the airborne radon levels.

E.1.5 Selection, Design, and Installation of the Radon Reduction Measures

As discussed in Section 2.5, the selection and design of a radon reduction measure for a given house will be determined by a number of factors, including: the degree of reduction required to reach 4 pCi/L; 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 design and construction features of the house; and the results of the pre-mitigation diagnostic testing.

Where radon reductions above 80 percent are required (i.e., where the initial radon levels are above about 20 pCi/L), it currently appears that some type of active soil ventilation approach will usually be required. The alternatives to active soil ventilation for achieving such high reductions are less practical (continuous natural ventilation through open windows, including during periods of extreme weather), and/or are developmental (house pressurization). If lower levels of radon reduction are sufficient, other reduction techniques can also be considered (e.g., heat recovery ventilators, sealing of entry routes, or perhaps passive soil ventilation), although active soil ventilation techniques will still be an important option.

In some cases, it will be cost effective to install a radon reduction system in phases. In such an approach, one would begin by installing the simplest, least expensive design which offers reasonable potential for achieving the desired radon reductions. If this initial installation does not provide sufficient reduction, the system would be expanded in a series of one or more pre-designed steps, until the desired degree of reduction is achieved.

Since there is no organization which certifies radon mitigation contractors on a national basis, evaluation of candidate contractors generally falls on the homeowner. Some States are developing contractor certification programs, which can aid in this evaluation. Some suggestions to aid in selecting a contractor are given in Section 2.5. Homeowners should consider installing a mitigation system on a do-it-yourself basis only if they feel conversant with the principles behind the system, and have had an opportunity to inspect a similar installation in another house.

E.1.6 Testing After the Reduction Technique Is Installed

After the radon reduction measure is installed, a several-day measurement of radon gas should be made to give an initial indication of the success of the system. Where the mitigation measure would be expected to affect the relative amounts of radon gas and radon decay products, radon progeny might also be measured. Possible measurement techniques include charcoal canisters, continuous monitors, or RPISU. 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 sufficient reductions, then it should be followed up by at least one alpha-track detector measurement over 3 months during the winter to obtain a measure of sustained system performance under the challenging conditions that cold weather presents. A homeowner might wish to make additional alpha-track measurements over a period of a year or more.

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 piping joints and slab/wall closures are adequately sealed.
- pressure and flow measurements in the piping 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 suction (or pressure) underneath the entire slab.
- grab sample radon measurements in individual pipes associated with active soil suction 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 suction system has been installed, in order to ensure that house air being sucked out by the suction system is not depressurizing the house enough to cause backdrafting of the combustion appliances.

Post-mitigation testing is discussed in Section 2.6.

E.2 Alternative Radon Reduction Techniques

The preceding discussion addressed the overall approach for implementing radon reduction measures in houses. The following discussion summarizes some of the key features regarding the alternative radon reduction techniques which are discussed in detail in Sections 3 through 8.

Indoor radon concentrations can be reduced using techniques which fall into two generic categories: techniques which prevent the radon from entering the house to begin with, and techniques which remove radon or its progeny after entry. (A third generic category, removal of the radon source, is not considered in this document because it is usually applicable only where the radon source results from industrial processing, and hence can be isolated and removed.) Techniques which prevent radon entry include: sealing soil gas entry routes into the house; soil ventilation, to suck or force soil gas away from the house before it can enter; adjustment of the pressure inside the house, to reduce or reverse the driving force for soil gas entry; and removal of radon from the well water entering the house. Techniques which remove the radon after entry include: ventilation of the house, and air cleaners to remove radon progeny (or radon gas).

Table E-1 presents a summary of these techniques. Detailed discussions of the techniques are provided in Sections 3 through 8 of this document. The summary discussion below is intended to supplement the information in Table E-1.

The order in which the various techniques are presented here should not be construed as suggesting a relative priority for their consideration.

E.2.1 House Ventilation (Section 3)

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 percent 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 thermal stack effect. Also, windows should be opened on more than one side of the house, preferably on all sides,

Table E-1. Summary of Radon Reduction Techniques

Method	Principle of Operation	Applicability	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs*
House Ventilation						
Natural (Sec. 3.1)†	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. 3.1)	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 $50 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 that for natural ventilation, plus cost for electricity to operate fans (about $65/year for a less powerful window fan, $275/year for a more powerful window fan or a central furnace fan).

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*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.

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

Table E-1. (continued)

Method	Principle of Operation	Applicability	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs*
Forced Air with Heat Recovery (heat recovery ventilators or HRVs) (Sec. 3.2)	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 stand-alone method to achieve 4 pCi/L only when initial radon level 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 of 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 used 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 $30 per year for a 200 cfm unit) and for inlet air preheat (if used).
Sealing of Soil Gas Entry Routes (Sec. 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 of 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.

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*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.

Table E-1. (continued)

Method	Principle of Operation	Applicability	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs*
Active Soil Ventilation						
Drain Tile Ventilation (Sec. 5.2)	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 tiles drain to a sump. Costs depend upon: depth of tiles; height of, and 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, $120/year heating and cooling penalty resulting from increased house ventilation.
Sub-Slab Ventilation (Sec. 5.3)	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 maintaining at least 0.5-1.0 in. WC suction at the gas flows encountered.	Installation by contractor would likely cost between $900 and $2,500, 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, $120/year heating and cooling penalty.

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*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.

Table E-1. **(continued)**

Method	Principle of Operation	Applicability	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs*
Block-wall Ventilation (Sec. 5.4)*	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 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 tightened, 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, $240 to $480/year heating and cooling penalty.
Isolation/ Venting of Area Sources (Sec. 5.5)	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 is 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.

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*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.

Table E-1. (continued)

Method	Principle of Operation	Applicability	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs*
Passive Soil Ventilation (Sec. 5.6)	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. 6.1)	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 of 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 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 be dependent upon characteristics of 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 depressurization. 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.

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*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.

Table E-1. (continued)

Method	Principle of Operation	Applicability	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs*
House Pressurization (Sec. 6.2)	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 $1,500 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. 7)	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 attach. 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 to recommend either the use of particle-removal air cleaners for radon reduction, or discontinued use of existing air cleaners.	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 health 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 costs include electricity to operate fan(s) circulating the air through the cleaner and to develop charge in cleaner where cleaner operates on electrostatic principles.

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*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.

Table E-1. (continued)

Method	Principle of Operation	Applicability	Radon Reductions Achievable, %	Confidence in Performance	Installation and Operation Considerations	Estimated Installation and Operating Costs*
Removal from Water (Sec. 8)	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 tanks, 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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*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.

to provide proper cross-ventilation; under some conditions, radon levels might be made worse by wind-induced depressurization if windows are opened on only one 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 between the soil and the living area.

The primary shortcoming of natural ventilation is that extreme weather could make this technique impractical to use 365 days per 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 implemented during the winter, heating costs might increase by as little as 10 percent (if windows are left open only slightly, or if a crawl space is ventilated), or by as much as 300 percent 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 continuously blow fresh air into the house through the existing central forced-air heating ducting 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 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 percent 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 levels. 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 out through the HRV, transferring between 50 and 80 percent 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 percent. 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 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 understood.

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, or to changes in wind velocity). The homeowner must conduct the maintenance that is required (e.g., cleaning or replacing air filters, cleaning the core, annual rebalancing of flows). Due to these considerations, the confidence in the performance of fully ducted HRVs is estimated in Table E-1 to be moderate (rather than high, as for the other house ventilation approaches). The confidence in wall-mounted HRVs is lower, since effective distribution of the fresh air is an additional concern with wall units.

HRVs are typically balanced such that the inlet and outlet flows are equal, which is the condition providing the best heat recovery performance. Under this condition, the HRV will generally not reduce the influx of soil gas, which is 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 unbalanced, 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.

E.2.2 Sealing (Section 4)

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. Such a barrier is intended to totally prevent the convective movement (and sometimes the diffusive movement) of 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.

For the purposes of this discussion, soil gas entry routes are divided into two primary categories: major and minor. 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 drains, French drains, and uncapped top blocks in hollow-block foundation walls. Minor routes are small and can be distributed over broad areas. Examples of minor routes include hairline cracks and the pores in block walls. Because they are often numerous and widespread, minor routes collectively can be very important sources of radon in the house.

Accessible major entry routes should always be closed as a matter of course to reduce soil gas entry. A reasonable effort should be made to ensure that these closures are true gastight seals (see Section 4.1). However, the openings associated with these entry routes are generally so large that some meaningful radon reduction might 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 trapping water collection systems. In addition to these large routes, accessible smaller, "intermediate" holes and cracks in slabs and walls should be closed with mortar, caulk, or other sealant. These 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 (see Table 4 in Section 2). 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. 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 closure (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 drawn by an active soil ventilation system (see Section 5). Large amounts of house air leakage into the soil suction system would 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 needed. 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 is not justified for the purpose of reducing leakage into active soil ventilation systems.

If an attempt were to be made to reduce a high radon level 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 to be gastight. Also, the minor routes such as hairline 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 numerous with many being 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 is not felt to be a viable technique by itself for treating houses with high radon levels. At present, it appears that homeowners will generally be best served simply by doing the best reasonable job at 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.

E.2.3 Soil Ventilation (Section 5)

Where radon reductions above 80 percent are required—and, often even where lesser reductions are needed—it currently appears that some form of active (i.e, fan-assisted) soil ventilation will need to be part of a practical, permanent solution. In high-radon houses, natural ventilation can be implemented as an immediate, temporary fix. Also, major accessible entry routes can be sealed as a potentially helpful reduction step which will be necessary anyway when a soil ventilation system is installed. But it should generally be anticipated that the installation of an active soil ventilation system could ultimately be necessary. With any soil ventilation system, the objective is to maintain a pressure field through the soil and aggregate under and around the house, which will suck or force the soil gas away from the house before it can enter.

Drain tile suction. Where a house with a slab has drain tiles for water drainage purposes around the inside or outside of the footings along all four of the perimeter foundation walls, suction on these tiles should be the first active soil ventilation approach considered. Even if the tiles are beside only two or three of the perimeter walls, drain tile suction might be very effective, if there is a good layer of crushed rock (or permeable soil) under the slab. However, radon reductions might be less when the drain tile loop is not complete. The advantages of drain tile suction are that:

- it can be very effective (up to 99+ percent reduction when the tile loops around all four walls). The suction will be distributed around the entire house perimeter via the tiles, with the suction being particularly effective where it is needed the most (in the footing region and near the wall/floor joint) due to the location of the tiles;
- it is often the least expensive of the soil ventilation approaches; and
- where the tiles drain to a point outside the house, the entire installation can be outdoors, thus offering advantages in convenience and appearance.

If there is a major soil gas entry route (such as a block fireplace structure) in the center of the slab (remote from the perimeter tiles), the performance of the drain tile system might be reduced.

The tiles might drain either to an above-grade discharge or dry well outside the house, or to a sump inside the house. Where the tiles drain outside, the drain tile suction system involves tapping into the underground discharge line with a vertical PVC pipe, onto which a fan in suction is mounted above grade level. A water trap is installed in the point discharge line between the fan riser and the discharge point or dry well, to prevent the fan from simply drawing air up from the above-grade discharge or dry well. If there is more than one discharge line, all must be trapped. Where the tiles drain to an interior sump, the sump must be covered with an airtight cap, and suction drawn on the sump cavity.

The fan used must be sufficient to maintain at least 0.5 to 1.0 in. WC suction at the soil gas flows encountered, in order to establish a sufficient low-pressure field under the entire slab. Accessible openings in the slab inside the house must be closed so that large amounts of indoor air do not flow out into the suction system through these openings, preventing the system from maintaining a sufficient pressure field. It is recommended that the high-radon fan exhaust gas be discharged above the house eaves away from windows, to avoid flow of the discharged soil gas back into the house.

Sub-slab suction. In houses with slabs where drain tile suction is not an option, the next active soil ventilation approach to consider is sub-slab suction. With this approach, individual PVC pipes are inserted into the soil/aggregate under the slab—either vertically down through the slab from inside the house, or horizontally through the foundation wall beneath the slab. A fan draws suction on these pipes.

Active sub-slab suction has been one of the more widely used radon reduction techniques. Where a good layer of crushed rock (or permeable soil) exists under the slab, sub-slab systems have demonstrated ability to maintain an effective low-pressure field under the slab, often giving reductions above 90 percent. When the permeability under the slab is not so good, sub-slab suction will still often be applicable. However, more care is then required in designing the system (e.g., more suction pipes might be needed, pipe positioning might be more important), and radon reductions might not always be as good. Diagnostic testing can be conducted before the sub-slab system is installed, measuring the pressure field that can be established under the slab. These results will indicate the relative ease with which a sub-slab system might treat a particular house, and can aid in the design of the system when the sub-slab permeability is good. Further developmental work is needed to demonstrate reliable design criteria that can be used when the permeability is not good.

As with drain tile suction, sub-slab suction systems require a fan capable of maintaining at least 0.5 to 1.0 in. WC, and closure of accessible openings in the slab. The high-radon fan exhaust should be released above the eaves away from windows. Operation of the sub-slab ventilation system in pressure (blowing outdoor air under the slab) would avoid the concern regarding release of the fan exhaust when in suction. However, sub-slab pressurization has not been widely tested, and introduces other potential operational concerns.

Block wall ventilation. In houses with hollow-block foundation walls, ventilation of the void network inside the walls can sometimes provide effective reductions. However, the performance of block wall ventilation systems appears to be less predictable than that of sub-slab suction.

Good reductions with wall ventilation require adequate closure of major wall openings, so that the pressure field will adequately extend throughout the void network. Also required is the absence of major slab-related entry routes such as extensive slab cracks, remote from the walls, since the effects of wall ventilation will not always extend effectively under the slab. It is not always possible to reliably predict when adequate wall closure can be accomplished, and when slab-related routes will be too significant for treatment by the wall ventilation system. Also, wall ventilation will result in a greater heating penalty than will sub-slab systems, since the leakiness of the walls will result in the wall system drawing (or blowing) more air out of (into) the house. As a result of these concerns, it will usually be appropriate to consider a sub-slab suction system first, unless the house is ideally suited to wall ventilation and has poor sub-slab permeability. Addition of wall treatment as a supplement to sub-slab suction should be considered only when the sub-slab system alone demonstrates an inability to adequately prevent radon entry through the block walls.

The "baseboard duct" approach to wall ventilation will help ensure more uniform treatment of the walls, and possibly better treatment of the slab, in comparison with the alternative case where individual PVC pipes are inserted into each foundation wall. However, the baseboard duct approach is likely to be more expensive than a sub-slab suction system due to greater installation labor requirements, especially where the area being treated is finished.

Because a block wall suction system might draw enough air out of the house to cause back-drafting in some combustion appliances, the appliances should be carefully checked for signs of back-drafting (including flow measurements in the flue as warranted). If back-drafting is observed, consideration should be given to operating the wall system under pressure.

Isolation and ventilation of area sources. Where soil gas entry routes exist which cover a broad area, one could attempt to isolate and ventilate these sources. Examples include: installation of a gastight plastic liner over the earthen floor of a crawl space, with ventilation between the liner and the soil; and installation of a gastight false floor or false wall over a badly cracked existing floor or wall, ventilating the space between the new and the original floor or wall. Other mitigation options will often be more effective and/or less expensive than this isolation/ventilation approach (such as natural or forced ventilation for the crawl space, or sub-slab suction under cracked slabs). These other options should be considered before isolation/ventilation is decided upon. However, sometimes the isolation/ventilation approach will be the most cost effective.

Passive soil ventilation. The active (fan-assisted) soil ventilation approaches discussed previously might also be considered for operation as passive soil ventilation systems. 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 suction in the passive vent stack. The suction which can thus be established is very small, relative to that possible with a fan, and a very effective network for distributing this suction is needed if a passive system is to be able to maintain a sufficient pressure field 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 suction levels are so low, a passive system would be more subject to being overwhelmed when the house is depressurized by weather or occupant activities. Performance of passive systems could thus be more variable over time than that of 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.

E.2.4 House Pressure Adjustments (Section 6)

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 are only intermittent (such as fireplaces and exhaust fans), any radon reductions that are achieved will apply only over short time periods. However, it is known that these sources can sometimes be significant contributors to indoor radon, and that the benefits of addressing these sources can thus sometimes be significant, at least over short time periods. Therefore, to the extent that steps to reduce depressurization can easily be implemented by the homeowner, the homeowner is well advised to take these steps.

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 low-pressure 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 (see Table 5 in Section 2.2.2).

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.

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 developmental approach which has been tested in only a few basement houses to date. Radon reductions as high as 90 percent have sometimes been observed using this approach. Houses with basements (or with heated crawl spaces) might enable that fraction of the house which is in contact with the soil to be isolated from the remainder, and to be pressurized by blowing air into that portion 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 house pressurization appears to offer potential, the technique requires further testing before it can be designed and operated with confidence.

E.2.5 Air Cleaning (Section 7)

Since radon decay products are solid particles, these decay products 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 might 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. The difficulty is 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 percent 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 percent 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 percent 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 percent 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 the 2000 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 the 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.

E.2.6 Radon in Water (Section 8)

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 the 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 might 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. GAC units have been commonly 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 capability, radon removals of over 99 percent 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 (and possibly for a decade or more), 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.

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 percent 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+ percent that has sometimes been reported for GAC. 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).

E.2.7 Radon Reduction in New Construction (Section 9)

During the stage 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 building houses who are concerned about a potential for elevated radon levels 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 the soil gas entry routes, including, for example, steps to avoid 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, avoidance of 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 Reduction in New Construction: An Interim Guide," reproduced as Appendix B.

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. As discussed in Appendix B, 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 1
Introduction

1.1 Purpose

This document is designed to aid in the selection, design, and operation of alternative measures for reducing the levels of naturally occurring radioactive radon gas in existing houses. Some of these measures can also be adapted for use in new construction. The document has been prepared by the U. S. Environmental Protection Agency (EPA) for use by State radiological health officials, State environmental officials, radon mitigation contractors, building contractors, concerned homeowners, and others, to assist in evaluating indoor radon reduction approaches and in ensuring that the reduction techniques are installed and operating properly. This document distills data from a number of researchers and radon mitigators who have tested radon reduction measures under a variety of conditions.

This document is not intended to provide EPA-approved designs for radon reduction systems. Rather, the document simply attempts to convey an accurate description, and practical perspective, regarding the state of knowledge in the radon mitigation field. Technique design features described here are consistent with current good practice, but might sometimes have to be modified based upon unique conditions in a particular house, or based upon design improvements which are developed in the future. Neither can this document ensure that a radon reduction system, if designed as described here, will necessarily always provide radon reductions in the range indicated. Experience with residential radon reduction is still somewhat limited, and reduction performance can be very dependent upon house construction features which are concealed.

This edition of the document updates and replaces the earlier edition of the same title (EPA86a).* A summary of the radon reduction measures described in this document can be found in the companion EPA brochure entitled "Radon Reduction Methods: A Homeowner's Guide" (EPA87c). Further general discussion of the indoor radon problem, and of the health risks associated with indoor radon, is presented in an EPA brochure entitled "A Citizen's Guide to Radon" (EPA86b), and in the "Radon Reference Manual" (EPA87f).

1.2 Radon Sources and Approaches for Radon Reduction

Airborne radon gas inside a house can result from one or more of three potential sources: soil gas, well water, and mineral-based building materials. Any one of these three sources can result from *naturally occurring* uranium (and radium) in the soil and rock surrounding the house, or in the materials used during its construction. The soil gas and building material sources can also be created when a house is built on top of, or is fabricated from, materials which have had their radon emission potential increased through industrial processing (i.e., *"technologically enhanced"* materials). Technologically enhanced materials include uranium mill tailings, radium processing plant wastes, and wastes from phosphate rock processing. Among the naturally occurring sources, soil gas is often the predominant cause of indoor radon; where well water is a source, it is usually only a secondary contributor, but it can be significant in some areas. Naturally emitting building materials appear to be only relatively low-level, generally minor sources except in isolated cases.

There are three generic approaches for reducing or preventing elevated radon levels inside houses.

1. *Removing the radon source* (i.e., removing contaminated soil and/or building materials, and replacing them with uncontaminated materials). This approach is applicable primarily when the source is the result of industrial processing (or sometimes when the source is naturally emitting building materials), so that the entire source can be isolated.
2. *Preventing radon entry into the house,* through:
   - sealing soil gas entry routes,
   - ventilating the soil to divert soil gas away from the house,
   - adjusting the pressure inside the house, to reduce or eliminate the driving force for soil gas entry, and
   - treating the well water entering the house.

   This approach addresses the soil gas source of radon (and, in the case of water treatment, the water source), whether naturally occurring or technologically enhanced. (In addition, sealing of wall and floor sur-

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*Alphanumeric figures in parentheses, such as this, refer to the references listed in Section 11.

faces has sometimes been used in an effort to prevent radon emanation from building materials.)

3. *Removing radon from the house after entry*, including:
   - house ventilation, and
   - air cleaning.

   This approach would address any of the three sources, whether naturally occurring or technologically enhanced.

1.3 Scope and Content

The scope of this document is as follows.

1. The radon reduction techniques described in this document focus on naturally occurring radon which enters the house via soil gas. As stated previously, soil gas is generally the major source of naturally occurring radon in a house. This document addresses the full range of techniques that might be considered for eliminating radon resulting from soil gas.
2. Reduction techniques applicable to naturally occurring radon in well water are also described (in Section 8).
3. The techniques described here do not specifically address building materials as a source of radon, although some of the sealing techniques, and the techniques involving radon removal after entry, can be used to address building material sources.
4. The techniques described here do not specifically address technologically enhanced sources of radon. However, the techniques which apply to naturally occurring radon in soil gas can also generally be used to address radon from the technologically enhanced sources (i.e., techniques to prevent soil gas entry, and techniques to remove radon after entry). But source removal techniques—which are sometimes the approach of choice in the case of technologically enhanced sources—are not considered in this document. For information on treating technologically enhanced sources for indoor radon, the reader is referred to pertinent remediation programs conducted under the Uranium Mill Tailing Radiation Control Act of 1978, and under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 ("Superfund") as amended.
5. This document does not attempt to provide detailed guidance on air cleaners, but rather, provides only a brief overview of these devices in Section 7. Air cleaners are addressed in an abbreviated manner due to uncertainty regarding the benefits of these devices in reducing the health risk due to radon, as discussed in Section 7.
6. This document emphasizes those radon reduction techniques which have been subjected to a reasonable degree of testing in houses, and which have demonstrated reasonable efficacy. Techniques which have received only limited field testing, and for which the practical applicability has not yet been reasonably demonstrated, are addressed more briefly. The pressurization of houses is one example of a developmental technique which is conceptually promising, but not yet practically demonstrated.
7. This document focuses on techniques which can be retrofitted into existing houses, because most testing of radon reduction techniques to date has been in existing houses. In Section 9, reference is made to the use of some of these techniques in new houses under construction. The data base to confirm the performance of radon reduction techniques that can be incorporated into new houses during construction is currently very limited. However, testing of techniques for new houses is underway now. Details regarding measures that can be used in new construction will be included in future editions of this guidance document. In the interim, the reader is referred to EPA's "Radon Reduction in New Construction: An Interim Guide" (EPA87d), which is reproduced as Appendix B.
8. This document describes techniques which can be applied to the full range of dwelling substructure types, including basement houses, slab-on-grade houses, crawl space houses, and combinations thereof. Technique selection and design will often be influenced by the substructure type, and by the foundation wall construction materials (e.g., concrete block or poured concrete).
9. The techniques described here can be applied to a range of initial radon concentrations. The selection and design (and hence the cost) of a radon reduction measure can be influenced by the initial radon level, and thus the degree of reduction needed.

Within the scope defined above, this document contains the following types of information.

1. Discussion of the overall approach for reducing radon levels in houses (Section 2). This discussion includes:
   a. a brief review of the measurement methods that can be used to assess whether elevated radon levels exist in a house, and

protocols for getting these measurements made,

b. a listing of potential radon entry routes for which one should check if elevated radon levels are found,

c. a review of relatively simple radon reduction measures that homeowners can fairly readily implement themselves, requiring limited capital cost and limited experience in house repairs,

d. a review of the types of diagnostic tests that can be conducted prior to the implementation of a radon reduction method, as warranted, in an effort to identify the relative significance of the potential radon sources and to otherwise aid in the design of the radon reduction system,

e. a review of some considerations in the selection, design, and installation of the permanent radon reduction measure, and some general suggestions for homeowners on how to locate, select, and evaluate the work of mitigation contractors, and

f. a review of the types of radon monitoring and diagnostic testing that can be conducted after the radon reduction system is in place in order to confirm reduction performance and to identify needed improvements in the installation.

2. Detailed description of the alternative measures for reducing indoor radon levels in existing houses (Sections 3 through 8). Reference to new houses under construction is made in Section 9. In general, the detailed discussion for each reduction measure includes the following elements:

   a. the principles of operation,

   b. the conditions under which the measure is particularly applicable (or inapplicable),

   c. the radon removal performance that might be anticipated with the technique (expressed as the range of the performance levels which have been observed in prior testing), and the degree of confidence regarding the levels that might be achieved using the measure (based upon the extent and consistency of prior experience),

   d. details regarding the design and installation of the measure, often including examples of variations in the designs that might be considered in different applications (e.g., different house substructure types) and including specific diagnostic testing that can be considered for that particular reduction measure,

   e. operation and maintenance requirements in order to maintain performance, and

   f. an estimate of the costs that might be incurred.

   A summary of this information is included in Table E-1 of the Executive Summary.

3. A listing of State and Federal offices that might be contacted for further information (Section 10).

1.4 Confidence in Radon Reduction Performance

The design and installation of systems to reduce radon levels in houses is still a developing field. The design of these systems is not yet as exact a science as, for example, the design of a heating or air conditioning system. Much experience with radon reduction techniques has been gained since the earlier edition of this manual (EPA86a) was issued, and radon mitigators are gaining increased understanding of how techniques must be selected and designed for effective performance under a variety of conditions. Technique design features for a given house, and the type of reduction performance that might be expected, can now be selected and predicted with increasing confidence. However, there remain a number of aspects which are not yet fully understood. For example, many house design and construction features which can significantly influence radon reduction performance are hidden, and might not be adequately identified or detected through premitigation diagnostic testing. These features can include, for example, the distribution of the permeability permitting soil gas movement underneath a concrete slab (important in the design of sub-slab ventilation systems), or the nature of wall openings and soil contacts concealed within a block fireplace structure (which could require closure or particular treatment in conjunction with a sealing approach or a hollow-block wall ventilation technique). In addition, the impacts of air flow dynamics throughout a house on the entry rate of radon-containing soil gas are not fully understood. Thus, weather conditions or homeowner activities that influence house dynamics could influence the performance of the radon reduction system in ways which cannot be quantified beforehand.

It is felt that, by suitable application of selected radon reduction techniques described in this document, substantial radon reductions can be achieved in essentially any house. Many houses with elevated radon levels can undoubtedly have the radon reduced to the EPA guideline level of 4 picocuries of radon* per liter of air (4 pCi/L) average annual exposure, or less, using these techniques. However, the reader should be aware that:

1. it is not certain whether the substantial reductions which can be achieved will always be sufficient in every house to achieve the 4 pCi/L guideline, and
2. it is not certain how much modification to a system will be necessary, after it is installed, in order to achieve high performance. For example, with active soil ventilation systems, the optimum number and location of ventilation points for a particular house, and the necessary degree of concurrent closure of cracks and openings in the wall and slab will sometimes be determined by a greater or lesser degree of design modification after the initial installation is completed.

The later sections of this document include an indication of the radon reduction performance range that has been observed in prior testing, and an estimate of the range of costs that might be encountered in the installation and operation of each control technique. It is expected that, in many future cases where these techniques are installed in a particular house, the performance and costs will be in the indicated ranges. However, since the experience with radon reduction systems is still somewhat limited, it is quite possible that the performance and/or costs of a particular installation in a specific house will fall outside the ranges indicated here. The values could fall outside the indicated ranges because of: a) various technical aspects which are not yet fully understood; b) the experience and design approach of the particular installer; or c) other specific features associated with the particular house (e.g., house size, degree of finish in rooms where work must be done, unique structural features). The discussion of each technique includes an indication of the confidence in these estimates.

1.5 Background

1.5.1 Sources of Radon in Houses

Uranium-238 is a radioactive chemical element which is ubiquitous in nature, present at trace levels in most soils and in many types of rock. Uranium decays through a fixed series of radioactive elements, referred to as the uranium decay chain. At each step in the chain, radioactive particles and/or electromagnetic radiation are released, and a different element is created, until the original parent uranium-238 has decayed to nonradioactive lead-206. Each element in this decay chain is a solid except for one, radon-222, which is a gas.† As a gas, radon can move up through the soil. To reach ground level as a gas, a radon atom must first escape from the rock or soil particle in which its immediate parent in the decay chain, radium-226, was embedded (only perhaps 5 to 40 percent of the radon atoms do escape). Second, the atom must then move through the spaces between the soil particles (or the rock fissures) until it reaches the surface. In its trip to the surface, the radon atom becomes one trace component of what is referred to as "soil gas," gas which continuously moves through the soil. Other components of soil gas are nitrogen (from the air), oxygen (near the surface), water vapor, carbon dioxide, and possibly some soil organics and microorganisms. This process of reaching ground level takes some time.

Radon gas itself decays into other (solid) radioactive elements. Its half-life is 3.8 days—i.e., in that period, half of the radon present at the outset will have decayed into other elements in the decay chain. This half-life is sufficiently long that some percentage of the radon survives long enough to reach ground level. If the half-life were significantly shorter, a greater amount of the radon would decay before reaching the surface, and would thus become trapped (as its solid decay products) in the soil.

If no structure is situated at ground level, the radon which reaches the surface will mix with the outdoor air. The radon concentrations which result in outdoor air can vary from location to location, but are reported to average about 0.25 pCi/L. This concentration is generally well below, and is never higher than, concentrations observed inside buildings in the area. Even in areas in which uranium ore is present in the ground, outdoor levels appear to be relatively low, reportedly about 0.75 pCi/L (Br83). Thus —even though there is estimated to be some health risk even at these low levels, as discussed later—radon concentrations outdoors are not of serious concern. Radon levels in soil gas range from a few hundred picocuries per liter (Br83) to 36,000 pCi/L (Mi87) and even higher. Thus, outdoor levels of 0.25 pCi/L suggest that the soil gas is being diluted by a factor of from 1,000 to 150,000 in the outdoor air.

If a house is situated at ground level, radon concentrations in the dwelling will generally be higher than those outdoors, for two reasons. First, the movement of fresh air through the house is less than the movement outdoors (especially when all doors and windows are closed), so that the radon is not diluted to the extent it is outdoors. Second—

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*A curie is a measure of the number of radioactive disintegrations occurring per second; a picocurie is one-trillionth of a curie (0.000000000001 curie).

†For simplicity, this discussion is limited to radon-222, which is generally the primary radon isotope in indoor air. Another radon isotope that can be present is radon-220, commonly referred to as thoron.

and more important—a house will often tend to have a pressure at the lower levels indoors which is slightly lower than the pressure in the soil. This effect can occur due to the natural tendency of buoyant warm air in the house to rise and leak out around the upper levels, creating a "stack effect," much like hot air rising up the chimney when a fire is burning. This thermal stack effect can be important whenever the temperature indoors is warmer than the temperature outdoors, with the effect being the greatest when the weather is the coldest. Low pressure in the house can also be caused by winds, which create low-pressure regions along the roofline and on the downwind side, sucking air out of the house. Another cause of house depressurization is the exhausting of house air through exhaust fans and combustion appliances. The reduced pressure inside the house actually sucks radon-containing soil gas into the house. The differences in pressure involved here are so small that a homeowner will not notice them, but they play an important role in determining indoor radon levels.

The radon-containing soil gas can enter a house anywhere there is an opening between the structure and the soil, moving under pressure-driven (convective) flow caused by the pressure differences. Entry routes include not only obvious openings, such as visible holes in slabs and in basement foundation walls, but also less obvious ones, such as hairline cracks in slabs and walls, and openings hidden within the foundation wall. Radon entry routes are discussed in more detail in Section 2.2.1.

It should be noted that radon can also enter dwellings by a mechanism called diffusion, involving non-convective movement of radon atoms through cracks and pores (or even through the solid, unbroken concrete slab). However, it is expected that, in most cases, convective flow as described above will be clearly predominant.

The level of radon that will build up in a given house depends upon a combination of several site-specific variables.

1. The radium content of the soil and rock underneath the house. Some of the houses with the highest radon levels have been found to be built over or near well-defined strata of rock having naturally elevated contents of radium.
2. The permeability of the surrounding soil, and faults and fissures in the surrounding rock. As discussed previously, a key factor in the movement of radon up to ground level is its ability to cover the necessary distance before decaying. A soil that is more permeable (and rock that is highly fissured) will permit the radon to move more quickly, and thus to reach the surface with a lesser degree of decay. Also, with more permeable soils, the suction effect created by reduced pressures inside the house will be able to draw soil gas from a broader area underground, thus increasing radon supply into the house. A sandy soil would be relatively permeable, and a clay soil would generally be distinctly less permeable. Other factors, such as moisture content, can also influence permeability.
3. The nature and extent of the openings between the house and the soil (i.e., the entry routes). A house with more extensive entry routes will facilitate radon entry. In general, a dwelling with a basement provides the greatest amount of house/soil contact, and hence the greatest opportunity for entry routes to exist. A house with a crawl space generally provides the least contact between the building and the soil, if the crawl space is naturally ventilated. For any particular house substructure type, the nature and extent of potential entry routes will be determined by specific design features and construction techniques.
4. The driving force sucking soil gas into the house (i.e., the extent of depressurization created by weather conditions and homeowner activities.
5. The air exchange rate (i.e., the ventilation rate) in the house. The more frequently the air inside a house is replaced with fresh outside air, the lower the radon level will be, all other things being equal. All houses have some infiltration of outside air, even when all doors and windows closed. Closed-house ventilation rates of 0.5 to 1.0 air changes per hour are reasonably typical of relatively modern housing (i.e., the amount of outside air infiltrating into the closed house every hour is equal to 50 to 100 percent of the volume of the house).

Indoor radon levels that have been observed vary significantly. According to currently available data (Al86, Ne85), the national median indoor radon level might be estimated to be somewhat below 2 pCi/L, although the data are not sufficient to permit a rigorous determination of that median. Many houses have levels below 1 pCi/L, according to a number of measurement organizations. On the other hand, a few houses have been found with very high levels, above 2,000 pCi/L.

Radon levels can vary significantly over time within a given house, by a factor as high as 10 to 100 between summer and winter in some cases. Levels in a given house are generally expected to be higher during the winter (when cold weather increases the stack effect and when doors and windows are likely to be closed) than during mild weather. Even in a given day, radon concentrations in a house can vary by a factor of 2 or 3, or even more. The daily and seasonal variations can differ from house to house, and some houses may have variations smaller than those cited here. Radon levels can vary significantly from house to house, even when the various houses appear similar and are built close to one another.

Sometimes the issue is raised regarding whether tight, energy-efficient houses might be subject to higher radon levels than others due to the lower natural closed-house ventilation rate in the tight houses (perhaps 0.25 air changes per hour, or even lower). Higher levels will not necessarily result. It is true that the reduced ventilation rate will indeed provide less outdoor air to dilute any radon that enters the building. But, on the other hand, the reduced leakage of air out of tight houses under the influence of temperature and wind effects might also reduce the driving force sucking soil gas into the house. Therefore, the net effect on radon levels in the house is not clear. Currently, there are no definitive data demonstrating whether tight houses are consistently more or less radon-prone than others are. As discussed in Section 6.1, the current expectation is that proper tightening of houses could result in *reduced* radon levels.

The above discussion has focused on soil-generated radon migrating to ground level and directly into houses as a component of soil gas. Radon from the surrounding soil and rock can also migrate into underground aquifers supplying the water for local private and public wells. Radon is fairly soluble in water, and sometimes significant amounts of radon can build up in the underground aquifers. Much of the radon in the water can then be released as a gas when the well water is used in the house, contributing to the airborne levels. Assuming an average water usage rate, house volume and ventilation rate, and assuming that only half of the radon in the water is released, a rule of thumb is that 10,000 pCi/L of radon in the water will contribute about 1 pCi/L of radon to the indoor air on the average (Br83). Thus, it would require about 40,000 pCi/L in the water for the water to be solely responsible for an average airborne level corresponding to EPA's guideline of 4 pCi/L. In the immediate vicinity of the water-usage appliance, during the time while the appliance is in use, the radon levels could be much higher than this average.

In general, private wells are of the greatest potential concern, since they can result in radon-containing water from an aquifer being drawn directly into the house. Concentrations of radon greater than 1 million pCi/L of water have been measured in at least one private well in New England (Lo86). However, preliminary estimates of the national average for private wells (based upon limited data) suggest that the geometric mean nationally is more on the order of several hundred to 1,000 pCi/L (He85, Na85a, EPA87c). Radon in water provided from a public well might be expected to be lower than that from private wells, if that water from a public supply receives treatment or handling which can cause the radon to be released before it reaches the house.

Radon from the soil can also migrate into surface water supplies such as reservoirs. However, radon does not appear to reach significant levels in surface water (due to the natural de-gassing which can occur), with the national average surface water level roughly estimated to be between 10 and 300 pCi/L of water (Co86, Na85a).

While some well water will contain sufficient radon to make a significant contribution to the airborne radon concentration—and while well water treatment might thus sometimes be necessary to reduce airborne levels below 4 pCi/L—current experience suggests that, in many cases, soil gas entry into the house will be a far more significant source of indoor radon than will water usage.

1.5.2 Reason for Concern about Radon

As discussed in the previous section, radon gas is only one step in the radioactive decay chain. Radon-222 itself decays into the next element in the chain, polonium-218; this element decays to form lead-214, which then decays into bismuth-214, which decays to form polonium-214, which decays into lead-210. The half-lives of the polonium-218, lead-214, bismuth-214, and polonium-214 are relatively short (the longest being 27 minutes for lead-214); thus, these four elements decay relatively quickly, and they will never be found except in the presence of radon. Consequently, these four elements are collectively referred to as the "radon daughters," or "radon progeny."

The radon progeny are the source of the health concern about radon. These progeny are solid elements. However, since they are created from single atoms of radon gas, they initially exist as ultrafine particles. They initially have a positive electric charge resulting from the decay process. Due to their very small size and their charge, the progeny tend to adhere to anything that they contact: moisture droplets in the air, airborne dust particles, walls, furniture, etc. When they are inhaled, they adhere to the mucus lining of the lungs.

As indicated earlier, sub-atomic particles and/or electromagnetic radiation are released during any radioactive decay. Two of the radon progeny (polonium-218 and polonium-214) release particles known as alpha particles. Polonium atoms adhering inside the lungs will bombard the surrounding lung tissue with alpha particles. If these particles were to hit the external skin, they would be stopped without damage by the dead outer layers of skin. But lung tissue has no such dead layer and is therefore more sensitive. Long-term bombardment of lung tissue by alpha particles can increase the risk of lung cancer. This increased risk of lung cancer due to progeny deposited in the lungs is the reason for the current concern about radon.

Radon gas itself also releases an alpha particle when it decays to polonium-218. However, the gas is not considered the major problem, since nearly all of it is immediately exhaled. Only a small percentage of the inhaled radon will decay during its brief residence time in the lungs. Moreover, since radon gas will distribute (and decay) uniformly throughout the lung passages, it will not cause the serious localized alpha bombardment that can result when solid progeny selectively deposit in specific areas in the lung.

Because the progeny are thus the real elements of concern, rather than radon gas itself, a unique unit of measure exists for quantifying the amount of progeny in the air. This unit of measure is the "working level" (WL), and is based upon the cumulative alpha-emitting potential of all progeny present. If the progeny were in radioactive equilibrium with the radon gas—that is, if each of the four progeny were present in the air at the same activity level as the radon—then 1 WL would be present when there were 100 pCi/L of radon gas (and 100 pCi/L of each of the progeny). In practice, the progeny are never at equilibrium with the radon. Due to natural infiltration of outdoor air, radon atoms do not remain inside the house long enough to reach equilibrium with their progeny; in addition, since the progeny adhere to surfaces in the house, their airborne concentrations are reduced. The degree to which the progeny approach equilibrium in a specific house can vary significantly, with the progeny typically being in the range of 30 to 70 percent of the way toward equilibrium. It is commonly assumed that the progeny are about halfway toward equilibrium, in which case 1 WL of progeny would be present when the radon gas concentration is 200 pCi/L. (But considering the range of 30 to 70 percent, 1 WL in any given house could in fact correspond to anywhere between roughly 150 and 300 pCi/L.)

The lung cancer risk associated with long-term exposure to radon progeny has been estimated based upon health studies conducted on uranium miners and other miners. Based upon these miner health studies, risks of lung cancer resulting from a lifetime of progeny exposure in a house can be estimated. These are presented in Table 1 (EPA86b). In these risk estimates, a "lifetime" is defined as spending 75 percent of one's time in the house over a period of 70 years. For comparison, someone exposed to an average progeny level of 0.005-0.01 WL (about 1-2 pCi/L) over a lifetime has a risk of dying from lung cancer comparable to the average non-smoker. Someone exposed to 0.05-0.10 WL (10-20 pCi/L) has the same risk as someone smoking one pack of cigarettes per day, and someone exposed to 0.5-1.0 WL (100-200 pCi/L) has the same risk as someone smoking four packs per day. As apparent from the table, there is estimated to be some risk even at the low levels (about 0.25 pCi/L) which exist outdoors.

Table 1. Estimated Risk of Lung Cancer Death Resulting From Lifetime Exposure to Radon Progeny

Progeny Concentration (WL)	Approximate Corresponding Radon Concentration (pCi/L)	Estimated Number of Lung Cancer Deaths Due to Radon Exposure, Per 1,000 Persons
1.0	200	440 - 770
0.5	100	270 - 630
0.2	40	120 - 380
0.1	20	60 - 210
0.05	10	30 - 120
0.02	4	13 - 50
0.01	2	7 - 30
0.005	1	3 - 13
0.001	0.2	1 - 3

From Reference EPA86b.

It is emphasized that the risks cited above are for a *lifetime* of exposure to the indicated levels. More limited exposures to those levels would reduce the risk correspondingly.

In view of these significant health risks associated with indoor radon, EPA has established a guideline of 4 pCi/L (about 0.02 WL) for annual average indoor radon concentrations. By this guideline, the concentration in a house could sometimes be greater than 4 pCi/L so long as the occupant exposure over the year averaged 4 pCi/L or less. If annual average concentration is above 4 pCi/L, efforts to reduce the concentration are suggested (see Section 1.5.3). Another figure of interest is the occupational standard for radon progeny exposure for uranium miners established by the Occupational Safety and Health Administration. This standard limits miner exposure to 4 working level months (WLM) per year, where 1 WLM would correspond to exposure to 1.0 WL for a duration of 170 hours (the number of working hours in 1 month). Assuming that a homeowner spent 75 percent of the time in the house, and considering the differences in breathing rate between homeowners and miners, a homeowner would reach an exposure of 4 WLM in 1 year if the progeny level in the house averaged roughly 0.2 WL (about 40 pCi/L) over the year.

Questions have been raised regarding the use of health data from miners to estimate the risks faced by homeowners. One of the concerns prompting these questions is that the mine environment differs from the house environment in important ways (e.g., dust levels are higher in a mine).

Another key concern is that the radon concentrations (the dose rates) experienced by the miners were generally much greater than those experienced by homeowners except in the highest-concentration houses. The estimated deaths shown in Table 1 for the lower WL values assume that the health effects of radon depend only on the cumulative dose (i.e., the total WLM), and not upon the rate at which that dose is incurred. For example, a homeowner in a low-radon house could incur over 70 years a cumulative dose that a miner might incur in just a few years. This assumption that low dose rates do not reduce risk—that cumulative dose is the primary measure determining risk—appears to be supported by the available miner data at relatively low dose rates. More data on the effect of dose rate are necessary. It should be noted that the range of cumulative doses covered by some of the miner health studies does cover the cumulative (lifetime) doses estimated for many homeowners, and shows a statistically significant increase in lung cancer risk at those cumulative exposures (Pu87).

Studies are underway to more rigorously quantify the risks to homeowners in actual house environments. However, it is clear from available health data that sufficient doses of radon and its progeny can definitely produce lung cancer in humans (NAS81). It is EPA's position that the available data suggest a very real threat which is unambiguous at the higher dose rates experienced by miners (and by some homeowners), and which is too serious to be ignored at the lower dose rates representative of houses. The cumulative exposures that would be experienced by many homeowners are sufficiently high that an increased risk of lung cancer would be predicted based upon the miner data.

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 which remains in the water that is ingested. The current conclusion is that the lung cancer risks from radon which is released are much more significant than the risks from radon which remains in the water (Na85a).

1.5.3 Action to Reduce Radon Levels

The higher the initial radon concentration is within a house, the greater will be the degree of reduction that would be necessary to reduce the annual average level to 4 pCi/L (about 0.02 WL) or less. In addition, the higher the initial concentration, the more rapidly EPA recommends action be taken to reduce the levels (EPA86b), due to the higher estimated risk. The degree of reduction needed to reach 4 pCi/L, and the recommended urgency of action, are summarized in Table 2.

1.6 How to Use This Guidance Document

A step-by-step approach for using this document to help reduce radon levels in existing houses is suggested below.

Step 1. Make radon (or radon progeny) measurements to determine the extent of the radon problem in the house.

Section 2.1 briefly discusses alternative methods that might be considered for determining airborne radon or radon progeny levels in the house. This section summarizes EPA's interim protocols for conducting both initial screening measurements (intended to provide an initial reading in a reasonably short time) and follow-up measurements (intended to provide a confirmation of the screening measurement before any radon reduction steps are undertaken) (EPA86c, EPA87a). The levels thus measured will aid in the decision regarding the degree of radon reduction that is desired and the urgency of action. If elevated airborne radon levels are found and if water is supplied to the house from a well, water radon measurements should also be conducted to determine whether the well water might be an important contributor to the airborne radon.

Step 2. Identify the potential routes by which the radon is entering the house, and the sources of house depressurization which may be increasing the rate at which soil gas is entering.

Section 2.2 provides a checklist of many potential entry routes through which soil gas might enter a house, and a checklist of appliances, house design features, and other factors which can contribute to depressurization. Knowledge of the mechanisms by which the soil gas is entering will be important in the selection and design of any radon reduction measures.

Step 3. Implement near-term reduction measures which 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 2.3 describes some alternative near-term techniques that can be implemented, such as increased house ventilation and closure of major accessible entry routes. Some of these near-term approaches (in particular, house

Table 2. Extent and Recommended Urgency of Radon Reductions Efforts as a Function of Initial Radon Level (EPA86b)

Initial Progeny Concentration (WL)	Approximate Corresponding Radon Concentration (pCi/L)	Percentage Reduction Required to Attain 0.02 WL (percent)	Recommended Urgency of Reduction Efforts
1.0 or above	200 or above	98 or higher	Action to reduce levels as far below 1.0 WL as possible are recommended within several weeks after measuring these levels. If action is not possible, the homeowner should determine, in consultation with appropriate State or local officials, if temporary relocation is appropriate until the levels can be reduced.
0.1 to 1.0	20 to 200	80 to 98	Action to reduce levels as far below 0.1 WL as possible are recommended within several months.
0.02 to 0.1	4 to 20	0 to 80	Action to reduce levels to 0.02 WL or less are recommended within a few years, and sooner if levels are at the upper end of this range.
less than 0.02	less than 4	0	While these levels are at or below the EPA guideline, some homeowners, at their discretion, might wish to attempt further reductions.

From Reference EPA86b.

ventilation via open windows and doors) can be very effective, but cannot practically be put into practice all of the time (e.g., during extreme weather). Some of the near-term closure of major accessible entry routes might have limited effectiveness. Thus, these near-term approaches will often not be adequate by themselves to completely address the elevated levels on a permanent basis. However, they can generally provide at least some temporary relief, and they can generally be implemented fairly readily by a homeowner at limited cost.

Step 4. Conduct diagnostic testing as warranted to aid in the selection and design of a radon reduction technique.

Section 2.4 describes some of the diagnostic testing that can be considered to provide information to aid in mitigation selection and design in particular cases. Many of these diagnostic tests are intended to measure inherent properties of the house (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 assess the relative importance of different potential radon sources within the house. The particular diagnostic tests which are cost effective for a given house will depend upon the particular radon reduction techniques that are being considered (Step 5 below) and the nature of the house. Some of this pre-mitigation diagnostic testing might best be completed before Step 5 is initiated, to aid in the selection between radon reduction options. Other diagnostic testing would best be performed after the selection process is completed, to aid in the design (Step 6) of the particular reduction options that have been selected.

Step 5. Review the alternative radon reduction options which appear suitable for the particular house, and decide upon an appropriate phased approach (as necessary).

The Executive Summary summarizes the range of radon reduction options, including pertinent information for each (such as applicability, estimated performance and cost). Table E-1 can be used to help select the particular reduction technique, or combination of techniques, which should be considered for a particular house. This selection will be based upon the degree of radon reduction desired, the nature of the house, and the confidence levels and costs which are acceptable to a particular homeowner, as discussed in Section 2.5. Where combinations of techniques are to be installed, or where a single technique can be designed in various ways having various costs, it might sometimes be cost effective to install the system in phases (see Section 2.5.2).

Step 6. Design and install the selected radon reduction technique(s).

Details to aid in the design and installation of the various radon reduction approaches are presented in Sections 3 through 8.

Step 7. Make measurements after system installation in order to confirm radon reduction performance, and to understand and improve performance.

Following installation, the radon/progeny measurement methods described in Section 2.1 can be used to assess the degree of reduction 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.) Also, 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 Section 2.6, with specific applications described as warranted in the detailed discussions in Sections 3 through 8.

Section 2
Approach for Radon Reduction

The purpose of this section is to describe the various steps in the overall approach for reducing indoor radon levels. These steps begin by determining whether a radon problem exists in a house, and proceed through the selection, design, and installation of radon reduction systems. The final step is testing to ensure that the installed system is operating satisfactorily.

2.1 Measurement of Radon Levels in the House

In order to determine whether a particular house has elevated radon levels—or to assist in diagnosis once a radon problem is identified—measurements of radon or radon progeny in the house air are required. A variety of methods exist for measuring radon or progeny levels. Some methods involve simple-to-use devices which homeowners can purchase and use themselves; other methods require that a professional with specialized equipment visit the house. Some of the methods measure the concentration of radon gas (e.g., in pCi/L); others measure the concentration of radon progeny (in working levels). The method selected for a given application will be determined by measurement objectives, equipment availability, and costs.

There are two alternative objectives for making a radon measurement:

1. To determine the concentrations of radon to which the occupants of the house are being exposed; or
2. to assist in the diagnosis of the location and significance of radon entry routes into the house, as part of a mitigation effort.

Most of the available measurement techniques can be used for either of these objectives under the right circumstances. Some techniques generally lend themselves better to one or the other of these objectives. For example, long-term passive measurements are logically used for occupant exposure measurements, and grab samples are better suited for diagnostic purposes. For a particular technique, the protocol by which it is used will generally vary depending upon the objective. For example, the sampling location within the house would vary. In this section, the discussion will focus on the first objective, assessment of occupant exposure.

EPA has issued protocols for making measurements in houses using alternative measurement methods, with the objective of determining occupant exposure (EPA86c, 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), to estimate the health risk to the occupants and the urgency of remedial action. Persons making measurements are advised to apply the methods in a manner consistent with these protocols.

The Agency has also established a Radon Measurement Proficiency Program enabling organizations which provide monitoring services to voluntarily demonstrate their proficiency in making radon/radon progeny measurements (EPA86d). 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. Copies of the current list can be obtained through the appropriate EPA Regional Office or the State contact identified in Section 10.

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, as discussed in Section 1.5.1, even when the occupant has not done anything which 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, and possibly even greater). In some houses, the daily and seasonal variations will not be this great. It is clear that, if a meaningful measure of the occupants' exposure to radon is desired, it is best to obtain measurements over an extended period and during different seasons. Since the highest levels are likely to be experienced during cold-weather periods, it would be wise to ensure that some measurements are made during winter months.

The discussion below subdivides the measurement techniques according to whether they require passive or active sampling. Passive techniques do not require a pump or specialized sampling equipment to draw a sample of the indoor air, and they can thus be used by a homeowner without the assistance of a professional sampling team. The active techniques require that specialized sampling and/or analytical instrumentation be brought into the house. Either passive or active approaches can be used for initial measurements of occupant exposure to radon, but homeowners will generally find that the passive techniques will be more convenient and less expensive for the purpose of initial measurements.

2.1.1 Passive Measurement Techniques

Passive measurement devices have two primary advantages. First, they can be purchased and used directly by a homeowner without the aid of professional measurement teams, so that they are convenient and generally less expensive. Second, they can easily be used to give a weighted average (integrated) radon measurement over a period of time, ranging in duration from a few days to a year. Since radon levels can vary over a wide range in a given house, a measurement covering a period of days or months will give a better indication of occupant exposure than will a measurement of shorter duration.

There are two general types of passive measurement devices currently in common use:

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

In both cases, the user can purchase the 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 (generally between 2 to 7 days for charcoal devices, depending upon the supplier, and from a month or two up to a year for alpha-track devices). The device is then returned to the laboratory for analysis. For both types of devices, the result is the radon gas concentration (i.e., in pCi/L); these devices do not determine the concentration of radon progeny.

For a listing of some organizations from which these devices can be obtained, the reader is referred to EPA's most recent measurement proficiency report (e.g., EPA87b).

Protocols for using these devices have been published by EPA (EPA86c, EPA87a). Additional guidance will often be provided by the organization from which the device is purchased. A few of the key procedures indicated in the EPA protocol documents are listed below.

1. 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 as follows:
   - charcoal canister—2 to 7 days, as specified by supplier*
   - alpha-track detector—3 months (or less, if specified by supplier).

   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.
2. For the screening measurement, the device should be placed in the livable space closest to the soil, 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 to actually be used as living space. The devices should *not* be placed in sumps, or in small enclosed areas such as closets or cupboards. 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.
3. Screening measurements should be made under closed-house conditions—i.e., doors and windows should be closed as much as practical, and use of ventilation systems which mix indoor and outdoor air (such as attic and window fans) should be minimized. 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. 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.

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*A charcoal canister measurement period of 2 days is preferred by a number of suppliers.

4. 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 be conducted as follows:

   — 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 four 2- to 7-day periods, thus giving a more reliable measure of occupant exposure.

   These measurements should be made in the actual living area on each floor of the house that is 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 the time to make a good measurement of annual exposure before having to decide upon action to reduce the levels (see suggested urgency of remedial action in Table 2).

5. 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 (see Tables 1 and 2). Follow-up measurements should be completed within several months after obtaining the screening result. Suggested follow-up measurements are:

   — charcoal canister—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).

6. If the screening measurement yields a result greater than about 200 pCi/L, the follow-up measurement should be expedited, conducted under closed-house conditions over a period of days or weeks; a 3-month alpha-track exposure might not be appropriate. Short-term actions to reduce the radon levels should be considered as soon as possible. State or EPA officials should be contacted for advice.

7. In both screening and follow-up measurements, the charcoal and alpha-track devices 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 EPA86c and EPA87a.

2.1.2 Active Sampling Techniques

The use of active sampling techniques generally requires that a professional sampling team with specialized equipment visit the house. The various active sampling techniques offer several potential advantages. One key advantage is more rapid availability of the measurement results compared to the passive techniques. Other features of active techniques which can be of value under some conditions are: the ability of continuous monitors to provide, for example, hour-by-hour results, so that radon fluctuations with time can be observed; and the ability to measure radon progeny as well as radon gas. These techniques can be used to measure occupant exposure, and are often particularly useful in diagnostic testing.

Several active techniques are covered in the EPA protocols (EPA86c, EPA87a). These techniques are summarized in Table 3, subdivided according to whether they measure radon gas or radon progeny. Equipment availability, measurement costs, and individual preferences will dictate which techniques from Table 3 to choose in measuring radon exposure.

For a listing of some private organizations which can conduct these types of measurements, the reader is referred to EPA's most recent measurement proficiency report (e.g., EPA87b). Appropriate State agencies might also be able to conduct these measurements, or to refer the reader to local measurement firms.

The suggested sampling times given in the table for each technique are from Reference EPA87a, and refer to the two-step measurement approach (screening plus follow-up) for determining occupant exposure prior to any remedial action. This is the same approach that was discussed in Section 2.1.1 in connection with passive detectors. As indicated, the sampling times shown for the continuous monitors and for RPISUs should be considered minimums, with longer measurement times used wherever possible, in view of the variability in radon concentrations within a house.

For further details regarding these techniques and the EPA protocols for their use, see References EPA86c and EPA87a.

Table 3. Active Sampling Techniques for Measuring Indoor Radon and Radon Progeny

Technique	Principle and Output	Suggested Sampling Times*	
		Screening	Follow-up
Techniques for Radon Gas			
Continuous Radon Monitor	Automated grab sampler and radon decay counting device; house air automatically pumped into scintillation cell, counts (radon concentrations) recorded periodically (e.g., on an hour-by-hour basis). Can be programmed to operate unattended for days.	6 hours minimum, prefer longer than 24 hours	24 hours or longer†
Grab Sample for Radon‡	Indoor air flushed through scintillation cell for about 5 minutes; counts (radon concentrations) measured using counting device in laboratory. Gives a single measurement representative of the 5-minute sampling period.	5 minutes	Not recommended for follow-up measurements.
Techniques for Radon Progeny			
Radon Progeny Integrated Sampling Unit (RPISU)	Indoor air pumped continuously through filter in detector unit for as long as a week; progeny decays are continuously recorded on dosimeters which are subsequently analyzed in a laboratory. Gives a single weighted average (integrated) progeny measurement for the total sampling period.	100 hours minimum, prefer 7 days	100 hours or longer†
Continuous Working Level Monitor	Automated grab sampler and progeny decay counter, analogous to continuous radon monitor. Gives periodic (e.g., hour-by-hour) working level measurements. Can be programmed to operate unattended for days.	6 hours minimum prefer longer than 24 hours	24 hours or longer†
Grab Sample for Progeny‡	Indoor air flushed through filter for about 5 minutes; collected particles subsequently counted in laboratory to yield working level measurement. Analogous to grab sample for radon. Gives a single measurement representative of the 5-minute sampling period.	5 minutes	Not recommended for follow-up measurements.

*The suggested sampling times for each technique are from EPA's measurement protocols (EPA87a), in which the techniques are being used to determine occupant exposure. The screening measurement is intended for the case in which no prior measurement has been made in the house; this measurement is conducted once, in the lowest livable space in the house. The follow-up measurement is intended for the case in which the screening measurement is greater than about 4 pCi/L (or about 0.02 WL), and it is now desired to obtain confirming (and generally more comprehensive) results before deciding on action to reduce radon levels.

†If the radon levels measured in the screening testing are below about 20 pCi/L, follow-up measurements of the indicated duration would be made once each quarter for one year, with the measurements being made in actual living space on each floor of the house under normal living conditions. If the screening levels are above about 20 pCi/L, follow-up measurements of the indicated duration would be made only once, under closed-house conditions, in order to reduce the delay before initiating remedial action. If the screening levels are above about 200 pCi/L, follow-up measurements should be performed, and short-term remedial action should be considered, as soon as possible.

‡Because of the high uncertainties associated with the short measurement duration of grab samples, the results of a single grab sample should not be used by itself to make a decision on the need for remedial action. Thus, grab samples may be used for initial screening measurements, but are not recommended for the follow-up measurements.

Derived from Reference EPA87a.

As indicated earlier, these active techniques will sometimes be logical choices for certain diagnostic testing, to assess potential radon entry routes into a house, or to evaluate the performance of a radon reduction installation. Since the purposes of such diagnostic testing are different from the occupant exposure measurements, the procedures for the diagnostic application of these techniques may vary from those in the EPA protocols for exposure measurement.

Caution is suggested whenever grab samples (for either radon or progeny) are used to estimate occupant exposure. Since a grab sample will represent only the 5-minute period over which the sample was taken — and since radon concentrations can vary significantly from day to day, and even from hour to hour — there is a large uncertainty involved in using a single grab sample (or a small number of grab samples) to estimate long-term radon concentrations in a house. The EPA protocols include grab sampling as a possible technique for the initial screening measurement in a house (see Table 3). The standard screening measurement requirement, that the house remain closed for 12 hours prior to sampling, is particularly important for grab samples, to minimize bias from pre-existing open-house conditions. Grab sampling is not recommended for the follow-up measurements; the correlation between grab sample results and long-term average radon concentrations is too poor to permit grab sample results alone to be used reliably for making a decision on the need for remedial action. Nor should grab sample results be relied upon as the sole measure of whether a radon reduction installation has reduced radon levels in a house to acceptable values. The primary applications of grab sampling would logically be for obtaining a rapid screening estimate of occupant exposure, and for conducting diagnostic tests around a house or around a radon reduction installation. (Grab sampling is a very important diagnostic tool.)

2.2 Identification of Radon Entry Routes and the Driving Forces Causing Entry

If the measurements described in Section 2.1 indicate that a house has elevated radon concentrations in the living areas, the next step is to visually identify potential locations where the radon-containing soil gas might be entering the house, and to identify any appliances or house design features which might be contributing to the driving force which is causing soil gas to flow into the house. Such an identification of possible entry routes and sources of the driving force will be an important first step in any action to reduce the radon levels.

As discussed in Section 1.2, radon might enter a house as a component of soil gas, as a contaminant in well water, or as the result of radium present in mineral-based building materials. The presence of radon in the well water, or its release from building materials, can be identified by means of measurements described in Section 2.4 in connection with diagnostic testing. The discussion in this section focuses upon entry routes and entry mechanisms associated with soil gas as the radon source.

2.2.1 Identification of Soil Gas Entry Routes

Soil gas can enter wherever there is an opening between the house and the soil. Even in a well-built, tight house, there will invariably be numerous openings to the soil—sometimes large, often tiny. Houses are not built to be gastight below grade. In inspecting for entry routes, the reader should be aware that the hairline crack in a concrete slab—which visually appears tightly closed—can be a wide avenue to an infinitesimal atom of radon which is being sucked into the house by the pressure difference between the house and the soil.

Table 4 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, 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.

Figure 1 is a schematic depicting many of the entry routes listed in Table 4. For convenience, this illustration shows a hybrid house—some hollow block foundation walls, some poured concrete—in order to aid depiction of the full range of entry routes. The entry routes shown in the figure are identified according to their number in Table 4.

The building substructure plays an important role in determining the number and type of entry route. Table 4 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 just at grade level; and

Table 4 A Checklist of 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 underlying 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. (Some blocks are more porous that others — for example, true cinderblock is generally more porous than concrete block.)
7. With hollow-block walls, cracks through the blocks or along the mortar joints (including hairline 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 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.

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 since 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 there are drain tiles draining into the sump, the tiles 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 the perforated drain tiles or to a septic system). 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 purposes (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, or
   — hollow pipes which penetrate the slab (e.g., serving as the legs for a fuel oil tank).

Table 4 (continued)

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).
2. If a central forced-air HVAC system is situated in the crawl space, leaks in the low-pressure return ducting which would permit crawl space air to leak into the house circulating air.

*Some entry routes are illustrated by number in Figure 1.

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.

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. 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 foot 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.

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 greater number of entry routes would run the risk of having the greater 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 (although the real nature of the entry routes will vary with specific design features and construction methods). Thus, one might anticipate that basement houses would tend to offer a greater 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-neutralized 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.

The nature of the 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 generally 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, laterally as well as vertically. 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 there is no solid cap block as the top course in the block wall, the easiest place for the gas to enter the house will be the open voids in the top course of block. 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. The block wall thus serves as a chimney, providing a convenient conduit for soil gas entry. Even if the foundation wall is largely above grade—as in the basement house mentioned earlier, where the rear wall was totally 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 — then soil gas can enter the blocks underground and move up into the

Key:

- - →	Soil gas flow
A1	Identifier of soil gas entry route, from Table 4.
⟶	House air flow through airflow bypass

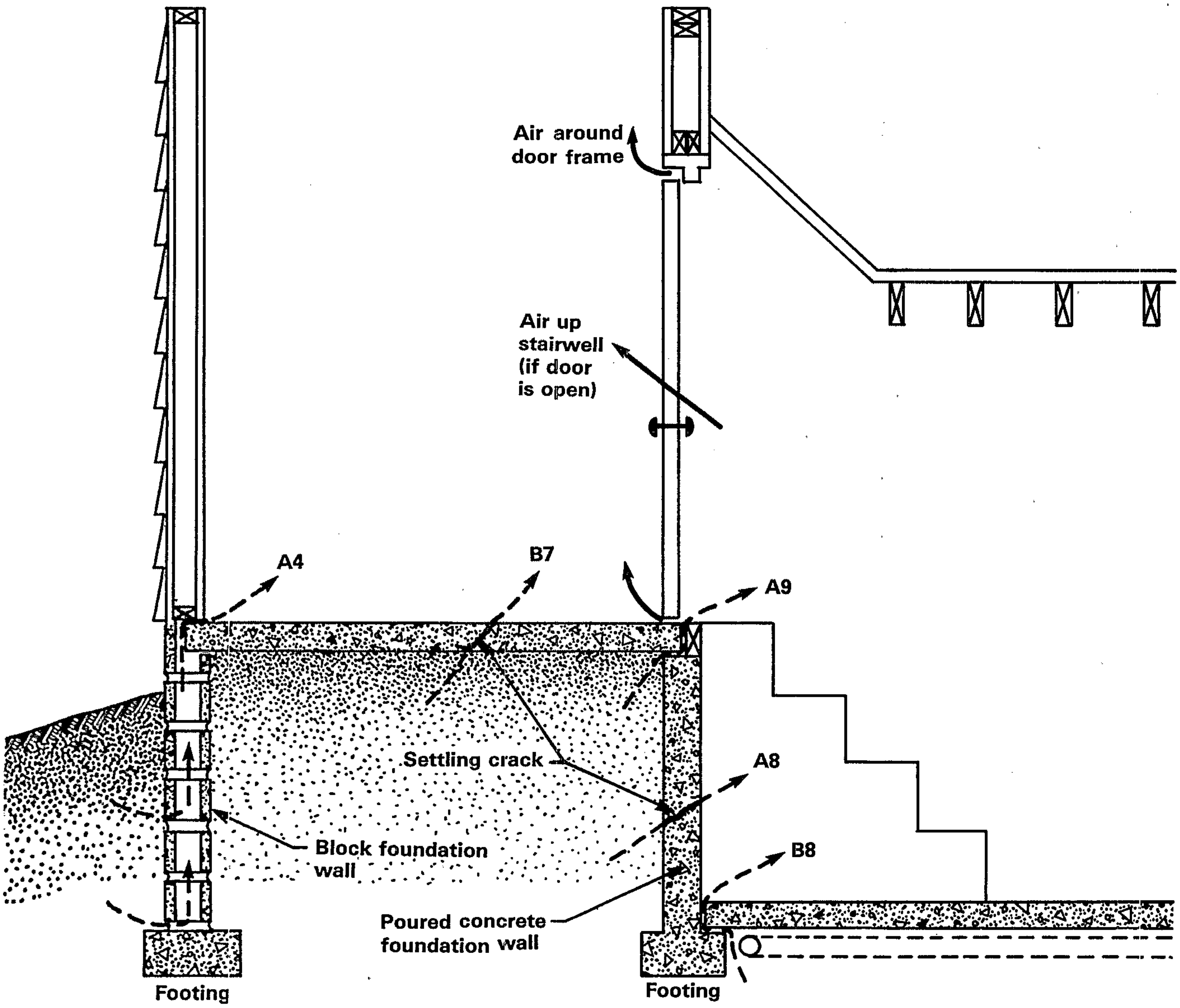
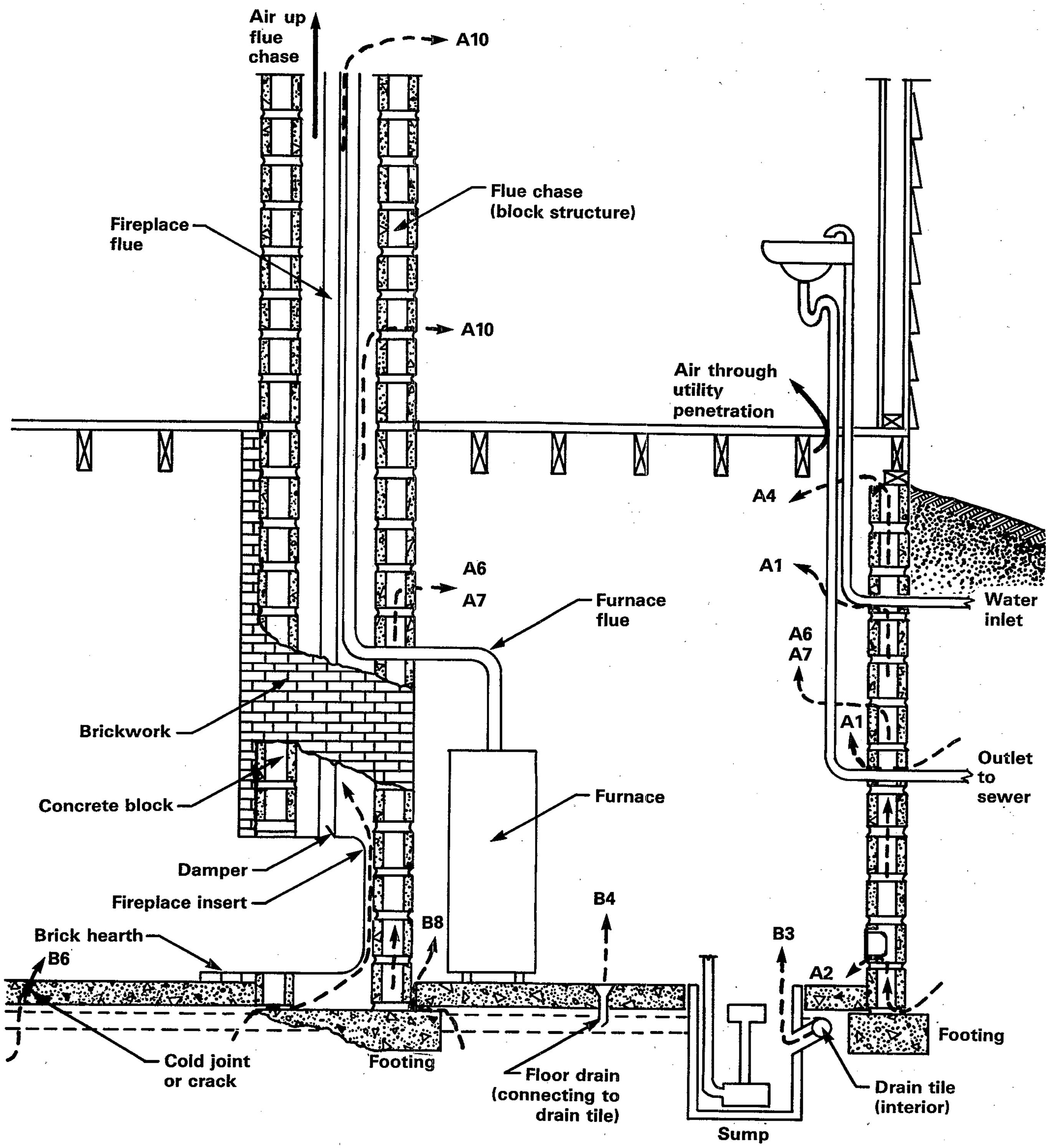


Figure 1. Some potential soil gas entry routes into a house.



Note: Hybrid house containing both hollow-block and poured concrete foundation walls shown for convenience to illustrate range of entry routes.

house through the wall. Thus, the wall can be a soil gas source, even though no face of the wall would appear 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 1, and is reflected in a number of the entry routes listed in Part A of Table 4.

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. This situation is illustrated in Figure 2. 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 and floor drains 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. 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 pumps the water to an above-grade discharge remote from the house. These drain tiles can also

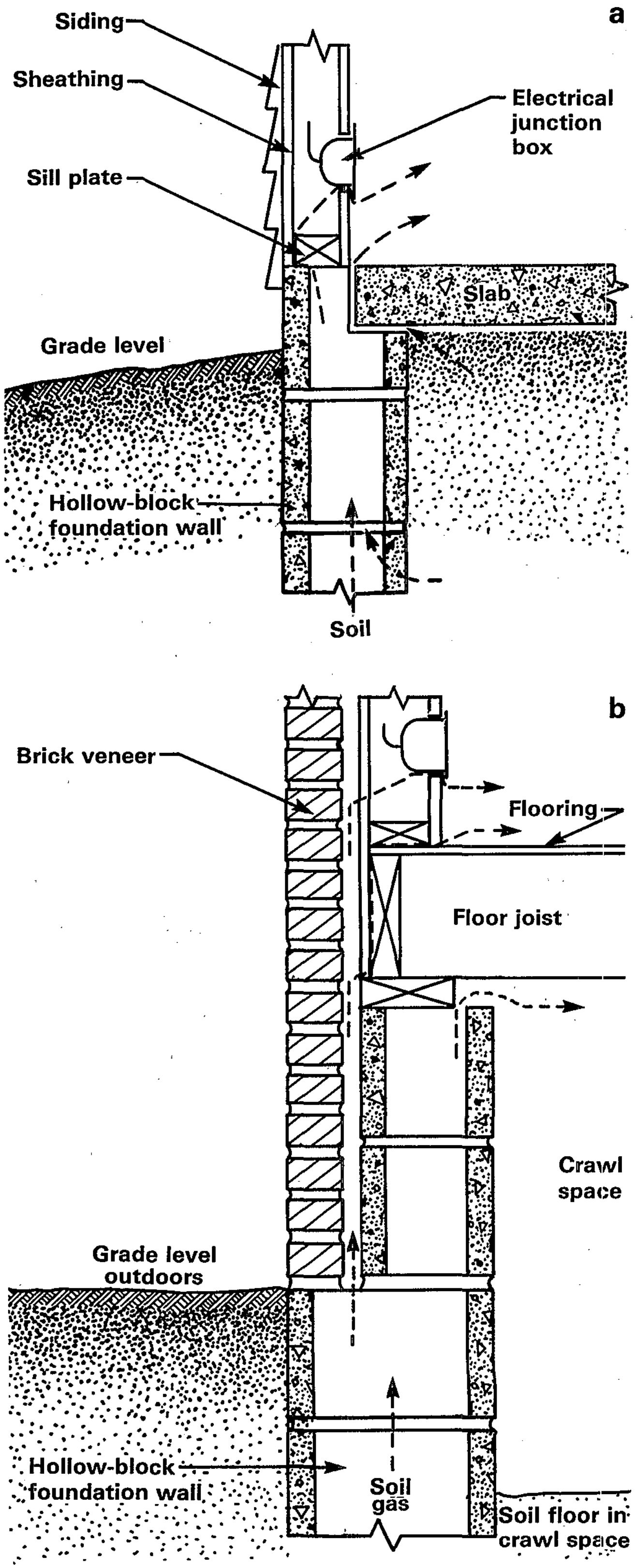


Figure 2. Hollow-block foundation walls as a conduit for soil gas into a) slab-on-grade and b) crawl space houses.

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. As a consequence, sumps are almost universally a major radon source whenever they are present.

Some floor drains also drain to the perimeter drain tiles, to a separate segment of drain tile, and/or to a dry well. 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 full of water. Floor drains which connect to a septic tank or sewer system sometimes are installed with a trap that includes a cleanout opening, permiting the trap to be bypassed when it is desired to clean out the line to the septic tank. This opening 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 opening 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 4 to inspect a house for soil gas entry routes, the reader should recognize that, in many cases, some entry routes will probably be hidden — for example, 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 in selecting the diagnostic testing which should follow and in determining the logical radon reduction alternatives for that house.

2.2.2 Identification of Features Influencing the Driving Force for Soil Gas Entry

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 5. 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 contribute to 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. These steps to reduce the driving force are discussed in Section 6.1.

Weather effects. Cold temperatures outdoors are an important contributor to the driving force. Whenever the indoor temperature is maintained at a level higher than the outdoor temperature, the buoyancy of the warm indoor air will make it want to rise. The colder the temperature outdoors, the greater the buoyant force on 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. The infiltrating air and soil gas themselves become heated once inside, then rise and leak out through the upper levels, continuing the process. The shell of a closed house can thus be pictured as 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 thermal 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 outleaking (exfiltrating) warm air. On the other hand, the buoyant force pressurizes the upper levels of the house (relative to the outdoors), forcing heated air out upstairs. Somewhere between the upper and lower levels will be a roughly horizontal "neutral plane," where the pressure indoors just equals the pressure outdoors. Below the neutral plane, the house is below outdoor pressure, and outdoor air (and soil gas) is leaking in. Above the neutral plane, house air is leaking out. Most of the gas leaking into the house below the neutral plane is outdoor air. Only a small fraction of the infiltrating gas is soil gas, with the size of this fraction being determined by the number and size of soil gas entry routes, and by the permeability of the surrounding

Table 5. A Checklist of 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 (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 (and between the living space and the attic). 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 by insulation).
   — attic access doors that are not weatherstripped.
   — recessed ceiling lights, which require a penetration through the floor above.
   — openings concealed inside block structures which penetrate floors between stories.
   — central forced-air heating/air conditioning ducts which connect upstairs and downstairs.

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 located inside the livable area,
   — fuel-fired water heaters, if located in livable area.

   These combustion appliances do not contribute to depressurization when a separate supply of combustion air is provided from outdoors.
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 driers 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 low-pressure 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 "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.

soil. However, because of the high radon concentrations which exist in soil gas, even a very small fraction of infiltrating soil gas can result in elevated indoor radon levels. The only way for the stack effect to be eliminated entirely would be for the house shell to be literally gastight (analogous to a hot air balloon); a gastight house is an impossibility.

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.

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 (Item B in Table 5). 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. To the extent that such openings through the shell can be closed above the neutral plane, the effect will be to at least partially cap, so to speak, the figurative chimney created by the house shell, reducing the temperature-induced flows. Unfortunately, some openings above the neutral plane must not be closed due to other considerations (the attic soffit or gable vents, for example). 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. It should be noted 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. 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, possibly 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 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 easily be closed, 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 a major bypass, it might not be possible to significantly reduce the upward air movement by closing other, secondary bypasses, so long as the stairwell remains open.

Attics are generally unheated, and have openings to the outdoors (soffit vents or gable end vents). As a result, it is ambiguous whether penetrations between the living area and the attic—e.g., around attic access doors and recessed ceiling lights—should be labeled as openings through the house shell, or as internal airflow bypasses. For the purposes here, they are called internal bypasses.

Homeowner activity effects. As listed in Item C of Table 5, there are a number of appliances in a house which suck air out of the house, and which might thus 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, and bathroom exhaust fans. A clothes drier is a form of exhaust fan whenever the moist air leaving the drier 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 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 only limited duration.

It must be emphasized that there are currently no substantial data to indicate either the extent of depressurization that will typically be caused by the various house appliances, or the effect that any such depressurization will typically have on radon levels. The extent of depressurization for any given appliance will vary from house to house, depending upon the tightness of the house. The impact of any depressurization on radon levels will vary, depending upon the degree to which the makeup air (to compensate for the exhausted air) comes from infiltrating outdoor air versus infiltrating soil gas, among other factors. The effects will also depend upon the amount of air withdrawn from the house by the particular appliance. As discussed in Section 6.1, some of the limited data show radon levels in specific houses to have increased by a factor of two to three as a result of the operation of a fireplace or a coal stove; other data from other houses show no significant increase from fireplace operation. While the impacts of house appliances on radon levels can thus vary, the reader should be alert to their potential effects.

The absolute value of the pressure changes that are occurring is very small. The overall ambient pressure that exists around a house is approximately 1 atmosphere. By comparison, the maximum pressure differential created by the buoyant forces between the top and bottom floors of a house indoors might be on the order of only 0.0001 atmosphere. The additional depressurization created by house appliances can be of a similar magnitude, but often appears to be less. These pressure differences sound small, but they can sometimes have an important impact on soil gas infiltration. Air movement indoors can be pictured as a delicately balanced dynamic system which can be influenced significantly by small changes in pressures.

2.3 Immediate Radon Reduction Steps by Homeowner

Many of the radon reduction measures described in Sections 3 through 8 will require installation by a professional mitigation firm, or by skilled homeowners. However, there are a few steps which essentially any homeowner can take, often at reasonably little cost. These steps vary in effectiveness in reducing radon, and they might not be sufficient, by themselves, to ensure levels below 4 pCi/L on a sustained basis in houses with high initial concentrations. But these steps can give some reduction — perhaps enough to achieve 4 pCi/L in some houses with only slightly elevated initial levels. Therefore, when homeowners discover elevated radon levels, they might wish to take some of these steps in the interim before deciding on more extensive measures.

2.3.1 Ventilation

The most effective measure that a homeowner can take to reduce radon levels is to open windows (and doors, if practical). Opening windows will have the effect of: a) facilitating the influx of outdoor air to compensate for any sources of depressurization, thus reducing the influx of radon-containing soil gas; and b) increasing the ventilation rate, thus increasing the in-flow of outdoor air to dilute any radon that does enter. While comprehensive data are not available to quantify the effect of open windows for various house plans and weather conditions, radon reductions as great as 90 percent—possibly even greater—might be achieved by opening windows (EPA78, Sc87a). It must be emphasized, though, that once the windows are closed, radon levels will rise rapidly again, probably reaching their closed-house values within a few hours (almost certainly within 12 hours or fewer). Thus, to be continuously effective, the windows would have to remain open at all times. But even if the windows can be open only part of the time, the resulting part-time reductions could be sufficient to reduce the occupants' daily average exposure substantially.

The following considerations are important in opening windows.

a. Windows should be open on all sides of the house at the same time (or at least on opposing sides). Open windows on different sides of the house help ensure effective cross-ventilation. Moreover, if windows are open on one side only, and if that side becomes the downwind side as the winds shift, then the house could become depressurized, and radon levels could increase.

b. Windows should be opened primarily on the lower levels of the house (e.g., in the basement). As discussed previously, the buoyant force on warm indoor air tends to depressurize the lower levels of the house (below the neutral plane), sucking outdoor air and soil gas into the house below the neutral plane to compensate for rising warm air which flows out above the neutral plane. Open windows below the neutral plane can significantly increase the extent to which this compensating in-flow consists of outdoor air, and decrease the extent to which it consists of soil gas.

   Moreover, since the stack effect is caused by warm air leaking out at the upper stories of the house, open windows upstairs would likely increase the outflow, potentially worsening the infiltration of soil gas. While open downstairs windows would likely provide the increased outdoor air needed to compensate for this increased upstairs outflow, the homeowner might be best served by opening just the downstairs windows. Upstairs windows might most logically be opened (in addition to downstairs windows) when the upstairs is the primary living area and when radon measurements confirm that open windows upstairs (as well as downstairs) result in net lower radon levels in the upstairs living area.

The major constraints limiting the opening of windows are the outdoor temperature and other weather conditions during cold (and hot) seasons, and the concern regarding unauthorized entry into the house. During mild weather, the costs of opening windows are generally zero. However, during cold (or hot) weather, the increased heating and air conditioning costs, and the discomfort, can make open windows impractical. To reduce the cost and comfort penalties, a homeowner could try opening a couple of windows on opposing sides of the house only an inch or two during cold or hot weather. Radon reductions would be reduced by limiting the increase in ventilation in this manner. However, even such limited opening of the windows could provide some meaningful radon reductions, and it could make open windows practical during the winter (or summer) in some cases. Further information regarding natural ventilation as a radon reduction measure appears in Section 3.1.

In some cases, a homeowner may wish to increase the ventilation rate by using a fan to blow outdoor air through the house. If a fan is used, it should always be placed so that it blows outdoor air into the house (and not so that it sucks indoor air out). A fan blowing into the house may pressurize the house slightly at the same time it increases ventilation, thus helping to reduce soil gas influx while it helps dilute radon. But a fan blowing outward can contribute to depressurization, possibly even increasing radon levels. See Section 3.1.

In a house with a crawl space which does not open into the living area, the crawl space can be vented throughout the year, if vents are already in place. As mentioned earlier, the crawl space, when vented, serves as a pressure-neutralized buffer between the soil and the living space which can be extremely effective in reducing soil gas influx into the house. Many crawl spaces have vents around the perimeter which are intended to be left open during warm and humid weather to reduce moisture. The suggestion here is that crawl space vents be left open also during cold weather to help reduce radon problems year-round. However, if these vents are to be left open during cold weather, it will often be necessary to insulate water pipes to avoid freezing. It might also be desirable to add insulation under the the floor of the living area above.

If a crawl-space house does not already have crawl-space vents in place, they can be installed as discussed in Section 3.1. As an alternative to venting the entire crawl space, it might sometimes be more cost effective to place a gastight plastic liner over exposed soil in the crawl space and to then ventilate between the liner and the soil, as discussed in Section 5.5. If the crawl space is paved, sub-slab ventilation systems (as in Section 5.2 or 5.3) can be considered. These systems are generally beyond the immediate, simple steps that a homeowner might consider, but are listed here for consideration by owners of crawl-space houses who might find opening of crawl space vents year-round to be impractical or expensive.

2.3.2 Closure of Major Soil Gas Entry Routes

Many of the openings through which soil gas enters a house (Table 4) will likely be small (such as hairline cracks in the slab) or hidden (e.g., behind wood framing or paneling). However, some openings are large and obvious, such as sumps and open top voids in block foundation walls. The radon reductions that can be achieved by closing individual entry routes are highly unpredictable, ranging from zero to some much greater percentage. To the extent that large openings are accessible, the homeowner is well advised to close them. Some reduction in radon levels will quite possibly be obtained. Even if the closure does not achieve sufficiently low levels by itself, it will often be an important prerequisite for any more comprehensive radon reduction system that might be installed later.

Closing the following types of major openings offers the greatest potential for radon reductions (see Table 4). More detailed discussion of techniques for closing these openings appears in Section 4.

1. *Open sumps.* A gastight cap should be sealed over the top of the sump (contoured around the sump pump discharge pipe, wiring, etc., as required). The cap would be configured like the one illustrated in Figure 12 in Section 5 (except without the vertical suction pipe shown in that figure), if water will not be flowing into it from on top of the slab. If water might enter the sump from on top, the trapped cover depicted in Figure 13 would be appropriate. If possible, the sump hole, now enclosed, might be passively vented by a pipe which runs from the sump to the outdoors (e.g., through a window opening).

2. *Floor drains.* Trapped floor drains should be filled with water. Water traps can dry out relatively quickly (sometimes in less than a month) if there is not a continuing supply of water to the trap. Thus, the water level should

be checked frequently. Some mitigators recommend plumbing a continual source of water to the drain, if the drain is otherwise rarely used. Untrapped drains should either be retrofitted with a commercially available trap insert (as in Figure 5 of Section 4), or fitted with a removable plug. If there is a cleanout hole, it should have a plug in place.

3. *Segments of missing slab.* If any earthen-floored segments exist in the house (e.g., fruit cellars or gaps in a concrete slab), a concrete slab should be poured in these areas (see Figure 3).
4. *Smaller, but still significant, holes in the slab.* Such holes should also be closed with cement or sealant (e.g., items B.2, B.5, and B.9 in Table 4). Some candidate sealants are listed in Table 14. French drains can be closed in a manner which allows them to continue to drain water, if necessary (see Figure 6).
5. *Voids in the top course of concrete block foundation walls,* if there is not a solid cap block and if the voids are accessible. Mortar or sometimes other materials are suitable for closure (see Figure 20). Interior load-bearing walls, as well as perimeter walls, must be addressed.
6. *Other significant holes in the foundation wall* (see, e.g., items A.1 and A.2 in Table 4). Mortar, caulk, or other sealants are appropriate, depending upon the nature of the hole (see Table 14).

In addition to relatively major openings such as those listed above, houses will have numerous minor openings, such as hairline cracks in the slab, and pores in the face of block foundation walls. Collectively, such minor openings can be an important entry route for soil gas. However, such openings can be very difficult and expensive to seal effectively and permanently. In addition, the radon reductions that can be achieved by sealing such small entry routes can be limited unless essentially all entry routes are effectively sealed, which is often impractical. Therefore, if closure of major entry routes does not provide sufficient reductions, the homeowner will generally be best advised to consider other mitigation approaches rather than attempting to seal minor openings.

In crawl-space houses, holes through the subflooring (providing openings between the crawl space and the living area) should be caulked or otherwise closed with an airtight sealant. (Stuffing fiberglass insulation into the opening, a practice which is sometimes encountered, does not provide an airtight seal.) Such openings might include places where water pipes or electrical conduits penetrate the floor, or openings around HVAC registers. Also, if a central forced-air HVAC system is located in the crawl space, leaks in the low-pressure cold air return ducts should be closed with duct tape or caulk in order to keep crawl-space air from leaking into the circulating house air.

2.3.3 Avoiding Depressurization

Some relatively simple steps can be taken to help reduce depressurization, which sucks soil gas into the house. One such step is to open windows, as discussed in Section 2.3.1, to provide a ready source of outdoor air to compensate for the depressurizing effects. Other steps that can be considered are listed below.

1. To reduce the rate of warm air exfiltration (and hence, potentially, the rate of soil gas infiltration) resulting from the thermal stack effect (see item B in Table 5):
   — close doors in stairwells between stories of the house, where possible,
   — close dampers in chimneys, and
   — close any visible openings through the floors between stories, or through the ceiling into the attic.
2. To reduce depressurization caused by appliance use and by other homeowner activities:
   — make sure that portable or window ventilation fans are not placed so that they blow indoor air outside,
   — when a fireplace, stove, or exhaust fan is operating, open a window an inch or two to neutralize the depressurization, and
   — never open windows on just the downwind side of the house.

Further discussion of these and other steps to reduce depressurization appears in Section 6.1.

2.4 Diagnostic Testing to Aid in Selection and Design of Radon Reduction Measures

When alternative candidate radon reduction approaches are being considered for a given house, certain observations or measurements (referred to here as "diagnostic tests") can be made to aid in choosing between alternatives. Or, after an approach has been selected, diagnostic tests can aid in the design of the system before it is installed.

The nature and extent of diagnostic testing conducted by radon diagnosticians and remediation firms currently varies between individuals. There is no one set of diagnostic testing procedures which can be considered universally applicable and "correct." One important consideration in choosing the appropriate diagnostic procedures is cost effectiveness to the homeowner, since the time spent by diagnosticians will generally cost the homeowner money. 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 in that house should be reconsidered.

The EPA is currently studying the merits of a variety of possible diagnostic tests, with the objective of ultimately providing guidance regarding protocols for such testing. As part of these protocols, guidance will be provided regarding which diagnostic tests should be considered under which circumstances. Guidance will also be provided on how the results from these tests can be used in mitigation selection and design. A report describing the initial approach for developing these protocols has been issued (Tu87a).

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, with a discussion of the conditions under which the individual tests might be most applicable. The decision regarding which of these tests are actually cost effective in a specific case is currently made by the individual diagnostician on a case-by-case basis.

The specific diagnostic tests that might be particularly applicable in the selection and design of specific radon reduction techniques are further discussed in Sections 3 through 8.

1. *Visual survey of entry routes and of driving forces causing entry.* A mandatory component of any diagnosis is an inspection of the house to identify potential radon entry routes and driving forces causing entry, as discussed in Section 2.2. This inspection must also identify other house structural features which—while not necessarily contributing to the entry routes—could be important in mitigation selection and design. Such other features include, for example, the presence of a complete loop of perimeter drain tiles around the footings of the house, or the presence of extensive wall and floor finish in the lowest story. Such an inspection of entry routes, driving forces, and other pertinent house features, is required before the diagnostician can suggest radon reduction approaches, or can identify the factors important in the design of the reduction system. Numerous examples of how this information is used are included in the discussions of the various reduction techniques (Sections 3 through 8).

   In inspecting a house for soil gas entry routes and sources of depressurization, Tables 4 and 5 can be useful checklists. Alternatively, Table 6 is an example of a house inspection form which has been used in some previous EPA testing (Tu87a). This form provides one logical format for helping ensure that the entries in Tables 4 and 5 are systematically addressed during the inspection, and that other pertinent house features are recorded.

   A major difficulty in conducting an inspection is that entry routes, certain house features contributing to the stack effect, and other structural features which could influence mitigation design, are often concealed—for example, 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 so that the system can be modified if performance after installation suggests that the assumptions were incorrect. In worst cases—for example, if there are large hidden openings in the slab or foundation walls which prevent an active soil ventilation system from maintaining adequate suction—the paneling, flooring, commode, etc., might ultimately have to be temporarily removed so that the openings can be closed. If a drain tile suction system is being considered (Section 5.2), some limited digging around the footings might be warranted in an attempt to determine the extent to which the drain tiles surround the house. If the current homeowner observed the house being built, or if the builder is available, information about some of these 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 the conducting of 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 also sometimes be useful, as can a mirror to enable viewing features in difficult-to-reach locations. A plumber's "snake" can be valuable for probing the extent of certain openings (for example, for probing the extent of the drain tiles which open into a sump). Another very useful tool is a smoke tube 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 gives an indication of whether

Table 6. Example of a House Inspection Form That Can Be Used During a Visual Survey (from Reference Tu87a)

RADON SOURCE DIAGNOSIS
BUILDING SURVEY

NAME: ____________________
ADDRESS: ____________________
____
____

HOUSE INSPECTED: ____________________
DATE: ____________________
ARRIVAL TIME: ____________________
DEPARTURE TIME: ____________________

PHONE NO: ____________________

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) other ____________________
      (5) frequency of use ____________________
      other mechanical ventilation ____________________

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

7. Locale - description: ____________________
____

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

Table 6 (continued)

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 (% on 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 ____________)

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 ____________

Table 6 (continued)

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, styrofoam, 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: ____________________
    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
    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:
       ____
    d. joint or other leakage path is present at junction between sump and basement floor - 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: ____________________
    basement heated: a. intentionally return air: ____________________
    b. incidentally

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

Table 6 (continued)

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

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 gases of rubber, styrofoam, 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

Table 6 (continued)

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

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

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

14. 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 soil (e.g., on grade, 6" above grade, etc.): __________
  - 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:
  a. estimate length and width of crack __________
  b. indicate if sealed with gasket of rubber, styrofoam, 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 __________

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: __________

Table 6 (continued)

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

12. Bypasses or chases to attic:

V. SUBSTRUCTURE SERVICE HOLES AND PENETRATIONS

(Note on floor plan)

Complete table to describe all service penetrations (i.e., pipes on conduit for water, gas electricity, or sewer) through substance floors 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" copper pipe, through floor, accessible.	Example: Approx. 1/8" gap around circumference of pipe with sealing styrofoam gasket.

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		
Air conditioner		
Clothes dryer		
Exhaust fans		
Other:		

Forced air duct/plenum seals - describe

Combustion Appliances: combustion air supplied (yes, no) there might be a significant soil gas flow into the house through that opening. 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 a definitive test, but it can be useful in some cases. (*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.)

2. *Radon measurements in room air.* The initial measurements that a homeowner makes to determine occupant exposure inside the house (discussed in Section 2.1) 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 those measurements. However, there will be individual cases where further measurements in the house air might be 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 (Item 3 below), to permit a direct comparison of the entry route concentrations with the simultaneously existing room air concentrations. Also, diagnostic radon measurements might be made with the house under different levels of depressurization, to assess the strength of the radon source under the house. One device which can be used to depressurize a house in a controlled manner is a "blower door," which is a highly instrumented exhaust fan. The radon measurements made under depressurization conditions would usually be grab samples, in order to minimize the time period over which the house must be depressurized.

   Of course, radon measurements in the room air will generally be conducted just before and just after activation of the control measure in order to assess its performance. Such measurements are considered here to be part of mitigation and post-mitigation testing (Section 2.6), not part of the pre-mitigation diagnosis.

3. *Radon measurements at potential soil gas entry routes.* 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 (Tu87a). 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 (Tu87a). Some diagnosticians, rather than drilling into the voids of block walls, attempt to measure a relative radon flux through the porous face of the wall (Ta85b). Those entry routes exhibiting the higher radon concentrations might reasonably be assumed to be relatively more important than those having lower concentrations. Thus, the routes with the higher concentrations might receive some priority in the design of the mitigation system. For example, if an active sub-slab suction system is planned (Section 5.3), more suction points might be placed near to 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 Item 8 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.

   It should be noted 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 a more important contributor than one with a higher level but a low flow. Since flow rates cannot be 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 flows. 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 upon radon measurements alone.

While radon measurements at entry routes can be helpful in suggesting which potential routes are more important, they cannot always be used to eliminate potential routes from consideration. Any route which exhibits a radon concentration above 4 pCi/L must be at least partially responsible for the elevated levels in the house. Thus, that route must be treated by the radon reduction system even if there are other routes showing much higher concentrations. Even if all of the higher-concentration routes were treated, this lower-concentration route, if untreated, could possibly keep indoor radon levels elevated if the flow rate through the route were high enough. Moreover, a route which does not appear significant initially could become important after the house and soil gas flow dynamics are altered by a radon reduction system, or by changes in weather conditions or homeowner living patterns. Adding to the uncertainty is the fact that there are unavoidable inaccuracies in measuring radon levels associated with some entry routes (especially small cracks which are sampled by taping over a segment of the crack). In these cases, not only is the flow rate of the entering soil gas unknown, as discussed in the previous paragraph, but there is also a large uncertainty in the radon concentration of the gas that is entering.

In summary, entry route radon measurements can suggest which routes warrant priority attention in the design of the mitigation system. However, it must be assumed that *all* visible entry routes (and anticipated concealed routes) must be treated in some manner, irrespective of their apparent radon levels, if the mitigation system is to be successful.

To accentuate the effects of the entry routes during these diagnostic measurements, some diagnosticians depressurize the house (e.g., using a blower door) while taking the grab samples at the entry routes.

4. *Radon measurements in well water.* If a house receives its water from a well, it will generally be necessary to measure the water radon level as part of the diagnostic effort. 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 (see sections 1.5.1 and 8). Under these conditions, water treatment might be required in addition to (instead of) soil gas-related reduction measures.

5. *Gamma measurements.* Gamma radiation should be measured at several locations throughout the house and around the outside of the house. Comparison of average gamma readings indoors with those outdoors provides a convenient and inexpensive screening test which can alert the diagnostician to whether building materials are an important radon source. The selection of the mitigation approach could be significantly affected if building materials are an important contributor.

   Gamma radiation is present in the environment as a result of naturally occurring radionuclides in the surrounding soil and rock, and as a result of cosmic radiation. If the gamma levels are approximately the same as they are outdoors, this result suggests that the building materials do not contain elevated concentrations of radionuclides which contribute to the gamma radiation. Since radium—the immediate parent of radon—is a gamma emitter, comparable gamma levels indoors and outdoors suggest that the building materials do not contain radium and hence are not a radon source. It is not uncommon for gamma levels indoors to be slightly lower than those outdoors, if the house has a concrete slab which has a lower radium content than the surrounding soil. In such cases, the concrete slab provides some shielding of the gamma rays coming up from the soil.

   However, significantly higher indoor gamma levels indicate that building materials are a source of gamma radiation. If the gamma-emitting radionuclides in the building materials include radium, then the building materials will be a source of radon. The specific building materials which are the source of the gamma can fairly readily be identified, using portable instruments to measure gamma levels.

   If gamma emissions are high enough, and if the affected building materials have a large exposed area in the house, removal and replacement of these building materials (or sealing or coating the material surface to prevent radon and/or gamma emanation from the materials) should be considered. To further evaluate the need to address these building materials, radon flux could be measured to provide a rough suggestion of the degree to which the materials are contributing to radon levels in the house. Such flux measurements could consist of sealing a closed container containing charcoal canisters over a part of the affected surface for a couple days (Tu87a). In addition to the concern about the materials' contribution to the indoor radon levels, there is concern regarding the exposure of the occupants to the gamma radiation. A proposed regulation that would apply to houses contaminated with uranium mill tailings (40 CFR 192.12) is that remedial action to reduce gamma levels should be undertaken whenever the levels created inside the house by the mill tailing contamination are more than 20 μrem per hour higher than the natural background levels outdoors. Microrems per hour are a measure of the equivalent dose rate resulting from radiation. While this standard does not apply to houses where the elevated gamma levels result from natural building materials, the figure of 20 μrem per hour above background might be considered when making decisions for the case of natural building materials.

6. *Measurements of house leakage area and ventilation rate.* As discussed previously, every house has a characteristic ventilation rate —i.e., outdoor air will infiltrate into the house (and indoor air will exfiltrate out of the house) at a rate sufficient to replace the house air once within some period of time, typically once every 1 to 2 hours (or longer in tight houses). This natural infiltration occurs because, even when all doors and windows are closed, there is an unavoidable "effective leakage area." The smaller the leakage area, the tighter the house, and the lower the ventilation rate (the longer it will take to exchange all of the air in the house). In addition to air leakage from the outdoors into the house, there will be leakage of indoor air between stories, depending upon the tightness of the interface between stories (i.e., the extent of airflow bypasses, as discussed in Section 2.2.2).

   Under some circumstances, it would be useful to measure the ventilation rate/leakage area through the house shell, and between stories within the house. For example, if a heat recovery ventilator (HRV) is an option being considered for treating all of (or perhaps one story of) a house (Section 3.2), the ventilation rate of that house (or of that story) is important. HRVs perform primarily by increasing the ventilation rate, diluting the radon that enters the house. The relative increase that HRVs can make in the ventilation rate, and hence their radon reduction effectiveness, will be greater when the initial ventilation rate is low. When the initial ventilation rate is high, an HRV of a given flow rating will give correspondingly lower radon reductions, as discussed in Section 3. Determination of the natural infiltration rate would thus suggest how great a reduction an HRV might be expected to provide. As another example, if basement pressurization is being considered (as discussed in Section 6.2), the ability to achieve pressurization (or the sealing and fan capacity needed to achieve it) will be determined by the extent of the leakage area in the house shell and by the leakage area between stories. As a third example, large leakage areas in the upper story might suggest a need to seal leakage points in the upper shell, in an effort to reduce the warm air exfiltration creating the thermal stack effect.

   While the leakage area through the house shell will remain unchanged from season to season, the closed-house natural infiltration rate (i.e., the flow through this leakage area) will vary. Infiltration in a given house can typically be three times higher in the winter than in the summer, due to the stack effect. This should be considered when planning, and interpreting the results from, ventilation rate measurements.

   A *blower door* is commonly used to measure effective leakage areas and ventilation rates. The blower door can be operated to determine the leakage area for the shell of the entire house, or, in some cases, the leakage area for an individual story within the structure (Tu87a). When operated to evaluate individual stories, the blower door can also give some information on the leakage area between stories.

   Non-toxic *tracer gases* are another approach for measuring both the ventilation rate of the house, and the movement of air between rooms and stories. For the measurement of the house ventilation rate, tracer gases can be used by one of three techniques:

   a) the dilution technique, where the tracer gas is initially brought up to a uniform concentration in the space to be measured, and where the ventilation rate is then determined by observing the dropoff in the tracer gas concentration over time (generally several hours).

   b) the steady state injection rate technique, where the tracer gas is continuously fed into the space at a constant rate, and the ventilation rate is determined by observing the concentration in the house air that is maintained by this constant feed.

c) the constant concentration technique, where the flow of tracer gas into the space is continually adjusted as necessary in order to maintain a constant concentration of the tracer in the house. The ventilation rate is determined from the flows of tracer that are required.

Sulfur hexafluoride (SF_6) is one of the more commonly used tracer gases, and can be used by any one of the three techniques. SF_6 is injected into the house from a gas cylinder; concentrations in the house air are determined either using a gas chromatograph in the house, or by collecting house air samples for chromatographic analysis at a remote laboratory. Another common tracer gas is perfluorocarbons (several different perfluorocarbon compounds can be used). Perfluorocarbon tracers (PFTs) are generally used by the steady injection rate technique. The PFT is released at a steady rate over a period of time from a permeation tube; concentrations in the house are measured using small tubes of sorbent which sorbs the perfluorocarbons over the period they are being released. The tubes of sorbent are subsequently analyzed to determine the amount sorbed by each detector. Tracer gases can be used in this manner to determine the ventilation rate of the entire house, or of any selected zone within the house.

Tracer gases can also be used to determine air movement between various zones in the house (e.g., between stories). In this application, the tracer gas would be released in one zone, and the buildup of the tracer over time would be observed in another zone. Perfluorocarbons facilitate simultaneous determination of ventilation rate and interzonal air movement. Different perfluorocarbons can be released simultaneously in different zones of the house (with all being sorbed in each of the detection tubes). Analysis of the detection tube from a given zone would thus reveal not only how much total air from elsewhere is entering that zone (the ventilation rate), but how much of that air is coming from each of the other zones.

7. *Pressure measurements.* Some diagnosticians find it helpful to measure differences in pressure in certain cases (e.g., between the indoors and outdoors, or between points indoors, or between the soil and the house). For example, the pressure differential between indoors and outdoors during a radon measurement will give some perspective regarding whether that measurement represents a high or low degree of house depressurization. (When a blower door is operating, that pressure difference is determined as part of the blower door operation.) Pressure measurements with air-exhausting appliances in operation indicate the degree of depressurization caused by these appliances, which the mitigation system must be designed to counteract. Pressure measurements between the house and the soil give a measure of the actual driving force sucking soil gas into the building (at the time of measurement), which, again, the mitigation system must be designed to offset. If differentials are measured between the indoors and the outdoors, outdoor positions on different sides of the house should be considered. The pressure difference between indoors and outdoors on the upwind side will not be the same as the difference between indoors and outdoors on the downwind side.

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

   In practice, pressure differential measurements are most fruitfully applied in *post*-mitigation diagnostic measurements (described in Section 2.6), or in conjunction with the sub-slab permeability measurements or block-wall pressure field measurements described in items 8 and 9 below.

8. *Measurement of sub-slab permeability.* If a sub-slab ventilation system is being considered (Section 5.3), 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 "permeability"). 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 suction system is to be used, and if this system is to maintain suction at all of the entry routes around the slab, the number and location of the needed suction points will depend upon the permeability under the various portions of the slab. The greater the permeability, the easier it will be for a suction point to maintain suction 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 permeability. By that approach, the initial sub-slab installation would be made using best judgment (based upon the visual inspection, item 1 above). 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 suction points are required. This approach avoids the cost of the pre-mitigation permeability measurement, but increases the risk that the initial installation will have to be modified at some expense later. Among the circumstances under which it might be a reasonable risk to skip the pre-mitigation permeability 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 permeability 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.

One more quantitative approach for assessing sub-slab permeability is to measure what is referred to as the "pressure field extension." The pressure field extension reflects the ability of suction drawn at one point under the slab to maintain (reduced) suction at various other points remote from the suction point. One convenient technique for measuring the pressure field extension (Sa87a) involves the use of a variable-speed high-suction industrial vacuum cleaner—capable of drawing up to 80 in. WC suction—to draw suction on a hole through the slab at some central location. The suction hole through the slab could be as large as 1.5 in. in diameter, in which case the suction hose from the vacuum cleaner can be inserted all the way through the slab and temporarily sealed using putty between the hose and the concrete. Alternatively, the suction hole can be as small as ⅜-in., in which case the hose is placed flush on top of the concrete over the hole, with a putty seal between the lip of the hose and the concrete. The suction by (and the gas flows into) the vacuum cleaner is then adjusted while pressures are measured under the slab at several test points around the perimeter of the slab, remote from the suction point. Pressure is also measured at a closer point, within perhaps 8 in. of the suction point. These pressures can be measured using a suitably sensitive manometer or pressure gauge tapped (with a putty seal) into ⅜-in. holes through the slab at the test points. (Some diagnosticians might use a smoke stick, rather than a manometer or pressure gauge, to determine qualitatively whether the flow is down into the test hole.) The exhaust from the vacuum cleaner must 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, ideally, is to determine the level of suction to be maintained at the closer test point to ensure that the suction at the remote perimeter points will be at least enough to counteract any depressurization in the basement that might result due to the thermal stack effect, wind, or appliance operation. At present, it is estimated that the sub-slab depressurization around the slab perimeter must be maintained at at least 0.015 in. WC to prevent soil gas entry when the basement becomes depressurized.

The results of this diagnostic test include the suction in the closer test hole, and the suctions in the remote perimeter test holes, as a function of flow through the vacuum cleaner. Under favorable conditions (good permeability), the suction in the closer test hole will be no greater than several tenths of an inch of water, despite the high suction in the vacuum cleaner (due to the large pressure loss incurred as the soil gas accelerates up to the velocity in the vacuum); the suctions at the remote points will often not be much greater than 0.015 in. WC, and will sometimes be less. The loss of suction 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 loss of suction will also be a measure of the amount of house air leaking down through the slab openings.

The ultimate sub-slab suction installation can include a hole in the soil under the slab (see Figure 14) having a radius equal to the distance between the suction hole and the closer test point. The pressure at the closer test point can thus be viewed as the pressure which the sub-slab suction system must maintain in that suction hole if the sub-slab depressurization around the slab perimeter is to be maintained at 0.015 in. WC. The performance curve of the fan for the sub-slab system, and the diameter and length of the suction pipe (and hence the pipe pressure loss), can then be selected to provide the needed suction in the suction hole at the indicated flows.

This diagnostic test procedure has been used in designing a number of sub-slab suction installations to date. Where sub-slab permeability is relatively good, the procedure appears fairly successful. When the pressure field extension is good, indicating high sub-slab permeability, one sub-slab suction point is often adequate to treat an entire slab. In large houses, or where the permeability is less high (although still good), a second suction point might be needed. The second point might be located and designed 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 one vacuum test was conducted. This assumption is probably reasonable when permeability is good.

The difficulty with sub-slab pressure field measurements is that it is currently not clear how the testing might cost-effectively be conducted, and how the results might be interpreted, in cases where the permeability is not good. When the pressure field extension is poor, a vacuum cleaner test at one or two suction holes will generally not give the mitigator much information with which to design a sub-slab suction system. The vacuum cleaner suction 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 in this case 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 — multiple suction points, careful placement of the points, high-performance fans.

Testing has shown that "poor" pressure field extension does not necessarily mean that sub-slab suction 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 suction holes around the slab, more extensively mapping the distribution of sub-slab flow resistance. However, the required number of vacuum cleaner suction points might be so large that this approach might 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 might still not be effectively 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 (Sc87d). Thus, if the results from the pressure field mapping suggest that a very large number of suction points would be needed to achieve 0.015 in. WC everywhere, a mitigator might be inclined to start with a fewer number of 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 the extensive mapping.

Therefore, if the initial test of sub-slab pressure field extension shows poor extension (poor permeability), some mitigators might decide that the most cost-effective approach would then be to install a system based upon best judgment, 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 in cases where permeability is poor.

9. *Measurement of pressure field inside block walls.* If active ventilation of the void network inside hollow-block foundation walls is planned (Section 5.4), it might be useful to make measurements on the wall voids which are analogous to those described above regarding sub-slab permeability. The objective would be to determine how far any pressure effects within the voids (either suction 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 relatively 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 suction (or pressure) is applied. The information on pressure field extension could be used to help select the number and location of wall suction 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.

   In the case of 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 likewise be into block cavities at appropriate locations radiating out from the suction holes.

   Again, some diagnosticians feel that this type of testing might not be cost effective until *after* the performance of an initial mitigation installation suggests that is required.

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

10. *Soil permeability measurements.* Some diagnosticians believe that it might ultimately prove useful in some cases to measure the permeability of the soil surrounding the house. The permeability of the surrounding undisturbed soil is distinguished from the

permeability of the crushed rock and soil directly under the slab. This measure of general soil permeability might indicate the effectiveness of an active sub-slab ventilation system in treating below-grade entry routes on the outside face of the foundation wall, or how the performance of the sub-slab system might be affected if the fans were operated to blow into the soil rather than to draw suction.

Alternative devices and protocols for measuring general soil permeability have been tested (e.g., Tu87a). However, EPA's evaluation of diagnostic procedures has not yet identified an accepted protocol for measuring general soil permeability, or a validated methodology for how such permeability results can fruitfully be used in mitigation system design. Therefore, it is not yet possible to provide firm guidance regarding when or if this type of diagnostic testing will be cost effective.

11. *Working level measurements.* Measuring the working level of radon progeny can sometimes be informative as a supplement to measuring radon gas. Simultaneously measuring radon gas and working level will reveal the "equilibrium ratio" (i.e., the degree to which the radon progeny have achieved radioactive equilibrium with the parent radon gas, as discussed in Section 1.5.2). This ratio is calculated by dividing the working level reading by the radon gas concentration (in pCi/L), and then dividing the result by 0.01 (which is what the WL/radon gas ratio would be at equilibrium). For example, if the radon concentration in a room measured 20 pCi/L, and the working level measured 0.1 WL, the equilibrium ratio would be:

$$\frac{\text{(0.1 WL/20 pCi/L) actually present}}{\text{(1 WL/100 pCi/L) if equilibrium existed}} = 0.50$$

Equilibrium values in the range of 0.3 to 0.7 are typical. An equilibrium ratio near or below 0.3 might suggest that the ventilation rate prior to the measurement had been higher than usual, since the ratio is decreased when radon residence time in the house is reduced by increased ventilation rates. Low equilibrium values could also suggest that the degree to which the progeny have been "plating out" (i.e., attaching to surfaces inside the house) has been atypical (with increased plate-out decreasing the equilibrium ratio). Conversely, equilibrium values near or above 0.7 suggest a lower-than-usual ventilation rate (or lower-than-usual plate-out).

Practically, it is not clear that pre-mitigation measurement of working level (in addition to radon gas) will often influence the selection or design of mitigation measures. Thus, pre-mitigation working level measurements are generally a matter of preference and convenience. However, if a mitigation measure is being considered which could influence the equilibrium ratio—in particular, an air cleaner (Section 7), or a heat recovery ventilator—then it is important to measure both working level and radon gas concentrations before and after the reduction system is installed, so that the effect of the system is reasonably understood.

12. *Logging of weather conditions and household activities.* Whenever short-term radon measurements are being made in a house, it is suggested that a record be kept of the weather conditions and on-going household activities which might be influencing the measurements. Such conditions might have contributed to house depressurization (or ventilation), or to the release of radon from well water resulting from increased water use in the house. Outdoor temperatures are fairly easily recorded. Wind speed and direction cannot generally be recorded without special equipment, but qualitative notation of these conditions is not difficult. Use of depressurizing appliances can be noted (item C in Table 5), as can well water use.

If pressure is being measured in conjunction with radon (item 7 above), then the depressurizing effects of weather conditions and of many household activities might already be accounted for by the pressure measurements. However, a log of these weather/household factors can still be valuable. For example, if the logs show that conditions remained relatively mild during this testing, it might be expected that some of the measured parameters might change (such as the importance of particular radon entry routes) under more challenging conditions. Or if increases in radon levels correspond to periods of water use in the house, then water treatment might be an important element of the radon reduction strategy.

2.5 Selection, Design, and Installation of the Radon Reduction Measure

After the appropriate pre-mitigation diagnostic testing has been completed, the information is available for the selection, design, and installation of the initial radon reduction measure. This section gives an overview of the approach for completing this step. Much more detailed discussion of the design and installation of the individual measures is provided in Sections 3 through 8.

2.5.1 Selection of the Mitigator

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." The mitigator will generally also be the diagnostician who performed the diagnostic testing described in Section 2.4.

If the radon reduction steps which particular homeowners feel comfortable in undertaking themselves (as discussed in Section 2.3) are not sufficient to reduce indoor radon concentrations to acceptable levels, then the homeowners should hire a contractor experienced in house diagnostics and radon mitigation. To obtain a list of candidate contractors 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 (see Section 10), local public health officials, local building trade associations and realtor associations, local building supply houses, the chambers of commerce, house improvement firms, or perhaps energy conservation consultants. 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 will be unable professionally to provide a comprehensive listing 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 in a large number of houses might have a few clients who will be 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 contractors are suggested below.

1. How many houses has the contractor worked on in the past? How many of them have been similar to yours, in terms of substructure type and design features?

2. Does the individual who will be supervising the work appear to have a good understanding of the principles of radon entry and mitigation?

3. What kind of pre-mitigation diagnostic testing will the contractor do? Referring to Section 2.4, does this degree of diagnosis seem reasonable in light of the reduction measures which the contractor is considering? Does the proposed diagnostic testing seem to be more extensive than is really needed? Excessive diagnostic testing will only add unnecessarily to the cost.

4. Will the contractor take the time to explain exactly what the work will entail, and why? If the proposed approach differs from that described in this document for the measure being considered, can the contractor give a rational explanation? In the design of the installation, is the contractor considering the aesthetics of the house, and features that would alert you if the reduction system ever began to malfunction?

5. How will the contractor determine the performance of the system after installation? Will radon measurements of sufficient duration be conducted after installation (Section 2.6.1)? Will the contractor perform sufficient post-mitigation diagnostics to confirm that the system is functioning as expected (Section 2.6.2)?

6. What type of "guarantee" does the contractor provide? The state of knowledge regarding radon mitigation is such that a contractor 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 contractor 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).

7. If the contractor's cost estimate is significantly different from that of other prospective contractors, is it apparent why? Is this contractor proposing more or less work than the others? Is the additional work needed? One bidder might be proposing more diagnostic testing, which might or might not help ensure better radon reduction performance. Or one bidder

might be devoting more effort in improving aesthetics, which the homeowner might or might not be concerned with.

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.

Depending upon the types of radon reduction systems that might be considered for a particular house, and depending upon the skills of the individual homeowner, some homeowners might feel that they can install a system in their house on a do-it-yourself basis, without a contractor's help. The steps involved in installing these systems are all consistent with common construction practice (although special equipment is needed in a few cases). Thus, homeowners with experience in house repairs and improvement might be able to install some of these systems themselves. Some effective, professional-looking systems have been installed by homeowners. However, it is not recommended that homeowners undertake a major installation on their own unless they:

a) feel totally conversant with the principles behind the system to be installed; and

b) have inspected a similar installation that has already been completed in a similar house, in order to help ensure early recognition of some of the details and practical difficulties to which they must be alert.

Subtle features in an individual house could influence the design of a radon reduction system. A mitigation contractor who has had experience under a variety of conditions is more likely to be alert to these features, and to know "the tricks of the trade."

2.5.2 Use of 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 if the first step is not sufficient, until the desired degree of reduction is achieved. The alternatives to this phased approach—or the methods to help reduce the number of steps in the phased approach—include: performing increased diagnostic testing beforehand (at an increased expense for diagnostics) to ensure an improved initial system design; or installing a more extensive (and expensive) mitigation system to begin with, to ensure that radon levels will be reduced sufficiently 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 on a case-by-case basis. This decision will be based upon 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 might still not achieve the desired reduction.

A number of examples of phased installations will be discussed in later sections. Some of the initial, simple steps that homeowners might take themselves (see Section 2.3) can be considered, in essence, the first phase of mitigation, to the extent that such steps are permanent (e.g., closure of entry routes and airflow bypasses). A few other specific examples of phasing are suggested below for illustration.

1. A house with 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 (as illustrated in Section 5.2), and passive venting of the enclosed sump to the outdoors, might be attempted prior to any more expensive measures.
2. A house with slightly to moderately elevated radon levels has only a partial drain tile system, rather than the complete drain tile loop preferred in Section 5.2. Since drain tile suction systems can be very effective, relatively inexpensive, and aesthetically the least intrusive of the active soil ventilation techniques, suction on the partial system might be attempted initially.
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 suction points only in the unfinished portion. If this system turns out to be insufficient, then appropriate locations for suction points in the finished section of the basement, and the degree of refinishing that is desirable can be considered.
4. A basement house with hollow-block foundation walls and high radon levels might ultimately require suction on both the sub-slab and the wall void network. The initial installa-

tion might be designed to draw suction on the sub-slab, with treatment of the wall voids added later, if needed.

2.5.3 Some Considerations in the Selection, Design, and Installation of Mitigation Measures

The radon reduction measure that is *selected* for a given house will depend upon:

1. the degree of radon reduction required. In general, if a high degree of reduction is needed—i.e., reductions of 80 percent and higher—EPA's current experience suggests that an active soil ventilation approach will usually be required. Other possible approaches that might be considered include, for example: keeping basement windows permanently open (including abandoning the basement as living space if necessary in extreme weather); and pressurizing the house (Section 6.2), if this developmental approach appears feasible in that specific house. If a lower degree of radon reduction is sufficient, then other techniques can be considered (e.g., heat recovery ventilators, sealing major entry routes, or passive soil ventilation), although active soil ventilation techniques will still be an important option.
2. the cost/benefit trade-off. This is generally a personal decision on the part of the homeowner. One reduction technique might provide a greater degree of reduction than another, but at a higher installation and/or operating cost. Each homeowner will have to decide what level of reduction is reasonable.
3. the convenience and appearance that is desired by the homeowner. Some techniques are less intrusive than others. For example, a heat recovery ventilator, entry route sealing, or active suction on a drain tile system will often have less visual impact than will a sub-slab suction system with pipes sticking up out of the slab. This consideration might influence technique selection in some cases.
4. the desired confidence that the needed degree of reduction will be achieved. Or, stated another way, the desired reduction in the number of iterations required under the phased approach. Some techniques might offer a greater potential for achieving and maintaining the desired reduction.
5. the design of the house. House design will more often influence the *design* of the reduction measure rather than its *selection.* However, in some cases the technique that is selected may be influenced by house substructure and design features. A couple of examples of how house design features can influence mitigation selection are the presence of a complete drain tile loop (which would suggest selection of drain tile suction), and of French drains (which might sometimes suggest the selection of the "baseboard duct" soil ventilation approach described in Section 5.4).
6. diagnostic test results, as discussed in Section 2.4. For example, a house with a high natural ventilation rate might not be a good candidate for a heat recovery ventilator. Poor sub-slab permeability could sometimes suggest that a technique other than sub-slab suction should be considered.

Once the radon reduction measure has been selected, the next step is its *design.* Design will be influenced by the same six factors discussed above. Using sub-slab suction as an example, one might consider designing the system with additional suction points under the slab (i.e., near a larger number of potential soil gas entry routes) under the following circumstances:

- if diagnostic testing suggests that the permeability underneath some or all of the slab is limited;
- if the house requires a high degree of radon reduction, suggesting that careful treatment of all entry routes is particularly important;
- if the homeowner is willing to accept the increased cost, and perhaps increased inconvenience, of locating suction points in finished sections of the slab, where replacement or modification of wall and floor finish will be necessary to permit installation and to conceal the piping afterwards;
- if increased confidence is desired that the system will achieve a given degree of radon reduction on the first attempt.

The design of the house will always be important to the design of a sub-slab suction 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 suction 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. If the house is a slab on grade with a highly finished interior, these features could suggest that the suction 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. These types of considerations in mitigation system design are further discussed for the individual mitigation approaches in Sections 3 through 8.

Many mitigators contract with local building tradesmen to make the physical *installation* of the radon reduction technique in a house. The installation process must be carefully supervised by the diagnostician/mitigator, or by someone else familiar with the principles of the system being installed. Some steps might seem inconsequential to an installing workman who is not fully familiar with the principles of the technique. But these steps might in fact be very important in the ultimate performance of the system. For instance, if an objective is to mortar closed the partially visible open top voids in a block foundation wall (Figure 20), 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. Other examples are given in the later sections of procedures which must be carefully followed during installation.

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 installing workmen drill or dig into places which could not be seen by the diagnostician during inspection and design. Or the 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 consistent with the desires of the homeowner for a neat, aesthetic installation.

The final installation should be finished in a manner providing the appearance which the homeowner considers to be cost effective for the particular circumstances.

2.6 Testing After the Reduction Technique is Installed

The testing conducted after a radon reduction measure has been put into operation has two objectives:

1. Radon (and perhaps radon progeny) measurements to determine to what extent occupant exposure has been reduced by the technique (i.e., to characterize the performance of the technique in reducing radon levels); and
2. Diagnostic measurements 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.

2.6.1 Post-mitigation Measurement of Radon Levels in the House

The measurement methods that can be used for determining the radon and radon progeny levels in the house have been described in Section 2.1. A few considerations are discussed below for the specific case where these measurements are used to evaluate the performance of a radon reduction technique.

1. The *initial* measurement after the reduction technique is activated must cover a period long enough to give a meaningful indication of performance. However, the measurement should not be so long that steps to improve the system are delayed, if improvements are necessary. Such initial post-mitigation measurements might include measurements according to the EPA's "screening" protocols using charcoal canisters, continuous radon or working level monitors, or RPISU units (EPA87a). See Sections 2.1.1 and 2.1.2 of this document. Alpha-track detectors would have to be exposed for perhaps 3 months to provide accurate results at the presumably low post-mitigation radon levels. This period might be longer than optimum, if the objective is to obtain a quick measure of whether the mitigation technique appears to be performing well. Individual grab samples are never adequate, by themselves, as a measure of mitigation performance.
2. This initial measurement should generally be begun at least 12 hours (and perhaps longer) after the reduction system is activated, to help ensure that the house has reached "steady state" with the system in operation. Some data suggest that, in certain cases, the house might take more than 24 hours to reach its mean post-mitigation radon level.
3. It is desirable to take a radon measurement immediately before the reduction technique is activated, using the same technique selected for the initial post-mitigation measurement. Such a pre-operational measurement would permit a more reliable conclusion regarding how well the reduction system is operating. Since radon levels in a house can change dramatically over time, taking "before" and "after" measurements as close together as possible helps reduce the extent to which differences in the two measurements might be

influenced by time-related factors (e.g., major changes in weather conditions).

4. After all modifications/improvements to the radon reduction system have been completed, a radon measurement of longer duration than that described in item 1 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 would give the most rigorous 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, continuous monitors, or RPISU units, used once every 3 months during the year. These follow-up protocols are summarized in Section 2.1 of this document. Grab samples are never adequate for final characterization of reduction technique performance.

   A disadvantage of a 12-month track-etch measurement is that the long-term results of reduction technique performance would not become available 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 measurement made during cold weather. Due to the increased natural thermal stack effect during the cold months, and the typically prevailing closed-house conditions, this winter measurement would reveal how the mitigation system performs under the most challenging circumstances. 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 will have to be made. Is the radon level sufficiently high such that improvements to the mitigation system should be considered immediately? Or should further radon measurements be made before modifying the system, to determine whether the annual average might be below 4 pCi/L?

5. If the mitigation technique is expected to affect the radon progeny in a manner different from radon gas (such as a heat recovery ventilator or an air cleaner), the "before" and "after" measurements should both include measurements of radon gas and of progeny (working level).

6. 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 (EPA86c). Initial, short-term measurements (items 1 and 3 above) 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-mitigation and the 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. One 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.

2.6.2 Post-mitigation Diagnostic Testing

Some of the same types of diagnostic testing that were described in Section 2.4 are applicable after the radon reduction measure is installed. However, the relative importance of the various diagnostic techniques might vary for post-mitigation purposes, compared to the pre-mitigation application.

Again, no one set of post-mitigation diagnostic procedures can be considered universally applicable. Procedures will vary from diagnostician to diagnostician.

Some of the post-mitigation diagnostic tests that have been used by diagnosticians to date are listed below, with a discussion of the conditions under which the individual tests might be most applicable. Specific diagnostic tests that might be particularly applicable in conjunction with specific radon reduction techniques are further discussed in Sections 3 through 8.

1. *Visual inspection and smoke stick testing.* An important element of post-mitigation diagno-

sis is a careful inspection of the system to ensure that everything is installed and operating properly. For example, is all necessary piping and ducting configured as desired? Are piping/ducting segments connected with an airtight seal? Are fans installed and wired properly? Are all joints, openings, and airflow bypasses which were supposed to be closed, in fact closed adequately?

A tool which can be very useful in many cases during such an inspection is a smoke tube (or punk stick), which releases a small stream of smoke which can reveal distinct air movements. Such a smoke generator can be used to detect, for example:

- whether there continues to be soil gas or air movement through an opening or airflow bypass which was supposed to have been closed; whether an active soil ventilation system operating in suction is in fact maintaining house air flow *into* any unclosed openings in the slab or foundation wall;
- whether the joints between pipes in an active soil ventilation system have been sealed to be airtight;
- whether air movement in specific regions of the house has been distinctly affected by a house ventilation system.

2. *Pressure and flow measurements.* Whenever the radon reduction technique involves the movement of air through pipes or ducts (such as with a soil ventilation system or a heat recovery ventilator), it is generally desirable to measure pressures (suctions) and flows in all pipes and ducts. Such measurements confirm that the fan is in fact moving the air, and developing the suction or pressure that is necessary for the system to perform well. For example, in an active soil ventilation system, inadequate suctions or high flows in one leg of the piping system could indicate that there is excessive air leakage into the system through unclosed wall/floor openings near that leg. Perhaps those openings should be located and closed, and/or other steps taken, to ensure adequate suction in that leg, and to ensure that the high flows in that leg do not reduce the suction in the other legs. Perhaps additional fan capacity will be required. Low suctions and low flows, even though the fan *seems* to be operating properly, could indicate that the fan is losing capacity due to plugging of inlet or outlet piping (e.g., with ice in cold weather), or perhaps is facing too much pressure loss in the inlet or outlet piping due to numerous elbows, piping which is too narrow in diameter, etc. Another example of the need for flow measurements is with heat recovery ventilators, where the mitigator will need to confirm that the system operation is "balanced" (i.e., the stale air flowing out is equal to the fresh air flowing in), or perhaps is pressurizing the house (fresh inflowing air is somewhat greater).

   Pressure measurements can also be very valuable in the sub-slab and in block-wall voids in evaluating active soil ventilation systems, as discussed in item 3 below.

   Some diagnosticians might elect to measure pressure differentials between indoors and outdoors, or between different locations inside the house, during post-mitigation testing. Such measurements could aid in understanding the extent to which the radon reduction system is being challenged by house depressurization (see Section 2.4).

   The small pressure differences of interest here can be measured using micromanometers, or using certain commercially available gauges which are sufficiently sensitive (able to detect pressure differences of perhaps 0.01 in. WC). Flow velocities in pipes and ducts can be measured using pitot tubes or hot-wire anemometers.

3. *Sub-slab and wall void pressure field measurements.* If a sub-slab suction system has been installed, the suction can be measured at various points under the slab in an effort to assess how well the suction field is extending to the various soil gas entry routes around the slab. If pre-mitigation pressure field extension was measured using an industrial vacuum cleaner (item 8 in Section 2.4), it would be advisable to repeat the suction measurements using a micromanometer or pressure gauge in the perimeter test holes through the slab after the sub-slab system is installed. These measurements would confirm whether the fan and piping network design for the sub-slab system were in fact maintaining sub-slab suctions around the slab perimeter (e.g., 0.015 in. WC) that would have been expected from the pre-mitigation vacuum cleaner testing. If perimeter suctions are less than anticipated, the suction measurements would suggest the appropriate corrective action—e.g., an additional sub-slab suction point at a location where the suction is inadequate, or a larger fan. If no pre-mitigation pressure field extension measurements were made, it could be desirable to drill ⅜-in. test holes through the slab at various remote points after the mitigation system is installed, so that a manometer

or gauge can be tapped in to determine the pressure field extension being maintained by the system.

Such measurements can be particularly useful when the initial sub-slab system has not provided sufficient radon reductions, and it is necessary to assess where additional suction pipes should be installed. Even if the initial system has given adequate reductions, these measurements could be useful as an indicator of whether the depressurization being maintained under the slab appears sufficient to maintain system performance when the house becomes depressurized by weather conditions and appliance operation.

As discussed in Section 2.4, sub-slab systems sometimes appear able to maintain good performance even when the sub-slab depressurization is not, say, 0.015 in. WC everywhere. Thus, if the sub-slab system seems to be giving good radon reductions, it might not be straightforward to determine a course of action if these measurements show that sub-slab depressurization is less than 0.015 in. WC (or that the sub-slab is at a *higher* pressure than the house) in some locations. But even considering this limitation in the ability to interpret the results, these measurements can still be valuable. If a sub-slab system seems to be achieving good reductions, but sub-slab depressurization is found to be inadequate in many locations, the mitigator and homeowner are alerted that system performance may be marginal. Reduction performance should be monitored more carefully, perhaps over a longer period.

If active ventilation is being conducted on the void network inside hollow-block foundation walls, analogous pressure field measurements in the void network can be conducted by drilling into individual voids at locations radiating out from the ventilation points. These results would indicate where additional ventilation points might be needed along the perimeter walls and on load-bearing interior walls.

4. *Spot radon measurements.* Grab-sample measurements of radon concentrations can be useful in at least two ways. First, measurement of radon levels inside the individual pipes associated with active soil ventilation systems (operating in suction) will reveal from which leg of multi-legged systems the highest radon levels are being drawn. This information identifies "hot spots" around the house, and can sometimes be useful (in conjunction with the pressure measurements discussed in items 2 and 3 above) in making the decision where further suction points should be placed, if the performance of the initial system is not adequate. The second situation in which grab sampling can be used is in measurements aimed at evaluating the relative importance of remaining soil gas entry routes. Where the initial radon reduction installation does not achieve the desired degree of reduction, such measurements can aid in identifying which potential entry routes are not being adequately treated. The considerations associated with using grab samples to evaluate potential soil gas entry routes have been discussed in item 3 of Section 2.4.

5. *Ventilation measurements.* If the radon reduction measure that is installed can be expected to have a significant impact on house ventilation rates (e.g., a heat recovery ventilator), then it could sometimes be useful to make post-mitigation measurements of the house ventilation rate, in order to confirm that the ventilation has indeed been increased as anticipated. Since HRVs can influence air movement throughout the house in a complex manner, it could be useful to measure not only the increase in air changes per hour between outdoors and indoors, but also the differences in air flow between different segments of the house. The tracer gas approaches discussed in item 6 of Section 2.4 would have to be used for these measurements. The blower door approach is not applicable in this case, since the blower door establishes its own ventilation pattern for the house which would override the effects of the HRV.

6. *Testing with the house depressurized.* In some cases, where initial post-mitigation testing must be conducted during mild weather, it can be informative to conduct some part of the post-mitigation testing with the house artificially depressurized (e.g., using a blower door). The extent of depressurization should be roughly equivalent to that which might be anticipated in the house during cold weather, about 0.05 in. WC. Radon measurements in the house air can usefully be made during the period of depressurization (by means of grab samples, if the depressurization cannot be maintained long enough for a longer-term radon measurement). Other types of diagnostics during depressurization could include smoke tube testing and grab samples to evaluate potential soil gas entry routes, since these tests could be influenced significantly by house depressurization.

7. *Working level measurements.* If the radon reduction technique is expected to influence the

equilibrium ratio (as with an air cleaner or a heat recovery ventilator), then it is important that the radon progeny working level be measured *in addition to* the radon gas concentration, both before and after activation of the reduction technique. This measurement will indicate the degree to which the progeny have been reduced (independent of the radon gas), and the degree to which the equilibrium ratio has been changed. See item 11 in Section 2.4.

8. *Logging of weather conditions and household activities.* As discussed in Section 2.4, a log of certain key weather conditions and household activities could be important in interpreting the post-mitigation results.
9. *Measurements to identify combustion appliance back-drafting.* Some radon reduction measures can have the effect of depressurizing certain areas of the house. Specifically, active soil suction systems can depressurize a basement, because the systems can suck basement air out of the house through slab and wall cracks (see Section 5). Basement pressurization systems (Section 6.2) can cause depressurization of the upstairs. When part of the house becomes sufficiently depressurized, any combustion appliances in that area might not be able to maintain normal upward movement of the combustion products up the flue. In such a case, the combustion products will enter the house, a hazardous situation. In some cases, such as with fireplaces, this back-drafting will be obvious, through smoke and odors inside the house. With other appliances, it can be less obvious. In these cases, flow measurements must be made in the flue with the mitigation system in operation, to ensure that the gas movement in the flue is consistently upward.

Section 3

House Ventilation

One approach to reducing indoor radon levels is to increase the ventilation rate in the house (and/or in the crawl space). From a practical standpoint, increased ventilation can be achieved in two ways:

(1) Without an attempt to recover heat (or air conditioning) from the house air displaced by the outdoor air. This type of ventilation can be accomplished by purely natural means (by opening doors, windows, and/or vents), or with the aid of a fan (such as a window fan).

(2) With an attempt to recover this heat (or air conditioning). The devices used to recover the heat are referred to here as "heat recovery ventilators" (HRVs), and are also commonly called "air-to-air heat exchangers."

3.1 Natural and Forced-Air Ventilation (No Heat Recovery)

3.1.1 Principle of Operation

Even when all the doors and windows in a house are closed, there will be a natural exfiltration of indoor air out of the house (e.g., through cracks around the windows). To compensate for this outflow, an equal amount of outdoor air plus soil gas will leak into the house. Most of the infiltrating gas will be outdoor air; usually, only about 1 to 5 percent will be soil gas (Er84). The radon levels inside the house will be determined to a large extent by the relative amounts of outdoor air versus soil gas which infiltrate.

As discussed in Section 2.2.2, weather conditions are usually the major factors influencing exfiltration/infiltration. When the temperature outdoors is colder than that indoors, the upward buoyant force on the warm indoor air will create the natural thermal stack effect. The indoor air rises, leaking out through penetrations through the upper levels of the house shell (above the neutral plane). The outdoor air and soil gas leak into the lower levels of the house, below the neutral plane. Winds also contribute to the exfiltration/infiltration, with indoor air exfiltrating from the downwind, low-pressure side of the house, and with outdoor air infiltrating on the upwind, high-pressure side. The exfiltration/infiltration phenomenon can result in air flows sufficient to exchange all of the air in a closed house from perhaps once every half hour (2.0 air changes per hour) in a fairly leaky house, to once every 10 hours (0.1 air changes per hour) in a very tight house. Exchange rates of once every 1.1 to 2 hours (0.9 to 0.5 air changes per hour) are probably typical of U. S. houses (Gr83).

Both natural and forced-air ventilation are intended to increase the closed-house ventilation rate. Natural ventilation consists of opening windows, vents, and doors to facilitate the flow of outdoor air into the house, driven by the natural thermal and wind phenomena. Forced-air ventilation involves the use of one or more fans to blow outdoor air into the house. Natural and forced-air ventilation reduce radon levels through two mechanisms.

1. Reducing the driving force sucking soil gas into the house. Open windows or a fan delivering air below the neutral plane will greatly facilitate the flow of outdoor air into the house to compensate for indoor air that exfiltrates due to thermal and wind phenomena. As a result, less soil gas will be drawn into the house. In effect, openings to the outdoors are being created in the house shell below the neutral plane, so that more of the infiltrating makeup gas is outdoor air, and so that the fraction which is soil gas is even smaller than before.

2. Dilution of the radon that enters the house, using an increased supply of outdoor air. Radon-containing indoor air is displaced by low-radon outdoor air in the area being ventilated. For the dilution mechanism alone, doubling the ventilation rate would reduce the radon to 50 percent of its original value; quadrupling ventilation would reduce radon to 25 percent; and increasing ventilation by a factor of 10 would reduce radon to 10 percent. With forced-air systems, a third mechanism might also come into play: pressurization of the house by blowing in outdoor air. Reducing or reversing house depressurization could reduce or eliminate soil gas influx, as further discussed in Section 6.

Forced-air ventilation could consist of continuously blowing outdoor air into a closed house through the existing central forced-air furnace ducting. Alternatively, vents could be installed through the side of the house, and the fan mounted to continuously blow air in through these vents. Fans could also be mounted in windows. Ceiling-mounted whole-house fans, which typically exhaust house air into the attic, are not recommended. Because whole-house fans typically operate to exhaust house air, they could depressurize the house, possibly increasing radon levels.

Advantages of natural ventilation, relative to forced-air ventilation, include its ease of implementation and its generally negligible installation cost. Homeowners can easily open windows or vents. However, open windows can sometimes give rise to house security concerns. The advantages of forced-air systems include the ability to more accurately control the amount of fresh air entering the house, and, depending upon system design, to eliminate the house security concerns associated with natural ventilation. Forced-air systems which move sufficient air might also increase radon reductions by pressurizing the house. Disadvantages of forced-air systems include the installation cost of some forced-air systems; the electricity cost associated with fan operation; the fan noise, depending upon system design; and, as discussed later, moisture condensation and freezing in the walls during cold weather. Both natural and forced-air suffer from the disadvantages of high heating and cooling cost penalties, and significant comfort penalties, when high levels of ventilation are implemented during cold or hot weather.

Natural or forced-air ventilation, used in a crawl space which does not open into any part of the house living area, creates a pressure-neutral, low-radon buffer between the living area and the soil.

3.1.2 Applicability

Natural and forced-air ventilation can generally be used in any house, regardless of substructure type or other house design features. These techniques are attractive because they can generally be implemented by the homeowner without professional assistance and with minimal capital cost (except for some forced-air ventilation systems). These techniques can provide substantial reductions in indoor radon levels and can thus be applicable to houses with high initial radon levels as well as those with lower levels. Apparent reductions well above 90 percent have sometimes been observed.

The major disadvantage of natural and forced-air ventilation, however, is that they often cannot practically be used as a permanent, year-round solution to elevated radon levels. Except where the weather is mild, and/or where only a limited increase in ventilation rate is needed (due to only slightly elevated radon levels), the homeowner will often incur an unacceptable increase in heating and cooling costs when ventilation is applied during cold or hot weather. This cost penalty is discussed in Section 3.1.6 (see Table 7). In addition, significant ventilation during cold and hot weather would likely make the house uncomfortable, even if the furnace (or air conditioner) load were increased in an effort to heat (or cool) the incoming air. Thus, increased natural ventilation and forced-air ventilation without heat recovery are viewed as approaches that should always be considered whenever the weather is mild. The approaches can be considered year-round in mild climates, and where only limited increases in ventilation are needed. However, in many parts of the country, the cost and comfort penalties will make these types of increased ventilation impractical during cold and hot weather, when radon levels are significantly elevated.

Assuming that a temperature of between 68° and 78°F is generally considered comfortable to most people (ASHRAE85), and considering data on heating and cooling degree days (DOC82), it is estimated that, on the national average, natural or forced-air ventilation could be used to reduce indoor radon concentrations up to 4 months per year (partly in the spring, partly in the fall) with little or no comfort or energy penalty in much of the U. S. These ventilation techniques would be applicable for longer periods each year in regions with mild climates.

In addition to the cost and discomfort associated with significantly increased ventilation rates during cold or hot weather, there are several other features of these ventilation techniques which will limit their applicability.

- Concerns over security could be a deterrent to leaving the windows open at night, or when the house is unoccupied. Thus, the applicability of natural ventilation could be limited to certain times of the day.
- Forced-air ventilation can cause moisture to condense and freeze inside the exterior walls during cold weather if the house is humidified, with possible resulting damage to wooden members. The outdoor air blown into the house would force humidified indoor air out through openings in the house shell, including openings concealed within walls. The moisture being added by the humidifier (or by other moisture sources in the house) can condense when the air contacts the cold surfaces near the exterior walls. This is an additional reason why forced-air ventilation is not applicable in cold weather.

- Forced-air ventilation systems can sometimes result in fan noise that some homeowners find objectionable, depending upon the system design. This concern would affect applicability in some cases.
- Increased movement of unfiltered outdoor air into the house would increase the levels of pollen and outdoor dust in the house. This can be objectionable to some homeowners during some times of the year.

Natural or forced-air ventilation can potentially form all or part of a permanent solution with crawlspace houses, if the crawl space is not open to the living area. With such houses, it might be possible to ventilate the crawl space year-round, without the concern regarding weather extremes and unauthorized entry, if suitable insulation is provided around water pipes, and between the crawl space and the living area.

Natural and forced-air ventilation could also potentially be a permanent solution (or part of a permanent solution) in a basement house, if the homeowner were prepared to abandon the basement as living space during extreme weather. In such a situation, insulation would be installed between the basement and the remainder of the living area, and around any water lines in the basement, and the basement windows would be left open year-round.

Ventilation might still be applicable as a means for obtaining some reduction year-round in a basement house, even if the homeowner is not willing to abandon the basement. The basement windows could be left open only an inch or two. This approach might provide meaningful radon reductions, perhaps without making the basement too uncomfortable, and perhaps without an unacceptable energy penalty. An individual homeowner would have to experiment with opening different windows different amounts to identify settings which provide acceptable comfort levels (acceptable temperatures and drafts).

For natural ventilation to be most effective, the lowest level in the house (the level where windows must be opened) should have windows or vents distributed around the perimeter. Effective natural ventilation cannot always be maintained if there are openings on only one side of the house. In fact, if the openings are on only the downwind side, opening these windows could actually *increase* soil gas influx since, under certain circumstances, the house could be further depressurized.

Given two houses with similar initial radon concentrations, natural and forced-air ventilation will tend to have the greater impact on (and be more easily applied in) the one having the lower closed-house infiltration rate. The ability of ventilation to dilute the radon in the house depends upon the extent to which the number of air changes per hour can be increased above the closed-house infiltration rate in the part of the house being ventilated. For example, doubling the number of air changes per hour will dilute the indoor radon by a factor of two. If the natural infiltration rate in one house were 0.25 air changes per hour, then doubling this rate (to 0.50 air changes per hour) would require a relatively limited increase in the actual flow of outdoor air into the house. But if the natural infiltration rate in a second house were 1.0 air change per hour, a doubling to 2.0 air changes per hour would require an increase in the actual flow into that house which would be four times greater than the flow increase required to double the rate in the first house. The house having the initial rate of 0.25 air changes per hour could thus achieve the doubling in ventilation rate with windows open to a lesser extent (or with a lower forced-air fan capacity), and with a smaller absolute impact on heating and cooling cost (if the ventilation is conducted during other than mild weather). This first house would also likely achieve the increased ventilation with a better comfort level since, at 2.0 air changes per hour, the second house would likely feel drafty.

Natural and forced-air ventilation can be applied on a part-time basis to reduce total cumulative radon exposure, but such part-time application will greatly reduce their effectiveness. For example, some homeowners might elect to leave the windows open during the day, but close them at night. While response times will vary from case to case, it will generally take a house at least 1 to 3 hours after windows are opened for radon concentrations to fall to their "increased ventilation" levels. After windows are closed, radon concentrations will increase rapidly. Ventilation is effective only while the ventilation system is in operation. A homeowner should not assume that a house can be "aired out" for the night by ventilating it during the day.

3.1.3 Confidence

For natural ventilation, there is high confidence that high levels of radon reduction will be achieved during the period of ventilation, if windows and/or vents are opened sufficiently, and if the ventilation is conducted in the manner described in the *Design and Installation* section which follows. The actual degree of reduction that will be achieved cannot be confidently predicted. It will depend upon the amount of outdoor air which enters, which influences the effectiveness with which soil gas influx is reduced and the extent to which indoor radon levels are diluted. The amount of air which enters, and its distribution, will depend upon the number and location of windows or vents that are opened, and the weather conditions. There has not been a definitive study conducted to determine the degree of radon reduction achievable by opening windows in different patterns in different houses under various weather and other conditions. However, reductions of 94 percent (EPA78) and 97 percent (Sc87a) have been reported in two cases with the windows wide open. With the windows wide open, it would be expected that both radon reduction mechanisms listed in Section 3.1.1 would be implemented to the maximum extent possible: radon influx would be significantly reduced, and dilution would be maximized. Reductions would be expected to be less when fewer windows are opened, or when the windows are only partially open. As the windows are opened less and less, mechanism 1 (reduction of radon influx) might begin to play less of a role so that, at fairly low increases in ventilation rate, the effect of ventilation might be largely due to mechanism 2 (dilution).

For example, consider the case of a house which has about 2000 ft^2 and a natural closed-house infiltration rate of 0.75 air changes per hour. Suppose that the windows are opened slightly to increase the natural ventilation by an additional 50 cfm (equivalent to about 0.2 air changes per hour in this house) — only a small fraction of the flow increase that probably resulted in the cases above where over 90 percent reductions were reported. If the reductions with the additional 50 cfm were due to dilution only then, nominally, a radon reduction of about 25 percent could be expected. An increase of 100 cfm would give a dilution-based reduction of about 35 percent. These reductions will be sufficient in some houses.

The magnitude of the increase in the natural ventilation rate can be controlled by the homeowner through: adjustment of the degree to which different windows/doors/vents are opened; the location of those which are opened; and, where practical, installation of additional windows or vents. It should be recognized that in no case can indoor radon levels be reduced below those in the outdoor air; this could limit the achievable percentage reductions in houses which are fairly low in radon to begin with.

For forced-air ventilation systems where one or more fans blow outdoor air into a closed house, confidence is high that high levels of radon reduction can be achieved, *if* the fan is large enough and distributes the incoming air effectively. No definitive study has been conducted of the degree of radon reduction achievable using forced-air ventilation. However, in concept, a properly designed forced-air system should be as effective as a comparable degree of natural ventilation, and perhaps even more effective if it provides the additional benefit of pressurizing the house. A primary concern with forced-air systems is that the fan(s) be able to move enough air to duplicate the effect of open windows, from the standpoint of both: a) providing sufficient air to compensate for temperature- and wind-induced exfiltration of indoor air out of the house, thus reducing soil gas infiltration (mechanism 1 in Section 3.1.1); and b) providing sufficient air to give the same degree of radon dilution that open windows can provide (mechanism 2). There are no definitive data on the forced-air flow rates required to achieve the 90+ percent reductions mentioned earlier for natural ventilation, but it is estimated that the flows would likely have to be greater than 500 to 1,000 cfm in a house of typical size and natural closed-house infiltration rate. Another consideration is that—for soil gas influx to be effectively reduced, per mechanism 1—it is critical that the forced-air system deliver sufficient air below the neutral plane of the house. Providing sufficient air below the neutral plane is generally not a problem with a natural ventilation approach where, say, basement windows are opened. Nor should there be a problem with a forced-air system where an adequate supply of outdoor air is blown directly into the basement. However, confidence could be reduced with a forced-air system using the existing central furnace ducting, where the fresh air is being distributed all over the house and the amount being supplied below the neutral plane is uncertain.

3.1.4 Design and Installation

Natural ventilation. With natural ventilation, there are two major considerations in selecting which windows, doors, or vents to open:

(1) They should be opened primarily on the lower levels of the house (below the neutral plane), due to thermal stack effect considerations. They should generally *not* be opened *only* on the upper levels.

(2) They should be opened on all sides of the house, if at all possible, or at least on opposing sides of the house. They should not be opened on only one side of the house, unless that side is consistently the upwind side.

As discussed previously, opening windows below the neutral plane is critical if natural ventilation is to effectively reduce soil gas infiltration (mechanism 1 in Section 3.1.1). If windows are opened only above the neutral plane, much of the benefit of this reduction mechanism could be lost. In fact, if windows are opened only above the neutral plane, increased exfiltration of house air through those windows could potentially increase the influx of soil gas, possibly making matters *worse.* Windows on the lowest level of the house will usually be below the neutral plane. In houses with full basements, the neutral plane will typically be a few feet above the floor of the story directly above the basement. Thus, the basement windows should be opened. For a slab-on-grade or crawl-space house, the neutral plane will typically be somewhere between waist and ceiling height on the first story. (The location of this plane can shift and tilt as, say, the HVAC system cycles on or off, or the winds change.)

If an upstairs level of the house is the primary living area, it might also be desirable to open windows on that level (as well as downstairs) when the weather is mild, to take advantage of the increased radon dilution that would result on the upstairs level. If windows are opened both upstairs and downstairs, the downstairs windows would likely provide the increased outdoor air inflow needed to compensate for the increased exfiltration resulting upstairs.

If windows were opened only on one side of a house, and if that side ever became the downwind side (as the winds shifted while the windows were open), the house could potentially become further depressurized, since a low-pressure region is created on the downwind side by the wind movement. Some data appear to confirm that open downwind windows can actually *increase* radon levels in the house, depending upon the velocity of the wind. An additional benefit of opening windows on more than one side, besides avoiding depressurization, is that the resulting cross-draft will improve ventilation. If the lower level of the house is a basement which has windows on only one side, no definitive data identify the best course of action. One approach might be to open the basement windows, and to make a number of radon measurements with and without the windows open, to confirm whether opening the windows on the one side is in fact beneficial. It may be feasible to have windows or vents installed on the side of the basement which has none.

Another issue is how many downstairs windows to open, and how wide. Intuitively, best results would be expected when all downstairs windows are open all the way. To the extent that fewer windows are opened, or that the windows are opened only partially, the radon reduction performance will likely be reduced. However, even if only some of the windows are open, and only partially, some potentially significant reduction might still be achieved. Two fully open windows, on opposing sides of the house, might be sufficient in many houses. Partial opening of the windows (perhaps opening only a few windows an inch or two) might make natural ventilation practical for some homeowners in extreme weather, when having the windows wide open would cause unacceptable increases in heating and cooling costs, and would make the house unacceptably uncomfortable. Each homeowner will have to experiment with different windows open to different degrees, to find the optimum combination. The only guidelines are: 1) the more open area that can be tolerated, the better, from the standpoint of radon reduction; and 2) the amount of open area on both sides of the house should be about the same.

Each homeowner will have to determine any other design considerations which should be taken into account. For example, latches might be installed on partially open windows to prevent them from being opened farther from the outside by intruders, or screens might be installed on open windows to keep out insects and rodents.

Forced-air ventilation. If a forced-air ventilation system is employed, there are several major considerations.

1. The fan(s) should always be oriented so that outdoor air is blown *into* the house, never to blow indoor air out.
2. The fan must be large enough to provide at least 500 to 1,000 cfm of air, if it is to provide high radon reductions, as discussed in Section 3.1.3.
3. The fan must deliver a sufficient amount of air below the neutral plane of the house, as discussed in Section 3.1.3.

An inward-blowing fan will, if anything, slightly pressurize the house, potentially aiding in reducing convective soil gas infiltration. An outward-blowing (exhaust) fan will tend to depressurize the house, thus potentially increasing soil gas entry. For this reason, commercially available ceiling-mounted whole-house fans are not currently recommended for radon reduction. These ceiling-mounted fans are typically designed to operate in the exhaust mode, exhausting as much as 3,000 to 7,000 cfm of house air into the attic (HVI86).

One possible design for a forced-air ventilation system is installing a fan to continuously blow fresh air into the house through the existing ducting and registers associated with a central forced-air HVAC system. The HVAC modifications needed to implement such a system should be designed and installed by a qualified HVAC contractor. In concept, ducting leading to the outdoors would tap into the existing HVAC cold air return ducting. A ventilation fan, separate from the existing central furnace fan, could be mounted in the ducting leading from outdoors, continuously blowing outdoor air into the cold air return duct and thus into the house. Alternatively, the existing central furnace fan could be operated continuously, drawing outdoor air in through the newly installed duct and mixing it with the house air recirculating through the cold air return. A variation of this latter option would be to replace the central fan motor with a two-speed motor which runs on low speed continuously, and switches to high speed when the furnace or air conditioner cycles on. For this system to be continuously effective, the fan providing the fresh air must be operating continuously, even when the furnace or air conditioner has cycled off.

The option involving the installation of a second fan in the outdoor duct has the advantage of ensuring a controlled amount of outdoor air. With the options involving use of the existing central fan, there is less positive control over how much air is drawn from outdoors versus how much is drawn from the house via the cold air return ducting. Where the central fan is used, the outdoor air actually being drawn in through the new duct must be measured, and adjustments made (e.g., in the size of this duct) to increase the flow of outdoor air if it is insufficient. (For comparison, a typical central forced-air furnace fan will move roughly 2,000 cfm; as indicated earlier, it is desirable that at least 500 to 1,000 cfm of this flow be drawn from the outdoor duct.)

A concern with this type of forced-air ventilation system is that it might be difficult to ensure that sufficient fresh air is delivered below the neutral plane. Since central furnace supply registers will be located throughout the house, an uncontrollable fraction of the fresh air might be delivered into the house through registers above the neutral plane, depending upon the design of the house. This potential problem would be most severe in houses having multiple stories above grade.

Even with the fresh air inflow being dispersed around the house by the central ducting, it is likely that this inflow of fresh air will create drafts which some homeowners might find objectionable.

Another possible design for a forced-air system would be to install one or more vents through the side of the house, and to blow outdoor air in through these vents. One common option for applying this approach would be to mount the fan itself onto or into the wall, with a protective cover and louver/grille on the outside. Alternatively, the fan could be mounted inside, with ducting connecting the fan to the vent. The fan should discharge the incoming air below the neutral plane (in the lowest story of the house). To reduce the draftiness that would otherwise result in the vicinity of the fan, the fan discharge could be ducted so that the incoming air is released at locations away from the primary living areas.

A third possible design for a forced-air system would be to mount a fan in one or more windows below the neutral plane. This approach is actually a variation of the one above, with an existing window being used as the vent. Window fans are commonly designed to move from 500 cfm to as much as 1,000 to 2,000 cfm. At the lower end of this range, more than one fan might be needed for 90+ percent reductions. Because of the location of these fans in a window, and because of their configuration, it might be less convenient to duct the discharge of these fans in an effort to reduce the drafts created.

The above discussion on forced-air ventilation designs has focused on outdoor air blown into a closed house. It is currently not clear under what circumstances there will be sufficient benefit to justify blowing air into houses having open windows (i.e., using forced-air and natural ventilation in combination). So long as sufficient windows and/or vents are opened, it is expected that the supplemental use of fans will not provide sufficient additional benefit to warrant their use. However, the use of natural and forced ventilation together could be beneficial, when the degree is limited to which windows and vents can be opened.

As another forced-air variation, some investigators have considered the continuous operation of the central forced-air furnace fan simply to recirculate the house air (EPA78, Go83). In this case, there is no outdoor air supply to the cold air return, as in the case discussed earlier. Fresh air flow into the house is increased only to the extent that the recirculation increases infiltration. While the investigators who have studied this approach observed radon reductions, it is not clear that reductions can be expected in all cases. This approach cannot be recommended at present. For example, where the central furnace and much of the cold air return ducting is located in a basement, operation of the central furnace fan can sometimes depressurize the basement by sucking basement air into the leaky cold-air return ducting. Such basement depressurization could increase radon levels in the house.

Considerations for crawl-space houses. The prior discussion has emphasized ventilating livable space inside the house. Natural and forced-air ventilation can also be considered to ventilate the crawl space under crawl-space houses, creating a pressure-neutralized, low-radon buffer between the living area and the soil.

If a crawl space which is isolated from the living area has vents on several (or all) sides, these vents can be left wide open all year for the purposes of radon reduction via natural ventilation. However, water lines in the crawl space will then have to be insulated to avoid freezing in cold weather. It could also become cost-effective to insulate under the floor between the crawl space and the living area.

If the crawl space does not have vents, serious consideration should be given to having vents installed. It is not known how much vent area is required to adequately reduce radon levels via natural ventilation in crawl-space houses under different circumstances. If vents are to be installed, the area should probably be at least that specified by local building codes for moisture control purposes in crawl spaces.

Another option if the crawl space has no vents (or inadequate vents) is to use forced-air ventilation. A fan could be mounted (e.g., in the crawl-space door) to blow outdoor air into the crawl space.

If the crawl space opens into the living area, it would be advisable to isolate the crawl space by constructing a door (or wall) to close the opening. Isolation of the crawl space will reduce the extent to which soil gas from the crawl space can enter the living area, and will facilitate the ventilation of the crawl space with less impact on the living area.

Natural or forced-air ventilation of the crawl space is one of the first mitigation options that should be considered for crawl-space houses. Another option that can be considered is covering exposed earthen floors of crawl spaces with plastic sheeting, and actively (or passively) ventilating the space between the sheeting and the soil. This latter approach is discussed in Section 5.5.

3.1.5 Operation and Maintenance

For natural ventilation systems, the only maintenance required will be occasional adjustments to the open windows, doors, or vents for comfort or other reasons. If a crawl space or an abandoned basement is being permanently ventilated, it might be advisable during prolonged cold weather to leave a faucet dripping in the house to keep pipes in the crawl space or basement from freezing.

For forced-air systems, periodic inspection and perhaps lubrication of the fan might be appropriate, along with fan repairs when needed.

3.1.6 Estimate of Costs

The installation cost for natural ventilation systems is often zero, except perhaps for the nominal cost of window latches, screens, etc., that might be desired. If vents or windows have to be installed (e.g., in a previously unvented crawl space), and if insulation must be installed (e.g., between the crawl space and the living area, and around water pipes), then this will add a cost which depends upon the specific house. Relocating water pipes into heated areas would also add to the cost.

The installation costs for forced-air systems will depend on the nature of the system. Where outdoor air is supplied through existing central HVAC ducting, the cost for installation by an HVAC contractor is estimated at about $1,000, including: the installation of ducting between the outdoors and the cold air return; a second fan (or a two-speed motor for the existing fan); and the wiring involved. Where the fan is installed in a wall of the house, the cost for installation by a contractor would be a few hundred dollars, depending on the nature of any discharge ducting. This cost would be reduced to the materials cost (fan, ducting, wiring) if the homeowners could install it themselves. For a window fan, the cost would be limited to the cost of the fan (about $50 to $200, depending upon the size and features of the fan), if the homeowners could install the fan in a window themselves.

The operating costs for ventilation systems will consist primarily of the increased heating and cooling costs resulting from the increased inflow of outdoor air. With forced-air systems, the costs of electricity to run the fan will also be a contributor.

The increase in heating and cooling costs will depend on the increase effected in the ventilation rate, the amount of heated area which is ventilated, the temperature at which the ventilated area is maintained, the weather conditions at the time of ventilation, and the cost of fuel. Therefore, the cost increase will vary significantly from house to house. Table 7 approximates how annual heating costs might be increased under different circumstances. (If the house is air-conditioned, cooling costs would also increase, but cooling costs are not reflected here.) The table shows the annual *increases* in heating cost (above and beyond the current heating cost, with only closed-house infiltration) as a function of different increases in the ventilation rate, different heating systems, and different weather conditions (expressed as heating degree days). The lower ventilation increases considered in the table (50 and 100 cfm) might be expected to give radon reductions of perhaps 25 to 50 percent in a typical house, as discussed previously. The houses discussed, earlier where over 90 percent reduction was observed, probably experienced increases of 500 cfm or more. Persons using this table will have to find out the heating degree days for their particular area. See Table 9. Values of 2000 degree days represent the Gulf Coast States, 5000 degree days represent mid-Atlantic coast and parts of the Midwest; and 8000 degree days represent northern New England and some States along the Canadian border. If fuel costs in a given area differ from the values assumed in this table, the table figures can be adjusted by multiplying them by ratio of the actual fuel cost divided by the assumed fuel cost.

Table 7 indicates that some limited use of ventilation might be practical throughout the winter. However, high ventilation rates will generally be economically impractical, if the space being ventilated is to be maintained at living space temperatures.

Table 7. Approximate Annual Increase in Heating Costs Due to Increased Ventilation

Increase in Ventilation Rate (cfm)	Increase in Air Changes per Hour, for 2,000 ft^2 House (ach)	Increase in Annual Heating Cost Due to Ventilation Increase ($)											
		Gas Furnace			Oil Furnace			Electric Resistance Heat			Heat Pump		
		Degree Days (F°)			Degree Days (F°)			Degree Days (F°)			Degree Days (F°)		
		2,000	5,000	8,000	2,000	5,000	8,000	2,000	5,000	8,000	2,000	5,000	8,000
50	0.2	29	72	116	25	62	100	64	160	256	36	89	142
100	0.4	58	144	232	50	124	200	128	320	512	71	178	284
250	0.9	145	360	580	125	310	500	320	800	1,280	178	444	711
500	1.9	290	720	1,160	250	620	1,000	640	1,600	2,560	356	889	1,422
1,000	3.7	580	1,440	2,320	500	1,240	2,000	1,280	3,200	5,120	711	1,778	2,844
2,000	7.5	1,060	2,880	4,640	1,000	2,480	4,000	2,560	6,400	10,240	1,422	3,555	5,688

Assumptions:
House is maintained at 75°F during heating season.
Gas furnace is 70% efficient; cost of gas \$7.00/1,000 ft^3 (\$7.00/million Btu).
Oil furnace is 70% efficient; cost of oil \$0.85/gal. (\$6.00/million Btu).
Electric resistance heat is 100% efficient; cost of electricity \$0.075/kWh (\$22.00/million Btu).
Heat pump coefficient of performance averages 1.8; cost of electricity \$0.075/kWh (\$22.00/million Btu).

How heating and cooling costs might be affected in alternative situations is illustrated below.

(1) *Example 1.* Natural ventilation of the entire house is implemented only when the weather is sufficiently mild so that the HVAC system is not operating. In this case, the increase in the heating and cooling costs is zero.

(2) *Example 2.* Natural ventilation of the entire house is implemented at all times, regardless of weather. This is the situation represented in Table 7. The highest increase in ventilation rate illustrated in that table—possibly reflecting all windows left wide open—represents an increase over the closed-house infiltration rate by a factor of about 10 for a typical house (from about 0.75 ach to 0.75 + 7.5 = 8.25 ach). Total heating and cooling costs do not increase by a factor of 10, since 65 to 75 percent of the heat loss from a typical house is through mechanisms other than air infiltration (i.e., conduction and radiation through the house shell). These other mechanisms will probably be influenced only in a limited way by the change in ventilation rate. Thus, total heating and cooling costs could increase by a factor of 2 to 3 or more as a result of the 10-fold increase in ventilation rate. The heating cost increases of Table 7 reflect this magnitude of increase for the 2000 cfm case. If fewer windows are left open by a lesser amount, and the ventilation rate doubles (approximately the 250 cfm case in Table 7), total heating and cooling costs will increase by perhaps a factor of 1.25 (i.e., by 25 percent) or more. If only a couple of windows are opened only slightly (perhaps an inch or two), in an effort to limit the ventilation increase to 50 to 100 cfm, heating and cooling costs will increase by perhaps 10 percent.

(3) *Example 3.* Natural ventilation of the basement only is implemented at all times. The basement is maintained as heated living space, and accounts for half of the heated area of the house. As discussed previously, the thermal stack effect causes air from the basement to be drawn upstairs. However, so long as indoor air exfiltration routes upstairs remain unchanged, opened windows in the basement would not be expected to significantly increase the flow of air up through the house. Thus, the ventilation rate of the upstairs could remain almost unchanged, despite large increases in the basement ventilation rate, so long as there were not major openings (such as unclosed stairwells) between the two levels. Therefore, as a first approximation, it is assumed that the heating and cooling penalty will be limited to the basement space; i.e., to half the house. Accordingly, the heating and cooling costs in Example 2 above would be roughly halved. If the basement windows are left wide open and basement ventilation increases by a factor of 10, total heating and cooling costs might increase by a factor of about 1.5 or greater. If the basement ventilation rate is doubled, costs might rise by perhaps 15 percent, and if only a couple windows are cracked open, costs might increase by less than 10 percent.

(4) *Example 4.* The basement is abandoned as living area during extreme weather, insulated from the remainder of the house, no longer heated, and ventilated at all times. Or, the crawl space is insulated, and ventilated at all times. As in Example 3 above, it is assumed that the ventilation rate upstairs is not significantly changed, so long as there are no major openings between the stories. (However, the

upstairs might feel colder, because the air infiltrating up from the basement will now no longer have been preheated in the basement.) The impact of this approach on the heating and cooling costs will depend upon the extent of insulation. The heating costs will likely increase by up to 20 percent. Cooling costs should increase by a lesser amount (but not in the crawl space, since the crawl space is presumably vented in any event during the summer).

The additional cost of electricity for forced-air systems will vary, depending on the size of the fans, the number of fans used, and the duration of use. Some smaller window fans operate on no more than 100 W; the cost of electricity to run one of these fans 365 days per year would be roughly $65 per year. The larger window fans draw as much as 400 W on high speed, as might a central furnace fan when fresh air is blown through the existing HVAC ducts; these larger fans would cost roughly $275 per year to operate continuously.

With forced-air systems, there will also be some cost associated with the maintenance and periodic replacement of the fans.

3.2 Forced-Air Ventilation With Heat Recovery

3.2.1 Principle of Operation

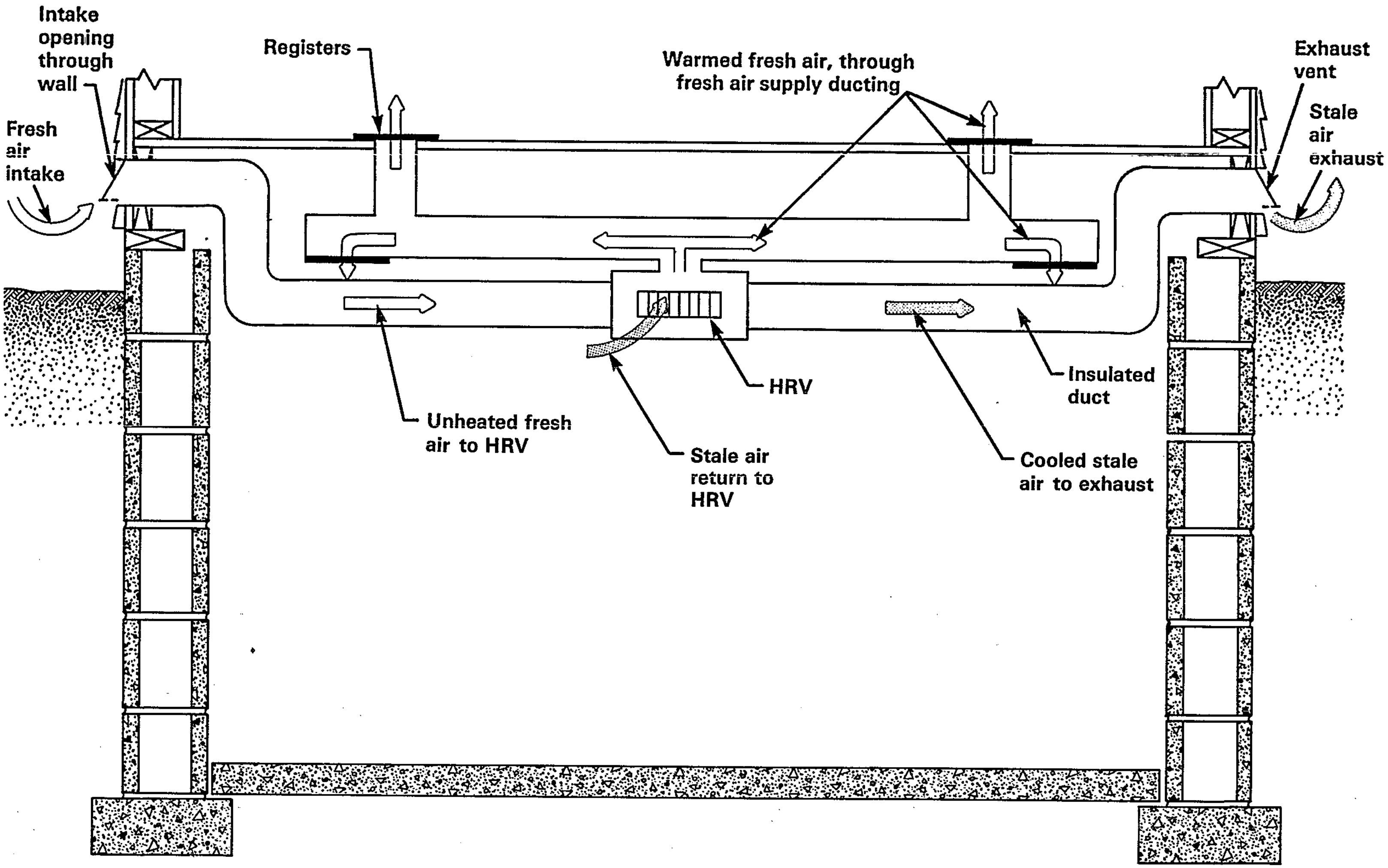
Heat recovery ventilators (HRVs), or air-to-air heat exchangers, are devices which use fans to accomplish a controlled degree of forced-air ventilation, while recovering some of the heat (or, in the summer, the coolness) from the stale house air which is displaced by incoming fresh air. HRVs typically include two fans, one blowing a controlled amount of outdoor air into the house, and the second blowing usually an equal amount of indoor air out. The incoming and outgoing air pass near each other in the central core of the exchanger. The two streams are nominally kept separate, but heat (and sometimes also moisture) is transferred from the warmer stream to the cooler. The central core can be one of three basic types:

1. the fixed-plate type, where the streams are forced through banks of numerous small channels, with incoming and outflowing channels beside each other. These banks can take on a variety of configurations, including various flat plate and concentric tube designs. The banks can be fabricated from aluminum, plastic, or even treated paper.
2. the rotary type, where a wheel of porous material rotates across both the incoming and outflowing air passages, in a manner which forces each air stream through the pores. Heat from the warm stream is transferred to the wheel as the warm air passes through the pores; this heat is transferred to the cool air stream when that segment of the wheel rotates into the cool air passage.
3. the heat pipe type, where the separated incoming and outflowing air streams pass over a common bank of sealed pipes which contain a heat transfer fluid. One end of the bank is in the warm stream, and the other, in the cold. Vaporization of the fluid in the warm end of the tubes and condensation in the cool end effect the desired heat transfer, on the same principle as an air conditioner or heat pump.

For residential applications, HRVs can take the form of window- or wall-mounted units (similar to a window-mounted air conditioner). Alternatively, HRVs can consist of a centrally installed unit including ductwork, analogous to a central forced-air HVAC system, withdrawing house air through registers at various points inside the house and delivering fresh air through registers at other points. Figure 3 shows one possible configuration schematically for a fully ducted HRV system. More detailed descriptions of some specific HRV designs for residential applications can be found in other documents (e.g., Fi80, ASHRAE83, NCAT84, EMR85, HVI86).

The primary advantage of HRVs, relative to natural ventilation or forced-air ventilation without heat recovery, is that heat recovery will reduce the house heating and cooling penalties associated with ventilation. The sensible heat recovery efficiencies for a number of residential HRVs varies from 50 to 80 percent (EMR87, HVI87), indicating that the heating penalties for a given degree of ventilation with an HRV will be only 20 to 50 percent of the penalties for the same degree of ventilation without heat recovery. Another advantage of HRVs is that, by warming (or cooling) the incoming fresh air and by controlling where it is injected, HRVs can reduce the discomfort resulting from ventilation during cold (or hot) weather. Thus, what the HRV offers is an opportunity to extend the applicability of ventilation as a radon reduction technique, to include periods of cold or hot weather when natural ventilation (or forced-air ventilation without heat recovery) might not otherwise be practical or economical.

However, as discussed later, the radon reductions potentially achievable with HRVs in houses with typical natural infiltration rates will generally be limited to perhaps 50 to 75 percent. Therefore, HRVs would be applicable as a stand-alone method for radon reduction only when the initial radon level is below about 10 to 15 pCi/L. In addition, the radon removal performance of HRVs can sometimes be difficult to predict prior to installation, and can vary over time. Moreover, depending upon the



Note: Air flows are labeled for cold weather, where cold outdoor air is being warmed in the HRV. In hot weather, hot outdoor air would be cooled and dehumidified.

Figure 3. One possible configuration for a fully ducted heat recovery ventilator.

climate and fuel costs, the savings in heating and cooling costs achieved through HRV use might be offset by the initial capital cost of the HRV. Where the capital cost offsets the operating cost savings, it would be more cost-effective to achieve the desired degree of ventilation using natural ventilation or forced-air ventilation without heat recovery.

As discussed in Section 3.1.1, natural ventilation (and forced-air ventilation without heat recovery) reduces radon levels through two mechanisms. First, the driving force sucking soil gas into the house is reduced, by facilitating the inflow of outdoor air below the neutral plane to compensate for house air exfiltration above the plane. (This mechanism is referred to here as the "stack effect compensation" mechanism.) Second, radon that does enter the house is diluted by the increased inflow of outdoor air. By comparison, HRVs probably function primarily through the dilution mechanism only. Because HRVs necessarily include an exhaust fan which exhausts house air at a rate generally equal to the fresh air being blown in, HRVs usually provide no net supply of outdoor air to compensate for exfiltration above the neutral plane. Thus, the benefits of the first mechanism can largely be lost with the HRV. With dilution alone as the primary mechanism, the radon gas reductions achievable using HRVs would be expected to be controlled by the "dilution curve." That is, doubling the natural infiltration rate will reduce radon to 50 percent of the original concentration, quadrupling the rate will reduce radon to 25 percent of the original, and so on. While rigorous comparative data are not available, comparable degrees of natural ventilation (or of forced-air ventilation without heat recovery) would be expected to provide greater reductions than HRVs, because soil gas influx might also be reduced.

In actuality, fully ducted HRVs can provide some net supply of air to compensate for exfiltration. The HRV ducting will penetrate the house shell at two points (at the fresh air intake and the stale air exhaust, as shown in Figure 3); these penetrations could act somewhat like open windows, facilitating air infiltration through the intake and exhaust ducts. However, this infiltration will be hindered by the obstructions in the ducting (i.e., the fans, the HRV core, the ducting elbows, and the registers). Moreover, any infiltration through these ducts would be augmenting or counteracting the forced-air flow which the fans are trying to maintain, thus potentially altering the balance between intake and exhaust flow rates. Thus, reduction of soil gas influx through the stack effect compensation mechanism would not be expected to be a major mechanism of HRV radon reduction. And, as discussed in Section 3.2.3, available data tend to confirm that, in fact, dilution alone is the primary mechanism.

Another mechanism which can influence HRV performance is the increase (or decrease) of radon influx into the house, or into upper levels of the house, as the result of localized depressurization (or pressurization). Such localized pressure effects in the house can be created by the location of stale air return and the fresh air supply registers throughout the house. As one example of these effects, where HRVs are configured to ventilate only the basement of a house, radon reductions can sometimes be less than would be predicted based upon dilution effects alone. This result suggests that increased soil gas influx due to localized depressurization might be partially offsetting the reductions due to dilution (see Section 3.2.3). As another example of pressure effects, if the stale house air is withdrawn entirely from the basement and the incoming fresh air delivered entirely upstairs, the basement would become further depressurized, increasing soil gas influx into the basement. But on the other hand, the fresh air delivery upstairs could potentially slightly pressurize the upstairs relative to the basement, reducing the rate at which the radon-containing basement air flows upstairs. The extent to which the above phenomena occur will be highly house-specific, but data on at least two houses suggest that these phenomena will occur at least sometimes (see Section 3.2.3). Another configuration suggested by some investigators (Br87, Re87) is to withdraw stale air from upstairs and to deliver fresh air into the basement, in an effort to pressurize the basement and to thus reduce soil gas influx. The effectiveness of this approach will be highly dependent on the degree to which airflow bypasses between the basement and upstairs (and openings between the basement and outdoors) can be closed.

In summary, the effects on soil gas influx of localized depressurization and pressurization by HRVs are difficult to predict, and can vary from place to place within the house. However, these effects can sometimes cause HRV performance in various parts of the house to differ significantly (negatively or positively) from that which would be predicted based upon the dilution mechanism alone.

Another factor which can influence localized depressurization and pressurization is the balance between the fresh air inflow and the stale air exhaust. HRVs are typically installed to operate in a "balanced" mode—i.e., with the incoming fresh air flow rate being equal to the flow rate of the exhausted stale house air. Balance is important from the standpoint of radon reduction. If inflow is greater than outflow, the house will be slightly pressurized, possibly providing some reduction in the rate of soil gas influx. If outflow is greater, the house will be slightly depressurized, possibly increasing radon influx and partially negating the dilution benefits of the HRV. Balance is also important from the standpoint of heat recovery. For example, if inflow is substantially greater than outflow, the incoming fresh air would not be as effectively warmed (or cooled) in the HRV. In the extreme, if the exhaust flow were stopped altogether, there would be no warming (or cooling) of the inlet fresh air at all. The unit would not be functioning as an HRV, but would simply be blowing fresh air into the house (forced-air ventilation without heat recovery).

Some investigators suggest deliberately unbalancing the HRV in some cases in a manner which results in a net fresh air inflow, in an effort to pressurize the house. To the extent that inflow exceeds exhaust, some pressurization might occur, although the effects will be very house-specific. If the imbalance is limited, it is uncertain whether the pressurization will be sufficient to provide meaningful additional radon reductions. Also, to the extent that influx exceeds exhaust, the "stack effect compensation" mechanism for radon reduction, discussed above, will come into play, possibly aiding in radon reduction. But, as discussed in the previous paragraph, the more the HRV is unbalanced to increase inflow, the less effectively it will serve as a heat recovery unit.

3.2.2 Applicability

Both technical and economic considerations determine the applicability of HRVs.

Technically, HRVs can be used in any type of house, regardless of substructure type or other house design features. HRV systems can be designed to ventilate an entire house, as depicted in Figure 3, or just a part of the house (such as one story). However, HRVs will practically be applicable:

- only where no greater than 50 to 75 percent radon reduction is required, if the HRV is to serve as a stand-alone reduction measure and if the house has a typical natural infiltration rate. Thus, if levels of 4 pCi/L or less are to be achieved using an HRV, the initial radon concentration in the house could be no greater than 10 to 15 pCi/L.
- preferentially where the air exchange rate can be most substantially increased by HRVs of practical flow capacities. Such cases include: tight houses (i.e., houses having natural infiltration rates of about 0.25 air changes per hour, or lower); and where only a part of the house needs to be ventilated.

The percentage radon reductions achievable with HRVs will be limited by primarily two factors. First, as discussed in Section 3.2.1, the dilution mechanism appears to be the primary radon reduction mechanism that comes into play with HRVs. Therefore, the ability to reduce radon will be directly related to the ability to increase the air exchange rate. Second, due to practical and cost considerations, the amount of ventilating flow capacity reasonably achievable with commercially available HRVs is limited. The larger units available for residential use are generally rated at between 150 and 300 cfm (HVI87, We87). In the discussion here, it is considered unlikely that the owner of a typical-size house could practically consider installing more than two HRVs, providing a maximum practical capacity of 300 to 600 cfm.

If the natural infiltration rate of a 2,000 ft^2 house is a typical 0.5 to 0.9 air changes per hour (ach), then—based upon dilution considerations alone—a 200 cfm HRV could nominally increase the ventilation rate of the entire house by 0.75 ach, theoretically reducing radon concentrations by 45 to 60 percent. If the HRV capacity were doubled to 400 cfm (by installing a larger unit, or a second 200 cfm unit), the theoretical radon reduction for the entire house would be increased to 65 to 75 percent. Thus, reductions of roughly 50 to 75 percent are about the maximum that might be expected in a house of typical size and infiltration rate, if the whole house is ventilated. Homes having initial levels above about 10 to 15 pCi/L would have to use some other mitigation measure other than, or in addition to, an HRV if 4 pCi/L were to be achieved.

HRVs can give higher reductions in tight houses. In a very tight 2,000 ft^2 house having a natural infiltration rate of 0.15 ach, a 200 cfm HRV (again increasing the ventilation rate by 0.75 ach) would theoretically reduce radon levels by 83 percent, and a 400 cfm unit would reduce concentrations by 91 percent. (In no case, of course, could levels be reduced below those of the outdoor air.) Therefore, for such a very tight house, HRVs could potentially achieve 4 pCi/L by themselves when initial levels were as high as 25 to 40 pCi/L.

HRVs might also give reductions greater than 50 to 75 percent in one part of the house, if the HRV system is designed to treat just that part. As one example, if the 2,000 ft^2 house discussed above has two stories of 1,000 ft^2 each, and the HRV were designed to treat only one of the stories rather than the entire house, reductions on the ventilated story might be increased. If the infiltration rate on that one story were in the typical range of 0.5 to 0.9 ach, a 200 cfm HRV could theoretically provide radon reductions on that story of 65 to 75 percent, and a 400 cfm unit might yield reductions of 75 to 85 percent. However, caution is urged in projecting reductions where HRVs are used to ventilate only part of a house. For one thing, parts of houses are rarely isolated from one another so effectively that one part can be treated without affecting the others, as assumed in the calculations above. Moreover, when the basement is the one story ventilated, increases in soil gas influx due to localized depressurization can apparently sometimes partially offset the benefits of dilution, as suggested by some of the data presented in Section 3.2.3.

HRVs might also give reductions greater than 50 to 75 percent, at least in parts of the house, if mechanisms other than dilution come into play in a beneficial manner (i.e., pressurization of part of the house). However, understanding of HRVs is not currently sufficient to ensure that an HRV system can consistently be designed for any house in a manner which will in fact bring the beneficial aspects of localized pressurization into play, and will avoid the negative aspects of localization depressurization.

In addition to the technical considerations determining HRV applicability, discussed above, there are also economic considerations. The major purpose for installing an HRV, rather than simply opening windows or using a forced-air fan without heat recovery, is to reduce the heating and cooling cost penalty associated with ventilation. Thus, HRVs will be applicable only where the operating cost savings due to the reduced heating/cooling penalties will offset the initial capital cost of the HRV. HRVs will be more likely to pay for themselves—or will pay for themselves more quickly—when:

- winter weather is particularly cold, and/or summer weather is particularly hot and humid. When the outdoor temperature is much lower (or much higher) then the indoor temperature, the heating (or cooling) penalty associated with ventilation *without* heat recovery becoming greater. Thus, correspondingly, the absolute cost savings that can be realized through recovery of 50 to 80 percent of this energy would be greater.
- fuel costs are high. The higher the cost to heat (or cool) the house, the higher the cost penalty for ventilating without heat recovery.
- the HRV is more efficient. By recovering a greater percentage of the energy from the exhausted house air, more efficient HRVs will reduce the increase in heating and cooling costs to a greater extent. Thus, the more efficient unit might pay for itself more quickly, depending upon how much higher it is in capital cost.

In a number of cases—especially where the climate is relatively mild—it will be found that a given degree of ventilation can be achieved more economically (and with less visual impact inside the house) simply by opening windows to the proper extent, rather than by using an HRV. Someone considering the use of an HRV would have to perform a calculation for the particular conditions (climate, fuel costs, HRV costs) to determine whether an HRV is cost-effective. Table 8 presents an approach for making this cost-effectiveness calculation, at least to a first approximation. The method shown in this table first calculates the heating and air conditioning costs for the selected amount of ventilation *without* heat recovery. The costs are then calculated for achieving this same degree of ventilation with an HRV. Comparison of these costs provides an estimate of the annual cost savings achievable using an HRV, and the number of years required for the HRV to pay for itself, relative to comparable ventilation without heat recovery. Table 9 lists heating degree days and cooling infiltration degree days for various cities, to aid in the calculations in Table 8. A sample calculation using Table 8 is shown in Table 10. Table 11 summarizes the results from repeating this calculation for a number of U. S. cities representing a wide range of climate conditions. The calculations in Table 11 consider different heating systems, and are based upon specific assumptions regarding HRV efficiency, HRV costs, and fuel costs, as listed in the table. The table indicates that in very cold or very hot, humid climates, such as Minneapolis and Miami, an HRV might pay for itself in about 5 to 7 years. In less extreme climates, the payback time is longer, and for mild climates (such as Los Angeles), the HRV will never pay for itself. These calculations are intended for illustrative purposes only, and not as general conclusions regarding HRV applicability in the identified cities. The applicability for a specific house would depend on the actual efficiency and cost of the HRV being considered for that particular house, and the actual fuel costs and HVAC system efficiency.

Where the time required for the HRV to pay for itself is as long as 10 years, one should reconsider whether in fact a better approach might be to simply open windows or install a fan to achieve the desired degree of ventilation without heat recovery. Where the cost-effectiveness of the HRV is marginal, the other disadvantages and advantages of HRVs should be weighed. Disadvantages to be considered include the uncertainties in predicting radon reduction performance, the possible variations in performance over time (which depend to some extent upon maintenance to the core, filters, etc.), and noise from the fans. Another consideration is that comparable ventilation without heat recovery might give somewhat greater radon re-

Table 8. **Approximate Estimation of the Cost-Effectiveness of an HRV (Relative to Ventilation Without Heat Recovery)**

Step I. Determine amount of fresh air to be supplied by HRV (in cubic feet per minute, cfm)

1. Obtain fresh air delivery rate for HRV being considered for purchase (in cfm)

or

2. Decide upon number of air changes per hour (ach) desired for the HRV (see Table 12), and calculate:

$$\text{Needed cfm} = \text{desired ach} \times \frac{(\text{house area, ft}^2) \times (\text{ceiling height, ft})}{60\ \text{min/hr}}$$

Step II. Calculate annual cost of heating and cooling this amount of fresh air *without heat recovery*

A. Calculate annual cost of heating this air

1. Obtain the heating degree days each year for your area (in Fahrenheit degree-days, F°-days). See Table 9.
2. Energy required annually to heat the air (in British thermal units, Btu) =
   cfm of ventilation × heating F°-days per year × 0.02 Btu/ft^3 F° (heat capacity of air) × 1440 min/day
3. Cost of providing this energy each year using the house heating system =

$$\frac{\text{cost/unit of fuel}}{\text{Btu content/unit of fuel}} \times \frac{100}{\text{heat system efficiency, \%}} \times \text{Btu of energy required}$$

where:

— cost per unit of fuel can be calculated from data on heating bill (cents per kilowatt-hour of electricity, or per gallon of fuel oil, or per 1,000 ft^3 of natural gas)

— Btu content per unit of fuel can be obtained from fuel supplier, but is typically:

— 3,413 Btu/kWh of electricity

— 140,000 Btu/gal. of fuel oil

— 1,000,000 Btu/1,000 ft^3 of natural gas (or 100,000 Btu/therm)

— heating system efficiency is sometimes indicated on the heating equipment, but might typically be:

  — 100% for electric baseboard heat

  — 180% for electric heat pumps (Coefficient of Performance = 1.8)

  — 70% or higher for relatively new oil- or gas-fired forced-air furnaces, lower for older furnace designs.

  — the Btu of energy required annually for heating is that calculated in step 2 immediately above.

B. Calculate annual cost of air conditioning this air
[*Note:* Calculate only if the house has air conditioning.]

1. Estimate the cooling infiltration degree days each year for your area (in Fahrenheit degree-days), using Table 9 (obtained from Reference Sh86).

   The figure for cooling infiltration degree-days addresses not only the temperature, but also the humidity. The load on the air conditioner includes not only the energy required to reduce the temperature of the outdoor air, but also the energy required to condense out moisture. (Figures for "cooling degree days" obtained from local weather stations should not be used in this calculation, since they do not address humidity.)
2. Energy required annually to cool the air and condense moisture (in Btu) =

   (cfm of ventilation) × (cooling F° - days per year) × (0.02 Btu/ft^3 F°) × 1440 min/day
3. Cost of providing this energy each year using the house air conditioning system =

$$\frac{\text{cost/unit of fuel}}{\text{Btu content/unit of fuel}} \times \frac{100}{\text{cooling system efficiency, \%}} \times (\text{Btu of energy required})$$

where:

— cost per unit of fuel can be calculated from cooling bill (e.g., in cents per kilowatt-hour of electricity for electric air conditioners)

— Btu content per unit of fuel can be obtained from fuel supplier (e.g., 3,413 Btu/kWh of electricity for electric air conditioners)

— cooling system efficiency is sometimes indicated on the air conditioning equipment. For central electric air conditioners, this efficiency might typically be about 200 percent (Coefficient of Performance = 2.0)

— the Btu of energy required annually for cooling is that calculated in Step 2 immediately above.

C. Calculate total annual cost of heating and air conditioning this air (no heat recovery).

Add the costs calculated in Steps II.A and II.B.

Table 8 (continued)

Step III: Calculate the annual cost *with* heat recovery

A. Calculate annual cost of heating this air with heat recovery

1. Cost of heating fresh air with heat recovery =

   $$\text{cost of heating without recovery (II.A above)} \times \left(1 - \frac{\text{HRV efficiency, \%}}{100}\right)$$

   The HRV used in the formula above should be the Sensible Recovery Efficiency (SRE) for the HRV being considered, as defined by the Home Ventilating Institute (HVI86) and the Canadian Department of Energy, Mines and Resources (EMR87), or an equivalent efficiency figure. The SRE at 32°F can be used in this calculation. The SRE corrects for heating of the air stream by the fans and the preheat coil, and for cross-leakage between inlet and outlet streams. See Section 3.2.4.

2. Cost of electricity to operate the HRV fans =
   1/2 × (combined wattage of the two fans) × (cost per kWh) × (hours of operation)

where:

— HRV fan wattage can be obtained from vendor (typically 20 to 200 W total)

— cost per kWh can be obtained from electric company or electric bill

— hours of operation depend upon extent of use, but would be about 3,000 hours if the HRV operated continuously during a 4-month heating season

— multiplication by half is based on the assumption that about half of the power consumed (i.e., the power to the fan blowing fresh air in) will be recovered in the form of heat, which will warm the incoming air stream, through heat generated by the fan motor and energy imparted to the air by the fan blades.

3. Cost of HRV maintenance will be greater than zero (e.g., filter replacement, fan maintenance). For the purposes of this estimate, assume that the maintenance cost is $50 per year for a general service visit by a trained technician, plus $10 per year for new filters.
4. Total annual cost of heating with heat recovery is the sum of steps 1, 2, and 3 immediately above.

B. Calculate annual cost of cooling this air with heat recovery

[*Note*: Calculate *only* if the house has air conditioning.]

1. Cost of cooling fresh air with heat recovery =

   $$\text{cost of cooling without recovery (II.B above)} \times \left(1 - \frac{\text{HRV efficiency, \%}}{100}\right)$$

   The HRV efficiency used in the formula above should be the Total Recovery Efficiency (TRE) for the HRV being considered, as defined in References HVI86 and EMR87, or an equivalent efficiency figure. Like the SRE in III.A above, the TRE corrects for heat imparted by the fans and for cross-leakage. The TRE also accounts for the ability of the HRV to transfer moisture out of the incoming humid outdoor air. The ability of the HRV to remove moisture is important in reducing the load on the air conditioner, which will otherwise have to condense this moisture.

2. Cost of electricity to operate the HRV fans =
   (combined wattage of the two fans) × (cost per kWh) × (hours of operation)

   where the elements of this equation are as defined in III.A.2.

3. Cost of HRV maintenance — maintenance costs not included in III.A.3 should be included here, to the extent they can be estimated.
4. Total annual cost of cooling with heat recovery is the sum of steps 1, 2, and 3 immediately above.

C. Calculate total annual cost of heating and air conditioning this air (with heat recovery).

Add the costs calculated in steps III.A and III.B.

Step IV. Calculate annual cost savings achieved through use of HRV
Annual savings = [cost without heat recovery (II above)] − [cost with heat recovery (III above)]

Step V. Calculate time required for HRV to pay for itself

A rigorous calculation of HRV cost-effectiveness would require calculation of the present-day value of energy savings over the lifetime of the unit. However, for a first approximation, simply calculate:

$$\text{Approx. time required to recover HRV cost (years)} = \frac{\text{installed cost of the HRV}}{\text{savings per year (IV above)}}$$

If this time is as long as perhaps 10 years, one should reconsider whether a better approach might be to simply open windows in order to achieve equivalent ventilation without heat recovery.

Table 9. Heating Degree Days and Cooling Infiltration Degree Days for Various Cities*

City	Heating Degree-Days (F°-days)	Cooling Infiltration Degree-Days* (F°-days)
Albuquerque, NM	4221	548
Amarillo, TX	4191	2139
Atlanta, GA	2980	2879
Birmingham, AL	2786	2793
Bismarck, ND	8985	724
Boise, ID	5882	262
Boston, MA	5853	1155
Brownsville, TX	533	10355
Charleston, SC	2168	4408
Cheyenne, WY	7262	144
Chicago, IL	6137	1371
Cleveland, OH	6182	1240
Dayton, OH	5596	1355
Denver, CO	5915	178
Des Moines, IA	6533	1812
Detroit, MI	6556	941
Dodge City, KS	5075	2664
El Paso, TX	2670	1345
Fort Worth, TX	2344	5194
Great Falls, MT	7684	69
Indianapolis, IN	5613	1773
Kansas City, MO	4828	2810
Lake Charles, LA	1523	5928
Las Vegas, NV	2548	905
Little Rock, AR	3187	3542
Los Angeles, CA	1698	565
Madison, WI	7659	1350
Medford, OR	4885	329
Miami, FL	218	8166
Minneapolis, MN	8034	1474
Nashville, TN	3697	2655
New York, NY	4910	1544
Oklahoma City, OK	3762	4475
Omaha, NE	6030	2134
Phoenix, AZ	1347	2292
Pittsburgh, PA	5943	894
Portland, ME	7400	618
Portland, OR	4603	172
Raleigh, NC	3541	2323
St. Louis, MO	4908	3060
Salt Lake City, UT	5820	250
San Antonio, TX	1542	5252
Seattle, WA	5208	79
Tallahassee, FL	1548	3878
Tampa, FL	597	5843
Washington, DC	4208	2339

*From Reference Sh86. Cooling infiltration degree days take into account the humidity as well as the temperature.

ductions, depending upon the HRV configuration, because the "stack effect compensation" mechanism for radon reduction could come into play. Advantages of HRVs include: the ability to reduce the discomfort associated with ventilation, by warming (or cooling) the incoming fresh air and by controlling where it is injected; the ability to ensure a consistent degree of ventilation (whereas with open windows, the ventilation might be variable); and the ability to avoid the house security concerns sometimes associated with open windows.

A number of investigators (using cost data from earlier years) have calculated that HRVs will be no better than marginally cost-effective in a number of climates, depending upon assumptions (Of82, *Fi83a*, Tu83). This conclusion is generally supported by the calculations in Table 11. Those contemplating the use of an HRV would have to perform their own analyses (using Table 8) for their climatic conditions and current cost information.

In a house having an HRV, the HRV would be applicable when the furnace or air conditioner is operating, and when it is otherwise not desirable to open windows. When the weather is sufficiently mild that the heating/cooling system is off, the homeowner should consider opening windows, since the radon reductions achievable through such substantive natural ventilation will likely be much greater than the reductions achievable with the HRV. When the windows are open, the HRV might as well be turned off.

Even when the furnace or air conditioner is operating in a house with an HRV, the homeowner might still consider opening windows in lieu of operating the HRV at times when the outdoor temperatures are only slightly below or above indoor temperatures. The rationale is that open windows can potentially give greater radon reductions than HRVs, because: a) the "stack effect compensation" mechanism can come into play; and b) open windows can permit a greater inflow of fresh air. Of course, there will be an increased heating or cooling penalty if the windows are opened when the furnace or air conditioner is operating. But the increased heating/cooling costs might be acceptable if the outdoor temperatures are only moderately low or high, and the increased radon reductions might make these penalties worthwhile to the homeowner. The desirability of this approach would vary from house to house.

If the HRV is to be used for ventilation during hot, humid weather, the unit should be one which recovers moisture as well as heat (i.e., one which can remove humidity from the incoming fresh air). As discussed in Section 3.2.4, much of the air conditioning costs in many areas result from the condensation of moisture, as distinguished from reducing the temperature of the air. HRVs which do not recover moisture will be less likely to be applicable for use in hot, humid weather.

If an HRV is to be used to ventilate an entire house (or a large portion of a house, such as an entire story), the applicable HRV design would be a fully ducted system, rather than a wall-mounted unit. The ducted system has a greater potential for achieving the necessary whole—house circulation (if the fresh air supply and the stale air return registers are suitably separated), and for providing the necessary ventilating flow rate. By comparison, wall-mounted units will necessarily have supply and return registers so close together inside the house that fresh air may short-circuit into the exhaust. Further, the intake and exhaust ports outside the house will be close, so that exhausted stale air

Table 10. Sample Calculation of HRV Cost-Effectiveness, Using Table 8

Assumptions:

Desired increase in ventilation—0.75 ach
House living area—2,000 ft^2
Heating degree days—4,208 F°-days
Cooling infiltration degree days—2,339 F°-days
Forced-air furnace, natural-gas-fired, 70 percent thermal efficiency
Gas cost—\$7.00 per 1,000 ft^3
Electric air conditioner with Coefficient of Performance 2.0 (efficiency 200 percent)
Electricity cost—7.5¢ per kWh
HRV Sensible Recovery Efficiency—75 percent
HRV Total Recovery Efficiency—67 percent
Installed cost of HRV—\$1,750
HRV fans consume 150 W

Step I. Determine cfm of fresh air to be supplied by HRV

$$\text{cfm} = 0.75\,\frac{\text{air changes}}{\text{hour}} \times \frac{(2000\ \text{ft}^2) \times (8\ \text{ft ceiling height})}{60\ \text{min/hr}} = 200\ \text{cfm}$$

Step II. Calculate annual heating and cooling cost for 200 cfm (*without* HRV)

A. *Heating Cost*

Energy required to heat 200 cfm =

$$(200\ \text{cfm}) \times (4208\ \text{heating F°-days}) \times \left(0.02\,\frac{\text{Btu}}{\text{ft}^3\text{F°}}\right) \times \left(1440\,\frac{\text{min}}{\text{day}}\right)$$

= 24.2 million Btu per year

Cost of providing 24.2 million Btu using gas-fired furnace =

$$\frac{\$7.00/1{,}000\ \text{ft}^3}{1\ \text{million Btu}/1{,}000\ \text{ft}^3} \times \frac{100}{70\ (\text{furnace efficiency})} \times 24.2\ \text{million Btu} = \$242\ \text{per year}$$

B. *Cooling Cost*

Energy required to air condition 200 cfm =

$$(200\ \text{cfm}) \times (2339\ \text{F°-days}) \times \left(0.02\,\frac{\text{Btu}}{\text{ft}^3\text{F°}}\right) \times \left(1440\,\frac{\text{min}}{\text{day}}\right) = 13.5\ \text{million Btu per year}$$

Cost of providing 13.5 million Btu of air conditioning =

$$\frac{\$0.075/\text{kWh}}{3{,}413\ \text{Btu/kWh}} \times \frac{100}{200} \times 13.5\ \text{million Btu} = \$148\ \text{per year}$$

C. *Total Heating and Cooling Cost*

\$242 + \$148 = \$390 per year

Thus, if windows were opened to provide 200 cfm of additional ventilation under the conditions assumed here, the combined heating and cooling bill for the house would rise by an estimated \$390/year.

Step III. Calculate annual heating and cooling cost for 200 cfm *with* HRV

A. *Heating Cost with HRV*

1. HRV recovers a net 75 percent of the sensible energy from the exhausted house air.

   Cost to heat 200 cfm when ventilation is accomplished using

   $$\text{HRV} = \$242\ (\text{from IIA above}) \times \left(1 - \frac{75}{100}\right) = \$60\ \text{per year}$$

2. Cost of electricity to run fans =

   $$(\tfrac{1}{2}) \times (150\ \text{W}) \times (\$0.075/\text{kWh}) \times \left(\frac{1\ \text{kW}}{1{,}000\ \text{W}}\right) \times (3000\ \text{hr heating season}) = \$17\ \text{per year}$$

3. Annual maintenance cost = \$50 for servicing + \$10 for filters = \$60

4. Total heating cost for 200 cfm using HRV = \$60 + \$17 + \$60 = \$137 per year

B. *Cooling Cost with HRV*

1. HRV recovers a net 67 percent of the total sensible plus latent energy.

   Cost to air condition 200 cfm when ventilation is accomplished

   $$\text{using HRV} = \$148 \times \left(1 - \frac{67}{100}\right) = \$49$$

Table 10 (continued)

2. Cost of electricity to run fans =

$$(150\,\mathrm{W}) \times (\$0.075/\mathrm{kWh}) \times \left(\frac{1\ \mathrm{kW}}{1000\ \mathrm{W}}\right) \times \ (3000\ \text{hr cooling season}) = \$34$$

3. Maintenance costs for entire year were included in III.A.3 above.
4. Total air conditioning cost for 200 cfm using HRV = $49 + $34 = $83 per year

C. *Total Heating and Cooling Cost with HRV*
Results from Steps III.A.4 and III.B.4 above = $137 + $83 = $220

Step IV. Cost Savings Achieved Through Use of HRV
Results from Step II.C minus results from Step III.C. = $390 − $220 = $170 per year

Step V. Calculate time required for HRV to pay for itself

$$\frac{\$1750\ \text{(installed cost)}}{\$170/\text{year savings}} = 10.3\ \text{years}$$

Since the time to recover the HRV installation cost is greater than 10 years for these assumptions, consider the option of achieving the 200 cfm of ventilation simply by opening windows, rather than trying to recover energy.

Table 11. **Time Required to Recover Investment in a 200 CFM HRV Under Various Assumed Conditions**

Location	Heating Degree Days (F° days)	Cooling Infiltration Degree Days (F° days)	Time to Recover Investment (years) Gas Furnace	Oil Furnace	Electric Resistance Heat	Electric Heat Pump
Los Angeles, CA	1698	565	*	*	23.6	*
Miami, FL	218	8166	7.2	7.2	6.8	7.1
Minneapolis, MN	8034	1474	5.9	7.0	2.5	4.6
Washington, DC	4208	2339	10.3	12.2	4.5	10.1

*Investment will never be recovered.

Assumptions:
HRV is fully ducted and delivers 200 cfm.
Sensible Recovery Efficiency is 75 percent (efficiency during heating season).
Total Recovery Efficiency of HRV is 67 percent (efficiency during air conditioning season).
Installed cost of the HRV is $1,750.
Gas furnace is 70 percent efficient; cost of gas $7.00/1,000 ft^3 ($7.00/million Btu).
Oil furnace is 70 percent efficient; cost of oil $0.85/gal. ($6.00/million Btu).
Electric resistance heat is 100 percent efficient; cost of electricity $0.075/kWh ($22.00/million Btu).
Heat pump Coefficient of Performance averages 1.8 for heating; cost of electricity $0.075/kWh.
Air conditioner Coefficient of Performance is 2.0; cost of electricity $0.075/kWh.

may exhaust into the fresh air intake. Also, ventilating flows from the wall-mounted units tend to be at the low end of the flow range for available residential HRVs. Thus, the ventilation effectiveness of wall-mounted units would be expected to be reduced. As a minimum, multiple wall-mounted units would probably be necessary if these units were intended to treat more than one room.

An HRV can be ducted to treat primarily one area of the house. For example, fresh air can be delivered primarily to the upstairs (if that is the primary living area), with stale air being exhausted from the basement, increasing upstairs radon reductions at the expense of the basement. Thus, HRVs are applicable for treating only part of the house.

3.2.3 Confidence

There is moderate confidence that moderate radon reductions can be achieved using fully ducted HRVs, with the expected reductions being greater for tight houses. Confidence is low to moderate for wall-mounted HRVs, because of the potentially reduced ventilation effectiveness of these units, discussed in the previous section.

As discussed in the preceding section, HRVs are generally expected to provide only moderate radon reductions. Reductions are limited because HRVs reduce radon levels primarily through the dilution mechanism alone, and because the cubic-foot-per-minute ventilation capacity is limited by practical considerations. Available data on HRV performance, presented later in this section, confirm that radon reductions are generally consistent with the dilution effects that would be anticipated based on the increase in ventilation rate created by the HRV.

However, the confidence in the performance of fully ducted HRVs is considered at the present time to be moderate (rather than high, as for the other ventilation approaches discussed in Section 3.1). The two primary factors limiting the confidence in ducted HRVs are:

- radon reductions in different parts of the house cannot always be reliably predicted prior to installation based solely upon the anticipated increase in ventilation.
- performance of the HRV depends upon proper balancing of the inlet and outlet flow rates. Such flow balances can vary over time (depending to a large extent upon maintenance by the homeowner).

The confidence in the performance of wall-mounted HRVs is lower, because of the additional concern that fresh air might not be effectively distributed by wall units as a result of the nearness of the fresh air supply register to the stale air return register.

Although available HRV data show whole-house radon reductions *generally* consistent with dilution effects, the results in different parts of some houses could not always have been predicted based solely upon dilution considerations. Other mechanisms appear to be coming into play. One such mechanism is localized depressurization and pressurization effects which influence both the influx of soil gas into the house, and the movement of radon between parts of the house. The results of these pressure effects (which can be either negative or positive) cannot be reliably predicted before installation. As discussed later in this section, data on HRVs ventilating just the basement in some houses suggest that soil gas influx was increased, partially offsetting the benefits of dilution. In other cases, where the HRV was apparently pressurizing the upstairs relative to the basement, upstairs reductions were greater than would be predicted based on dilution, at the expense of poorer reductions in the basement. This latter situation could be a positive result if the upstairs is the primary living area. Some investigators have proposed ducting the HRV to pressurize the basement, again attempting to obtain a positive result from HRV-induced pressure effects. However, the success of this approach has not yet been demonstrated. It would appear that, at present, the dynamics of air flow inside a house are not sufficiently well understood to permit the design of an HRV system to ensure that the negative effects of HRV-induced depressurization are avoided, or that any potential positive effects of HRV-induced pressurization are realized. Rather, the state of knowledge appears to be that pressure effects can play an unpredictable (and sometimes significant) role in determining HRV performance in different parts of a house. The role that pressure effects can play will depend greatly on the design of the HRV system, the design and construction details of the house, and the understanding and skill of the mitigator installing the system. Testing is underway to better understand these devices.

In addition to the uncertainty in predicting HRV performance, another concern limiting confidence is that the performance could potentially vary over time, largely as the result of variations in the balance between inlet and exhaust flows. Changes in balance could cause localized depressurization (or pressurization) effects, influencing radon influx. Primary causes of such changes in balance include the accumulation of snow, leaves, or other debris in the intake opening or exhaust vent through the side of the house; accumulation of dust in the air filters commonly located in the fresh air intake ducting and the stale house air return ducting to protect the HRV core; accumulation of dust in the HRV core; and ice accumulation in the core during the winter. Such accumulations can restrict the airflow in either the intake or the exhaust ducts (or both), altering the balance. In reducing airflow, these accumulations will also reduce the amount of ventilation (and hence the extent of dilution of the radon). Of particular concern are accumulations which preferentially restrict the intake more than the exhaust, since these will make exhaust greater than inflow, potentially depressurizing the house and increasing soil gas influx. These blockages of particular concern include plugging of the fresh air intake openings, of the air filter in the fresh air intake duct, or of the air channels on the fresh air side of the core. Such changes in balance and airflow can be reduced or prevented only through careful, sustained maintenance by the homeowner, including keeping the exhaust vents clear, changing the filters regularly, cleaning the core as needed, and de-icing the system as needed (if not done automatically). Some automatic defrost systems involve periodic operation of the HRV exhaust fan only, which would depressurize the house.

Changes in HRV balance can also vary as wind speed and direction vary. Wind changes would change the outdoor pressures at the points where the intake openings and exhaust vents penetrate the house shell. For example, if both openings were on one side of the house, and if that side became the downwind (low-pressure) side, the inlet airflow would be reduced (as the low pressure worked against the intake fan), and the exhaust flow would be increased, potentially depressurizing the house. These wind effects could be reduced or eliminated by ensuring that the intake openings and exhaust vents are on opposite sides of the house wherever possible. In any event, such wind-induced changes in balance would presumably be transient, unless the HRV were originally balanced under atypical wind conditions.

Care must be taken to ensure that the HRV is properly balanced when it is installed. Space constraints sometimes require that the HRV be located close to one wall, with the intake openings and exhaust vents positioned fairly close to the HRV. The runs of intake and exhaust ducting will be relatively short and can include a number of bends. Under these conditions, where there is not a straight run of reasonable length, it is difficult to accurately measure the airflows and ensure that the intake and exhaust are in fact balanced. Velocity measurements at multiple points across the cross-section of the duct are required in order to obtain a reasonable measure of airflow in a short, convoluted duct.

Since measurements of (and adjustments to) the balance of an HRV require multi-point flow velocity measurements in the HRV ducts, homeowners are not able to check the balance on their own. One option is to have an experienced service representative visit the house periodically (for a service charge) to measure and adjust the balance. An annual general servicing of the unit, including rebalancing, would help improve the confidence in satisfactory long-term performance.

In one study of 227 residential HRV installations, about 45 percent of the units were found to be roughly in balance, with the inlet and outlet flows equal within 10 percent. About 30 percent of the units had exhaust flows more than 10 percent greater than the intake flows, potentially depressurizing the house. In about 3 percent of the houses, the exhaust flow was at least twice as great as the intake. In the remaining 25 percent of the houses, the intake flow was more than 10 percent greater than the exhaust.

In summary, because the actual radon reduction performance of an HRV cannot always be predicted prior to installation, and because performance can potentially degrade over time depending on balance and maintenance, the confidence in ducted HRVs is felt to be moderate.

The available data on radon reduction using HRVs confirm that the reductions are moderate (50 to 75 percent), as expected, in houses having typical natural infiltration rates, and that the reductions are generally consistent with dilution effects.

Among the houses for which substantive measurements are available are three block basement houses where fully ducted HRVs were installed for demonstration purposes by a vendor of HRV equipment. The initial infiltration rates and the final ventilation rate (with the HRV), are not known for these houses, so that HRV performance cannot be related rigorously to changes in the ventilation rate. However, the houses all appeared as though they would have reasonably typical natural infiltration rates; i.e., between 0.5 and 0.9 air changes per hour. The first house, which had an initial radon level of about 130 pCi/L in the basement, was tested using a ducted HRV delivering 178 cfm of fresh air into the basement and exhausting an equivalent amount of stale air from the basement. Basement radon reductions over a 4-day period (measured using a continuous radon monitor) averaged 55 to 65 percent (EPA85). This reduction is roughly consistent with the increase in ventilation rate which 178 cfm would create in the basement alone if the initial infiltration rate were assumed to be typical, and if the communication of house air between the basement and upstairs were relatively limited (so that the effects of the HRV were in fact limited to the basement). The reduction in working level was about 80 percent in this basement, as determined by simultaneous 4-day measurements using a continuous working level monitor. Thus, the equilibrium ratio fell from about 0.43 without the HRV, to about 0.22 with the HRV operating. This reduction in the equilibrium ratio could result in part because the radon is "younger" as a result of the 2.5- to 3-fold potential increase in basement ventilation rate. Increased plate-out of the progeny, due to increased air movement or due to reduced concentrations of airborne dust particles, might also have played some role.

The second block basement house had an initial radon level of about 850 pCi/L in the basement. The HRV system tested in this house delivered about 150 cfm of fresh air partly upstairs and partly into the basement, while exhausting all stale air entirely from the basement. Three weeks of hourly readings in the basement with a continuous radon monitor indicated that the mean basement reduction achieved by the HRV was 50 to 55 percent (EPA86e). This reduction is consistent with what would be expected based upon dilution in the basement alone if the initial infiltration rate were about 0.5 ach.

The third block basement house had a ducted HRV system delivering 160 cfm into the basement and exhausting all stale air from the basement. Three weeks of hourly readings in the basement with a continuous radon monitor indicated that initial basement levels averaging roughly 25 pCi/L were reduced about 80 percent (We86). This reduction is generally consistent with the 5-fold increase in ventilation rate in this small basement that the HRV flow would be providing if the initial infiltration rate in the basement were 0.4 to 0.5 ach.

The results from these three houses indicate that, at least in some cases, radon reductions of 50 to 75 percent can be achieved in the basements of houses with apparently typical infiltration rates, consistent with the estimated increase in the ventilation rate of the basement. In addition to infiltration rate, the results are dependent upon HRV capacity and basement size.

Fully ducted HRVs (nominally 200 cfm) were also tested in an additional three block basement houses as part of an EPA-sponsored demonstration project (He87a). Different HRV configurations were tested in these three houses. The stale house air was always withdrawn entirely from the basement; the incoming fresh air was sometimes supplied entirely upstairs, and sometimes entirely into the basement. At least 48 hours of continuous radon measurements were made both upstairs and downstairs, before and after the HRV was activated. The results of ventilation rate measurements are not yet available, but again, it would appear that the houses had reasonably typical natural infiltration rates. The results of the tests on these three houses are summarized below.

- Of the nine different combinations tested (of house identity, HRV configuration, and fan speed), in only one case could the combined radon reductions upstairs and downstairs be explained solely on the basis of dilution effects. In all other cases, some other mechanism was coming into play. And in no case could the reduction upstairs and downstairs have been predicted a priori.
- In all three houses, when all fresh air was supplied only to the basement (referred to here as the "basement-only" system), the radon reductions were 37 to 45 percent. By comparison, reductions of 55 to 75 percent would have been predicted in the basement, based upon dilution in the basement volume alone. In two of the three houses, the poor basement reductions appeared to be explained, at least in part, by an increase in soil gas influx (resulting from localized depressurization created by the HRV stale air return) which partially offset the dilution effects.
- In one house with a basement-only system, the poor basement reduction was apparently explained entirely by circulation of some of the fresh air upstairs, contributing to 60 to 75 percent reductions upstairs. There was known to be good communication of house air between upstairs and the basement in this house, facilitating this circulation. In another house, *part* of the poor basement reduction with a basement-only system could be explained by fresh air circulation upstairs (contributing to 60 percent reduction upstairs). In this second house, no obvious major avenues facilitated communication between the stories. However, no special effort was made to isolate one story from another and, as in all houses, there clearly was some communication. This result on the second house illustrates that—if an HRV is used in an effort to ventilate just a part of a house—effects will likely be observed in other parts of the house as well, unless special efforts are undertaken to isolate the ventilated portion. As a result, reductions in the ventilated part can be poorer than would be predicted if the ventilation effects could indeed be isolated. In neither house could the relative reductions upstairs versus downstairs have been predicted beforehand. Thus, the confidence with which an HRV system can be designed to give preselected reductions in different parts of a house is in question. The improved reductions upstairs and poorer reductions downstairs could be desirable if the upstairs is the primary living area, but could be undesirable if the objective had been to achieve high basement reductions.
- In the third house with a basement-only system, almost no radon reduction was observed upstairs (with 44 percent reduction in the basement). If all soil gas passed through the basement before arriving upstairs, the upstairs reductions would be expected to be at least as good as those in the basement. For upstairs reductions to be so poor, there must have been a direct avenue by which soil gas could flow upstairs without first passing through the basement. A block fireplace structure in one wall of this third house is one possible avenue. This result further reveals the difficulty in understanding the flow dynamics inside a house, and in predicting the influence of an HRV on those dynamics.
- In two of the houses, when all fresh air was supplied upstairs (referred to as the "upstairs-downstairs" system), the radon reductions upstairs were 72 to 82 percent. These reductions are higher than the 65 to 70 percent maximum reductions that would be predicted upstairs based solely on dilution considerations, if the upstairs could be completely isolated from the basement. The corresponding radon reductions downstairs were low (6 to 21 percent, with an *increase* in basement radon in one case). One possible explanation for this result is that the HRV configuration (exhausting from downstairs and supplying fresh air upstairs) could have been slightly pressurizing the upstairs relative to the basement. Thus, the flow of relatively high-radon basement air upstairs

could have been inhibited. This effect would supplement the dilution effects in reducing radon.

In summary, these results from Reference He87a confirm that reductions in the vicinity of 50 to 75 percent can generally be expected with HRVs in typical houses. However, reductions can vary significantly in different parts of the house, in a manner which can make it difficult to predict performance. Mechanisms in addition to dilution can affect the reductions achieved.

Other data on the performance of ducted HRV installations have been reported by mitigators and vendors. For example, in 75 installations by one vendor, radon reductions of about 55 to 90 percent (working level reductions of 60 to 95 percent) have been reported. The upper end of this reported performance range extends above the 50 to 75 percent range generally expected from dilution considerations in houses of typical size and infiltration rate. In some cases, the relatively high reported reductions could be due, at least in part, to the fact that some of the HRVs are ventilating only part of the house; with the reduced volumes being ventilated in such cases, reductions in the ventilated areas could be increased. The size and natural infiltration rates of the individual houses, and the flow rates of the HRVs, could help explain the relatively high reductions. However, another key explanation could be that some of the vendor data are based upon 5-minute grab sample measurements, and/or upon before and after measurements which are separated widely in time. In view of the substantial variability in radon concentrations over time in a given house, such measurements would not accurately indicate long-term HRV performance.

Investigators testing ducted HRVs in tight houses (having low natural infiltration rates) have consistently reported radon gas reductions of 60 to 90 percent (and generally comparable reductions in progeny working level). The relatively high reductions in tight houses are consistent with dilution effects. HRVs of reasonable capacity can achieve a substantial increase in ventilation rate when the pre-existing infiltration rate is low. Nazaroff (Na81) observed radon reductions above 90 percent by increasing the ventilation rate by a factor of 11 in a house initially containing 30 pCi/L and having a very low 0.07 ach natural infiltration rate. The radon progeny working level appears to have been reduced by a similar amount. Lesser increases in ventilation rate gave lesser reductions, consistent with dilution effects. Holub (Ho85) obtained radon (and working level) reductions of about 85 percent in a 0.16 ach house (with about 7 pCi/L initially) by increasing the ventilation rate by a factor of over seven. Again, this result is consistent with dilution phenomena. And Nagda (Nag85) reports radon reductions of about 60 percent (working level reductions of about 40 percent) in a house initially having 1.4 pCi/L and 0.25 ach, through a 1.7-fold increase in ventilation rate, consistent with dilution.

No data have been found at this time to indicate the effectiveness of wall-mounted HRVs in reducing indoor radon levels.

3.2.4 Design and Installation

Ducted HRV systems are designed and installed by experienced heating/ventilation/air conditioning contractors. As discussed previously, HRV performance in reducing radon concentrations can be very sensitive to proper installation. Thus, it is crucial that a ducted HRV be installed by a contractor who has experience with HRV systems for radon reduction specifically. Wall-mounted HRVs are generally less complex, and can sometimes be installed directly by the homeowner.

The knowledge required by an HVAC contractor in designing and installing a ducted system will necessarily extend beyond what can be presented in this manual. The discussion which follows is intended to aid the homeowner in dealing with the contractor.

Pre-mitigation diagnostic testing. If an HRV is being considered, perhaps the most important single diagnostic test is measurement of the natural closed-house infiltration rate. The performance of the HRV in reducing radon will be highly dependent on the pre-existing natural infiltration rate. This rate cannot be reliably guessed simply by looking at the house. For example, suppose that a 2,000 ft^2 house were assumed to have an infiltration rate of 0.5 ach, when in reality it had a rate of 1.0 ach. A 200 cfm HRV in this house would be likely to provide a reduction of 40 to 45 percent (based upon dilution effects only, with 1.0 ach natural infiltration), instead of the 60 percent that would have been erroneously predicted based upon 0.5 ach. If the difference between 40 and 60 percent reduction is important in a given house, then it can be desirable to measure the infiltration rate before the HRV is installed.

As discussed in Section 2.4, infiltration rate can be measured using either tracer gases or a blower door. If the HRV is being considered for the ventilation of only one story of a house, then the measurements should include the infiltration rate of just that story, as well as the leakage area or air movement between that story and the other stories.

Selection of HRV capacity. The first step in designing the system is to select the capacity of the ventilator (i.e., the amount of increased ventilation desired). The flow rate required through the HRV will depend on the degree of radon reduction desired, and the volume and natural infiltration rate of the space to be ventilated. Table 12 presents a simple method for initially approximating the needed capacity, assuming that radon levels will be reduced by the same factor by which the ventilation rate is increased. (As discussed in Section 3.2.3, this assumption will not always be correct.) Table 12 calculates the necessary HRV capacity to achieve an initially selected degree of radon reduction. Alternatively, to assess a particular HRV capable of a given delivery rate, and to estimate what radon reduction it might provide, the steps in Table 12 could be followed in reverse order.

The volume of the space to be ventilated is important in estimating HRV capacity. In houses with central forced-air furnaces, the air between all stories of the house will be generally well mixed, and any benefits achieved by an HRV in any one section of the house will thus be distributed throughout the entire house. Therefore, in houses with central forced-air furnaces, the volume to be ventilated by the HRV will always be that of the entire house, even if the HRV itself directly ventilates only one story. But in houses with electric or hot-water space heating systems and with reasonably limited airflow bypasses, individual stories will be more isolated from one another and, if desired, one could consider sizing the HRV to focus the treatment on just one story. If only one story is treated, the volume being treated is greatly reduced, so that the desired reduction on that level might be achieved with a smaller HRV. Alternatively, the same HRV could provide a greater reduction than if the whole house were treated. But as discussed in the previous section, even with electric or hot-water space heating, stories of a house are never so totally isolated from each other that the ventilation effects can really be limited to only one story. Therefore, in applying Table 8 to size an HRV, the volume of the one story would be expected to yield the *minimum* HRV capacity that would be needed.

Note that—because of the pressure losses that occur as air flows through the HRV core, the ducts, and the registers—the actual fresh air delivered by an HRV will be less than the nominal rated capacity of the unit. Thus, the HRV that is installed must have a nominal capacity greater than the actual desired delivery rate of fresh air. The actual delivery rates that can be provided under different pressure losses are sometimes given by the manufacturer, or by organizations which test HRV equipment (HVI87, EMR87).

HRV energy recovery efficiency. The energy recovery efficiency of the selected unit can play an important role in determining how quickly (or whether) the unit will pay for itself in reduced heating and cooling penalties. When the HRV is used in cold weather, the major concern is its efficiency in raising the temperature of the incoming cold fresh air, by transferring heat from (and thus reducing the temperature of) the exhaust warm house air. This efficiency can be referred to as the efficiency in recovering "sensible" heat. When the HRV is used in hot, humid weather, the concern is not only with the efficiency in recovering sensible heat, but also with the efficiency in "recovering" moisture. That is, it is not enough simply to reduce the temperature of the incoming hot fresh air; it is also necessary to remove humidity from this incoming air, transferring the moisture to the exhausted cool house air stream. The reason is that, to the extent that the moisture remains in the incoming air, this moisture will have to be condensed by the air conditioner. To condense the moisture, the air conditioner must extract the "latent heat" of condensation from the moisture. In humid climates, more than half of the air conditioning costs can sometimes be due to the removal of such latent heat (condensing moisture), and less than half of the costs due to the removal of sensible heat (actually reducing the temperature of the house air). Some HRVs can remove moisture, and some cannot. A unit which does not recover moisture would not be a good selection for use where summers are hot and humid.

The more efficient the HRV, the greater will be the reduction in heating and cooling costs. Or, stated another way, for a given degree of ventilation, the heating and cooling cost penalty will be lower when the efficiency of the HRV is higher. Depending upon the capital cost of a more efficient unit, the more efficient unit might pay for itself more quickly. HRVs with low efficiencies might not pay for themselves at all. The calculations outlined in Table 8 address this issue of payback time as a function of efficiency.

Persons selecting between alternative HRV units will generally wish to compare the energy recovery (and moisture recovery) efficiencies of the units being considered. Unfortunately, efficiency figures for different units are not always comparable. Some reported heat recovery efficiencies are based on temperature measurements alone (i.e., the temperature change in the incoming fresh air stream, divided by the total temperature differential between indoors and outdoors). Such reported efficiencies do not take into account such factors as: the heat added to the fresh air stream due to operation of the supply fan, inequalities in flow between the fresh air intake and the stale air exhaust streams, cross-leakage of air between the two streams in the HRV, and the energy penalty resulting from operation of the electric resistance preheat coil, which is sometimes present in the fresh air intake ducting to heat this stream and thus avoid ice accumulation in the core during extremely cold weather. Some reported efficiencies *do* take

Table 12. **Rough Estimation of the Required Capacity of an HRV (Assuming Radon Reduction Is Directly Related to Increase in Ventilation)**

Step I. Determine the needed increase in the house ventilation rate to achieve the desired radon reduction.

Decide upon the radon concentration to be achieved using the HRV.

$$\frac{\text{Current radon concentration}}{\text{Desired reduced concentration}} = \text{factor by which radon is to be reduced}$$

(factor by which ventilation must be increased)

For example, if the current level is 10 pCi/L, and if the desired level is 4 pCi/L, then the house ventilation rate must be increased by a factor of $\frac{10}{4} = 2.5$

Step II. Determine current natural infiltration rate.

A diagnostician can measure the natural (closed-house) ventilation rate using tracer gases or a blower door, as discussed in Section 2.4.

In the absence of such diagnostic testing, the homeowner might make the following *very rough* assumptions for this estimate.

Infiltration rate of:
— energy-efficient house - 0.25 air changes per hour (ach)
— "typical," relatively modern house, not advertised as energy efficient - 0.5 to 0.75 ach
— "drafty" house - 1.0 ach

Step III. Determine the incremental increase in ventilation which HRV must provide

Incremental increase in ventilation needed from HRV (in ach) =

$$\underbrace{(\text{factor by which ventilation must be increased}) \times (\text{natural infiltration rate})}_{\text{total ventilation rate needed}} \underset{\text{minus}}{-} \underbrace{(\text{natural infiltration rate})}_{\text{ventilation rate which already exists}}$$

For example, if a 2.5-fold increase in ventilation is required, and the natural infiltration rate is 0.5 ach, then the increase which the HRV must create is

$(2.5 \times 0.5 \text{ ach}) - 0.5 \text{ ach} = 1.25 - 0.5 = 0.75 \text{ ach}$

Step IV. Calculate volume of space to be ventilated.

Volume to be ventilated, in cubic feet (approx.) = (area of space, in square feet) × (ceiling height, in feet)

If the whole house is being ventilated, the area is that of the entire living space (including all stories). If one section of the house can be reasonably isolated from the remainder, and if only that portion is to be ventilated, the area would be that of the one section.

Step V. Calculate total required fresh air delivery capability of the HRV.

Required HRV delivery capability (cubic feet per minute) =

$$(\text{Volume to be ventilated, ft}^3) \times (\text{incremental increase in ventilation, ach}) \times \frac{1 \text{ hr.}}{60 \text{ min.}}$$

For example, to achieve an increase of 0.75 ach in a house of 2,000 ft^2 (roughly 16,000 ft^3 if ceilings are 8 ft high), the HRV must deliver: $16{,}000 \text{ ft}^3 \times 0.75 \text{ ach} \times 1/60 = 200 \text{ ft}^3/\text{min}$

Step VI. Select HRV which can deliver the amount of air required.

HRVs are generally marketed with rated nomimal capacity. However, with the back pressures resulting from the necessary ducting, registers, etc., the actual fresh air flow from an installed unit will generally be less than the nominal capacity. The actual flow reductions will depend on the specific HRV and system design. The actual fresh air flow rates that can be provided under different pressure losses are sometimes given by the manufacturer, or by organizations which test HRV equipment (HVI87, EMR87).

some or all of these factors into account. Efficiency figures not correcting for these factors will generally be higher than the figures that do make these corrections. Efficiency figures including these corrections give a more meaningful indication of the actual energy cost savings that can be expected from use of the HRV. Thus, anyone comparing alternative HRV units should do so based upon efficiencies which include these corrections. Such corrected efficiencies for some specific units are reported by the Home Ventilating Institute (HVI87) and by the Canadian Department of Energy, Mines and Resources (EMR87).

For the recovery of sensible heat during cold weather, HVI and EMR define what is termed the Sensible Recovery Efficiency (SRE), which includes all of the corrections listed previously. For a dozen different HRV units which have been tested to date under the HVI and EMR program, SREs have ranged between 50 and 80 percent when the outdoor temperature is sufficiently high (32°F) that the preheat coil on the fresh air inlet is not activated. At extremely low temperatures (−13°F), when the coil is activated, the electrical energy penalty for operating the coil reduces the SRE to 40 to 75 percent (with the impact on the efficiencies of some individual HRVs being reduced significantly). In a separate field study conducted on a number of HRVs several years ago (Of82), where corrected energy recovery efficiencies were determined, the average efficiency was 56 percent.

For the recovery of sensible and latent heat during hot and humid weather, HVI and EMR define the Total Recovery Efficiency (TRE). The TRE accounts for moisture removal from the incoming fresh humid air, as well as for sensible energy recovery. Of two units with moisture recovery tested under the HVI and EMR program, the TRE of each was 67 percent (HVI87). Because the latent heat of airborne moisture is very important in determining TRE (and in determining air conditioning costs), HRVs not recovering moisture have low TREs (33 percent for the one unit reported). Units without moisture recovery would not be a good selection if the HRV is expected to be used during hot, humid summers.

Configuration of HRV ductwork. The configuration of the ductwork for a fully ducted HRV can have a significant effect on radon reduction performance. The configuration can influence, among other things, the degree of reduction in different parts of the house, and the radon reduction mechanisms which come into play. Figure 3 shows one possible configuration, but others might be preferable in various circumstances.

The HRV unit itself (the core and the fans) can be located in an inconspicuous part of the house—such as an unfinished basement or utility room—in an effort to minimize visual impact. The HRV should be located to simplify the ducting runs which might be necessary to different parts of the house.

Four runs of ducting effectively connect to the HRV:

1. The fresh air intake ducting, which brings cold (or hot) outdoor air through the house shell and into the HRV core. (This duct should be insulated.)
2. The fresh air supply ducting, which delivers the warmed (or cooled) outdoor air to one or more points throughout the house.
3. The return air duct, which withdraws warm (or cool) stale house air from one or more points throughout the house and brings it to the HRV core to warm (or cool) the incoming fresh air. In some cases, this return "duct" is simply a register in the side of the HRV housing.
4. The stale air exhaust, which blows the cooled (or warmed), stale air out through the house shell. This duct, in particular, must be insulated so that the cooled air does not regain heat from the house across the duct wall.

There are several considerations in the positioning of these ducts.

- The registers where fresh air is supplied must generally be well removed from the stale air return air registers, so that good circulation of air is achieved. If the supply and return registers are too close, an unacceptable amount of fresh supply air might short-circuit into the stale air return, thus reducing ventilation effectiveness. For example, if the supply and return ducts are on the same story, the supply might be on one end of the house and the return on the other. Alternatively, the return might be in the middle, with a supply register on either end. If the return is on one story (the basement, for example) and the supply registers are on (or partly on) another story (such as the upstairs), then the upstairs supplies might be on opposite ends of the house, and the return downstairs might be remote both from the door between upstairs and downstairs, and from any downstairs supply registers.
- In houses with basements, the stale air return is commonly in the basement. The fresh air supply might be: all upstairs, all in the basement, or partially upstairs and partially in the basement. Upstairs-only delivery will sometimes be preferred in houses without central forced-air furnaces when the upstairs is the primary living area; as shown in Section 3.2.3, delivery upstairs might pressurize the upstairs relative to the basement, further reducing ra-

don levels upstairs. If the basement is also important living space (or if the house has a forced-air furnace), one of the other two supply configurations will sometimes be preferred. Some investigators are considering a configuration for basement houses where the stale air return is upstairs, and the fresh air supply is entirely in the basement, in an effort to pressurize the basement.

- The fresh air supply registers should be placed in an effort to avoid drafts which could cause discomfort. Possible register locations to minimize drafts include ceilings or high on the walls (NCAT84), or perhaps in closets (Br87).
- Some vendors suggest that stale air return points should be located near the more serious potential radon entry routes, with the intent of sucking the radon into the exhaust. This approach might or might not be helpful. The localized depressurization caused by the return line could exacerbate soil gas influx through the problem entry routes, with possibly undesirable effects.
- The fresh air intake and stale air exhaust ducts should penetrate the house shell at least 6 ft apart (NCAT84, Bro87a), in order to reduce the entrainment of stale exhaust air back into the fresh air intake. If possible, these two penetrations should be on opposite sides of the house, not only to eliminate re-entrainment, but also to avoid house depressurization when the one side of the house becomes the downwind (low-pressure) side.
- The intake and exhaust penetrations should be located where they will not be blocked by snow or leaves, and so that automobile exhaust will not be entrained in the intake. The penetrations should be designed to prevent precipitation, debris, bugs, or rodents from entering.
- The stale air discharge should be a reasonable distance from a window or door that might be opened, to avoid flow of the exhaust air back into the house.
- The intake and exhaust ducts ideally should have a straight run of sufficient length (about eight duct diameters, if possible), to facilitate accurate measurements of inlet and outlet flows, for the purpose of balancing the HRV. However, sufficiently accurate measurements can be made by suitable traversing of the duct if such a straight run is not practical.
- Where the house has a central forced-air furnace, the existing furnace supply ducting can be considered for use as the supply ducting for the HRV. In such a case, the warmed (or cooled) fresh air leaving the HRV would be blown into the existing furnace supply ducting, and thus distributed throughout the house. Use of the existing ducting could significantly reduce the cost of installing the HRV.
- Manufacturer's recommendations should be followed.

Balancing the HRV. It is important that the flow rates in the fresh air intake duct and the stale air exhaust duct be equal. If they are unequal, the imbalance must be in the direction of intake flow exceeding exhaust flow, to pressurize the house (although this would reduce the desired warming or cooling of the fresh air). If the exhaust flow is greater than the intake, the house could be somewhat depressurized by the HRV system. Even if the fresh air and exhaust have the same nominal capacity, flows will not automatically be equal, because the fresh air side will commonly see a larger pressure drop in the form of longer duct runs in the fresh air supply ducts.

Balancing is checked by measuring the flows in both the intake and exhaust ducts. Standard procedures exist for making these measurements, involving the measurement of flow velocities across the cross-section of each duct. Where ducts are short and have elbows, velocity measurements at multiple points across the cross-section are particularly important, since the flow patterns in such ducts are skewed. If the flows are not initially in balance, they are balanced by adjusting a damper in one or both ducts.

It is important that the balancing be done when winds are calm (or, at least, are representative of prevailing wind conditions around the house). Since wind speed and direction can influence the air flows in the ducts (and hence the balance), it is important that the balancing not be performed when wind conditions are atypical.

3.2.5 Operation and Maintenance

Whenever the weather is sufficiently mild that the furnace or air conditioner is not operating—and whenever windows can be opened—it is suggested that the homeowner open the windows to implement natural ventilation. Effective natural ventilation will generally provide greater reductions than will an HRV, because the natural fresh air inflow will be greater, and because the stack effect compensation mechanism comes into play. Whenever windows are opened to any significant degree, the HRV might as well be turned off, since its contribution to ventilation will probably be limited. The cost of electricity involved in continued operation of the HRV while windows are opened is small, but turning the HRV off when it is not needed might prolong the lifetime of the unit and reduce maintenance costs. In addition, fan noise would be stopped.

As discussed in Section 3.2.2, a homeowner might also consider opening windows (and turning off the HRV) in some cases even when the furnace or air conditioner is operating, when the outdoor temperature is only slightly above or below house temperature. This approach sustains an increased heating or cooling cost penalty to achieve the higher radon reductions from natural ventilation. The decision regarding when (or whether) to open windows and turn off the HRV under these circumstances rests with the homeowner.

Vendors often suggest that the HRV be operated at low fan speed, because the heat transfer is somewhat more effective at the lower flows, and because fan power consumption is reduced. From the radon reduction standpoint, though, the higher fan speed (hence greater ventilation) would be expected to yield larger reductions. However, this is not necessarily ensured, since mechanisms other than dilution can sometimes come into play when the fan speed is increased (He87a). If it is intended that the HRV be operated on high speed to obtain the maximum ventilation, the heat recovery efficiency and power consumption at high speed should be used in the cost-effectiveness calculations (Table 8).

Maintenance of HRVs is very important if they are to remain in balance. Often, both the intake fresh air ducting and the stale house air return ducting will include filters to remove dust (to protect the core from plugging and, in the case of the intake ducting, to remove pollen and other outdoor dust). These filters must be periodically (e.g., semi-annually) replaced or cleaned to prevent dust buildup from inhibiting flow, changing the balance, and reducing the amount of ventilation. In some exchanger designs, the core itself is designed to be removed and cleaned. Another key maintenance requirement is to keep the intake openings and exhaust vents through the side of the house clear of snow, leaves, and other debris.

In some HRVs, moisture in the exhausted house air can condense and freeze inside the unit in particularly cold weather (Fi83b, NCAT84), reducing heat recovery efficiency and potentially affecting balance. Some HRV designs include an electric resistance preheat coil which automatically heats the incoming fresh air when the temperature drops too low, to avoid ice formation. (This preheat decreases the overall energy efficiency of the HRV.) Where ice buildup does occur, the HRV operation must be temporarily stopped for a period to permit defrosting. In HRV designs that do not include a preheat coil, automatic defrost capability is often built in. The defrost mode can consist of the intake air fan's shutting off, so that the warm house air exhaust operates alone until the ice has melted (NCAT84). Such periodic switching to the defrost mode not only reduces the overall heat recovery efficiency of the HRV, but, depending on the design of the defrost system, can also have the HRV operating periodically as an exhaust fan—depressurizing the house and potentially increasing soil gas influx. In some HRVs the homeowner must be alert to the frost buildup, and must manually turn off the device (or turn it to the defrost mode).

In some HRVs, the fans require periodic lubrication, and belts need to be replaced. In addition, the fans will occasionally have to be replaced. One estimate (NCAT84) indicates that good-quality HRV fans might be expected to last from 5 to 7 years under continual operation.

To ensure continued balance of the HRV inlet and outlet streams over the long term, it might be desirable to have the balance checked and adjusted periodically. (The filters and core should be cleaned before any rebalancing is done.) An experienced service representative (e.g., from the firm which initially installed the HRV) would have to visit the house to measure the balance, resulting in a service charge. Some sources suggest that rebalancing, as part of a general servicing of the HRV, be conducted annually (EMR85).

Many HRVs include one or two condensate drains, to remove water from the core. This water results from condensation out of the house air that is exhausted during the winter, or out of the incoming outdoor air during the summer; it can also result from rain or snow in the incoming air. The condensate drains must be checked and cleared, if necessary. Buildup of water inside the core, as the result of a clogged drain, could interfere with proper operation of the HRV.

3.2.6 Estimate of Costs

The initial cost of the HRVs recently reviewed by Consumer Reports (CR85) ranged from about $500 to $1,200 for five different ducted units (able to deliver between about 25 and 130 cfm)—*not* including installation. The uninstalled capital cost was roughly $400 for the two approximately 50 cfm wall-mounted units tested. The total cost of the ducted units *with* installation will vary depending on the extent of the ducting required, and the difficulty in installing the ducting (e.g., the amount of ceiling, floor, and wall finish that might be affected). However, it is estimated that the total installed costs of the ducted units (delivering up to 150 to 200 cfm) would likely range between $800 and $2,500. The installed cost would be at the lower end of this range when one of the less expensive HRVs was installed using the existing supply ductwork for a central forced-air furnace, so that the cost of installing new ductwork would be reduced. Costs could potentially come down if HRVs find a larger market.

If more than 150 to 200 cfm of ventilation were desired using HRVs, capital costs would be higher. A review of the cost of 300 cfm (nominal) HRVs from several vendors indicates that the uninstalled costs of such units vary from 25 to 50 percent higher than the cost of 150 cfm units from the same vendor. Thus, doubling the ventilation rate by using a single larger HRV would appear to increase the capital cost by roughly 25 to 50 percent (or perhaps less, depending upon how installation costs are affected by the larger unit). If the ventilation rate were doubled by installing two 150 to 200 cfm units, installed costs would roughly double over the cost of a single 150 to 200 cfm unit. When multiple HRVs are installed in one house, it is common that each unit ventilates a different part of the house, and each has its own ductwork system. Thus, it would be expected that the installed cost would increase in direct proportion to the number of HRVs installed.

The primary operating cost of an HRV will consist of the heating and cooling penalty associated with the ventilation. This penalty will be only a fraction of the penalty sustained when the ventilation is conducted without heat recovery. If the HRV is 50 to 80 percent efficient, the heating and cooling penalty with the HRV will be only 20 to 50 percent of the penalty without heat recovery. Other operating costs associated with the HRV are for the power required to run the fans, periodic filter replacement, and fan repairs. The power required to operate two 200 cfm (nominal) fans (intake and exhaust) in a 150 to 200 cfm unit might be about 150 W. Assuming typical electricity costs of about 7.5 cents per kWh and operation for 3,000 hrs per year (about 4 months' continuous use), the annual cost of electricity would be about $30. It is estimated that roughly half of this electrical energy might be recovered in the form of heat in the fresh air intake stream. The costs of filter replacement and fan replacement will be very unit-specific. For one line of HRV equipment, replacement filters cost $7 apiece.

If the HRV is given a general servicing by a trained technician each year, this servicing could add perhaps $50 or more to the annual costs.

Section 4

Sealing of Radon Entry Routes

The term "sealing," as commonly used, can have two 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. Such a barrier is intended to prevent the convective movement (and sometimes the diffusive movement) of 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.

The purpose of the entry route treatment determines whether true sealing is required, or whether simple closure is sufficient. True sealing is required when sealing by itself is used with the intent of bringing high-radon houses down to guideline levels. True gastight seals are difficult to establish and maintain. Simple closure is generally sufficient when the purpose is to prevent house air from flowing out through the entry route when suction is being drawn by an active soil ventilation system (see Section 5). Large amounts of house air leakage into the soil suction system would 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 needed. 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 is not justified for the purpose of reducing leakage into active soil ventilation systems.

The types of entry routes that can be addressed for sealing or closure are listed in Table 4 of Section 2.2. The nature of the entry routes can depend upon the house substructure.

For the purposes of this discussion, soil gas entry routes are divided into two categories: major and minor. Major routes include areas of exposed soil inside the house, sumps, floor drains, French drains, and uncapped top blocks in hollow-block foundation walls. These routes can be major sources of soil gas entry, and will have to be closed or sealed in some manner as part of any mitigation strategy. Minor routes are small routes, such as hairline cracks and the pores in block walls. Collectively, minor routes can be very important sources of radon in the house. However, they do not necessarily always have to be sealed as part of mitigation; for example, active soil ventilation systems can be successful without minor routes being sealed. If minor routes are to be treated by sealing, they will require a true gastight seal if the treatment is to be effective.

Even if a total house sealing effort is not planned as the sole mitigation approach, a reasonable effort should be made to ensure that the necessary sealing or closure of a major entry route is in fact a true gastight seal. The discussion of major routes in Section 4.1 describes such true sealing. However, these entry routes are generally such important isolated radon sources that some meaningful radon reduction might be achieved even if it is not practical to establish a gastight seal.

If an attempt were to be made to reduce radon levels below 4 pCi/L in a house with high radon levels using sealing techniques alone, it would be necessary to apply a permanent, gastight seal over every soil gas entry route. Special care would be required to ensure that the major routes were sealed to be gastight. Also, the minor entry routes such as hairline 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 be sealed, possibly requiring partial dismantling of the structure. Because entry routes are numerous with many being 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 is not felt to be a viable technique by itself for treating houses with high radon levels. At present, it appears that homeowners will generally be best served simply by doing the best reasonable sealing job on the accessible major entry routes—and by then moving on to some other approach if that level of sealing does not give adequate reductions.

4.1 Sealing Major Radon Entry Routes

For purposes of this discussion, major entry routes are here defined as those house construction features that offer the potential for infiltration of significant quantities of soil gas to the indoor air. Estimates of the infiltrating soil gas contribution to total infiltration range from 1 to 5 percent for Swedish basements (Er84) to 30 to 63 percent for air infiltrating from crawl spaces (Na83). As identified in Table 4 and in Figure 1 of Section 2, major entry routes are:

1. Earthen floors in basements and crawl spaces,
2. Basement sumps, especially those connected to drainage tiles, or weeping tile systems located under basement slabs or which serve as perimeter footing drains,
3. Floor drains, especially those that discharge to below-grade dry wells,
4. Perimeter (or French) drains in basements formed by temporary construction forms placed at the floor/wall juncture, and
5. Uncapped top blocks in hollow-block walls.

4.1.1 Sealing Exposed Soil or Rock

Exposed earth and rock (as in basement cold rooms, non-functioning water drainage sump areas, or in crawl spaces) are areas that should be considered for excavation of fill and replacement with a concrete cap. Figure 4 shows an example of the preparation and layering of fill material, sand bed, 6 mil polyethylene sheet vapor barrier, and concrete cap which has been used successfully to form a radon impermeable barrier (Ta86, Ta85a, Ch79, Er87). Figure 4 indicates that great care must be taken to ensure that a seal is obtained between the concrete cap and the existing slab and the wall. Section 5.2 provides specific guidance concerning the sealing of functional water drainage sumps that may also be used to produce sub-slab ventilation for the removal of soil gas.

4.1.2 Sealing of Drains and Sumps

Perhaps the most commonly noted radon entry locations are floor drains and sumps that are connected to drainage or weeping tile systems in the soil beneath or surrounding the house. Radon can readily enter the house if there is not a functional water trap to isolate the tile systems or sumps from indoors. Therefore, rebuilding the system so that it includes a water trap is often an effective measure. In many instances, water is directed into the trap at a slow rate to ensure that the trap remains full of water. A cost of $500 to add a water trap to a floor drain and $1,500 to add a water trap to and modify a sump has been estimated (Fi84). Refer to Figure 13 for an example configuration for a trapped sealed sump.

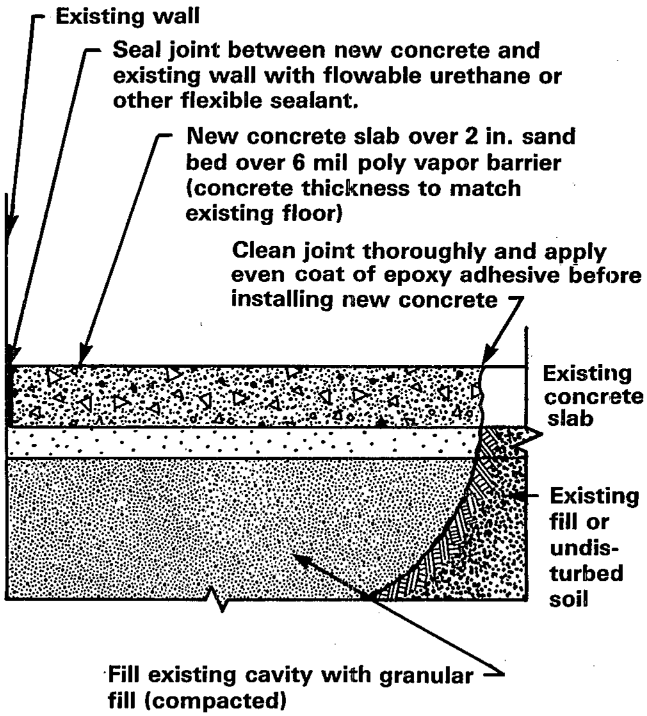


Figure 4. Cavity fill detail.

Recent development of waterless trap drain covers offers another approach to sealing drains and sump covers. Design of the Dranjer floor drain assembly is shown in Figure 5. The check valve design is intended to provide for an airtight seal prohibiting the entry of soil gas into the house when the drain is not working. While it is known that airtight seals on drains may reduce indoor radon concentrations by an average of 46 percent (Du85), specific performance data for the above design are not now available. It is obvious that the check valve design counts on a clean seating of the ball and seat for airtight sealing against soil gas radon entry. The cost of the Dranjer unit not including installation has been advertised as $22.50.

4.1.3 Sealing of Perimeter (French) Drains

Perimeter or French drains are a common construction feature in many houses being mitigated as part of EPA's Radon Mitigation Demonstration Program. In most cases, the perimeter drain feature has not been functional or needed for control of basement wall water seepage; nevertheless, a method for sealing this potential radon entry route while preserving its water drainage function has been addressed by EPA researchers as part of the

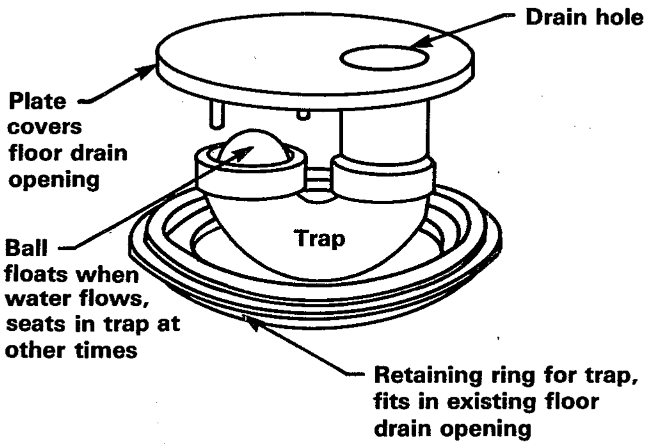


Figure 5. One design for a waterless trap (Dranjer™).

New Jersey Piedmont Diagnostic Mitigation Study (Ma87, Se87) and work in New York State (Br87). Figure 6 is a schematic drawing of the closure that has been provided for selected houses.

Apart from obvious radon entry reduction benefits, the perimeter drain sealing provides a reduction in indoor air losses to sub-slab or wall ventilation systems and ensures better communication between wall and sub-slab areas for extended soil gas collection by either type of active soil gas collection system. It is important to note with reference to Figure 6 that sealing of the perimeter drain of itself may only be effective for reducing indoor radon concentrations if the other possible entry routes—for example block-wall faces and mortar joints—are sealed as well.

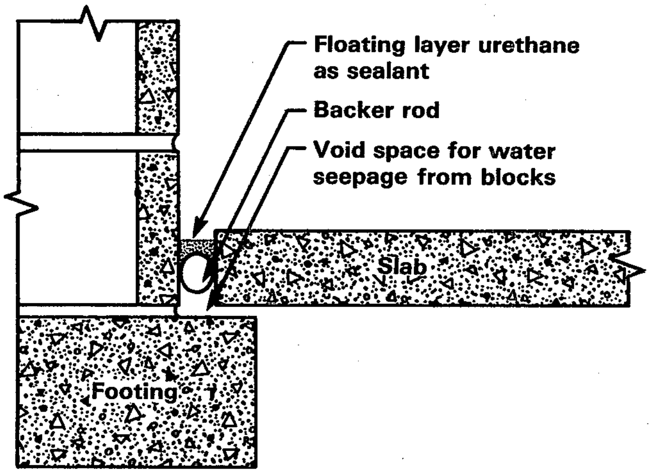


Figure 6. Perimeter drain sealing.

4.2 Sealing Minor Radon Entry Routes

4.2.1 Principle of Operation

Sealing of minor radon entry routes into a house relies on the same principle of operation as for major entry routes—namely, the physical separation of the source from the house interior by a gastight sealant or gas impermeable barrier.

For purposes of discussion, minor entry routes are defined as those breaks, whether designed or caused by deterioration, that allow soil gas to enter the indoor air. Examples of these breaks are cracks in substructure walls or floors, gaps around pipes, and utility services entering the house below grade. In some houses constructed with hollow block walls, the inherent porosity of the masonary block may provide for radon soil gas entry. The discussion that follows will focus on the use of techniques and sealants which are available for closing with an airtight seal—that is, sealing cracks, large and small, and pore spaces in certain substructure components.

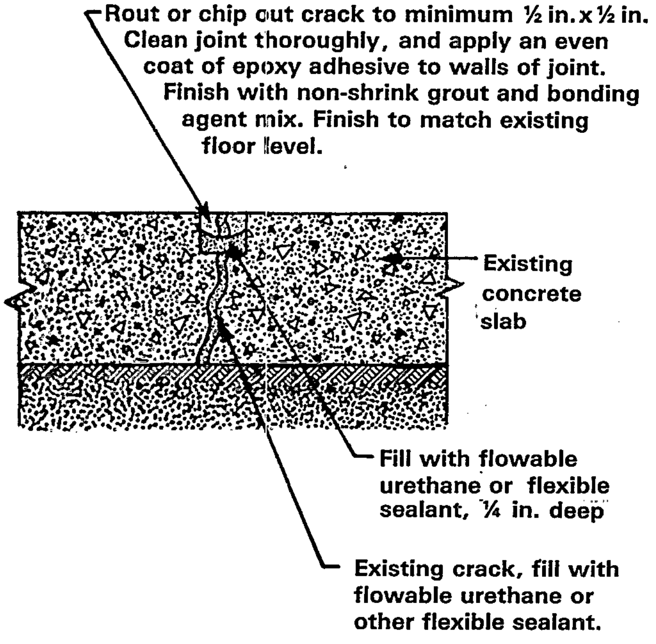
Several types of sealants are available. High viscosity materials (such as caulking, foams, and asphaltic substances) are commonly available to prevent infiltration into the living area. Lower viscosity substances (such as paints and flowable polymers) may also be used to seal small openings such as pores. Films or sheets of gas-impermeable materials are useful when large flat surfaces are to be covered.

A significant limitation in the use of sealing as a radon reduction technique is that bonding between the sealants and the appropriate surfaces is difficult to make and maintain. Substructures move slightly (sometimes significantly) during their lifetime (Ne85). These movements open new paths for gas flow into the house, and reopen old ones which must then be resealed. Most sealants harden and/or deteriorate with age and cracks develop in what was once a gastight seal, thus requiring resealing. Therefore, the choice and application of sealants require careful attention if they are to be effective and not give a false sense of protection against radon.

4.2.2 Applicability

The practical application of sealing is limited by the ability to identify and access soil gas entry routes in a house. In existing houses, this limited access to the total surface area of soil gas exposure is a major impediment to a completely successful sealing program. Also, settling foundations and flooring cracks open new entry routes or reopen old ones, lowering the effectiveness of the sealed system. As a first step in sealing against soil gas entry, the surfaces in contact with the soil must be thoroughly inspected for cracks, breaks, or pipe and drain pass-throughs. The porosity of the surface itself must be considered also. For example, a 4-in. poured concrete surface may be considered impermeable to soil gas, but a cinder or concrete block should not be considered impermeable. Mortar joints must also be inspected as suspected soil gas entry routes.

Once entry routes are identified and classified, plans for ensuring proper bonding between the sealant and the surface begin. Improper bonding or bonds which fail lead to a false sense of confidence in the sealing system. Two considerations are involved here. First, the surface that is to bond to the sealant must be properly prepared. This usually requires cleaning and removing all loose material such as dust and loose mortar. Some sealants require additional surface preparation using specified substances. These depend on the sealant type and are described in the application instructions. Surface preparation for proper sealant bonding is always necessary. Secondly, if a caulk, paint, or similar sealant is to be used, then entry routes must be widened enough to allow sealant penetration into the opening to ensure proper bonding. Again, sealant instructions list specific dimensions. Figures 7, 8, 9, and 10 are examples of application of sealants to floor cracks, poured concrete wall cracks, openings around pipes in slabs, and floor/wall joints (adapted from Ta86).

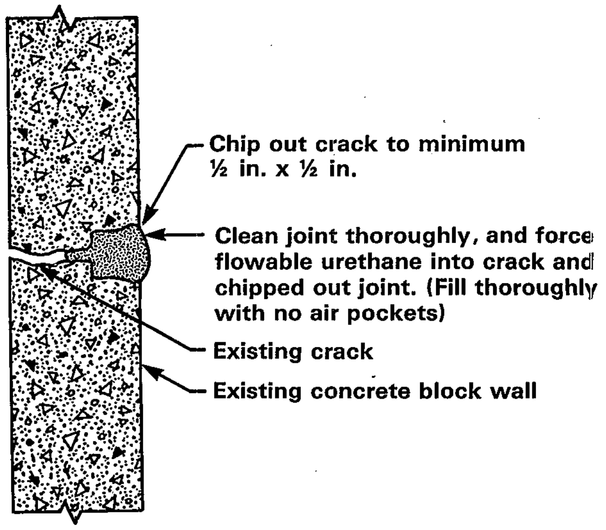

Rout or chip out crack to minimum ½ in. x ½ in. Clean joint thoroughly, and apply an even coat of epoxy adhesive to walls of joint. Finish with non-shrink grout and bonding agent mix. Finish to match existing floor level.

Existing concrete slab

Fill with flowable urethane or flexible sealant, ¼ in. deep

Existing crack, fill with flowable urethane or other flexible sealant.

Figure 7. Crack fill detail.


Chip out crack to minimum ½ in. x ½ in.

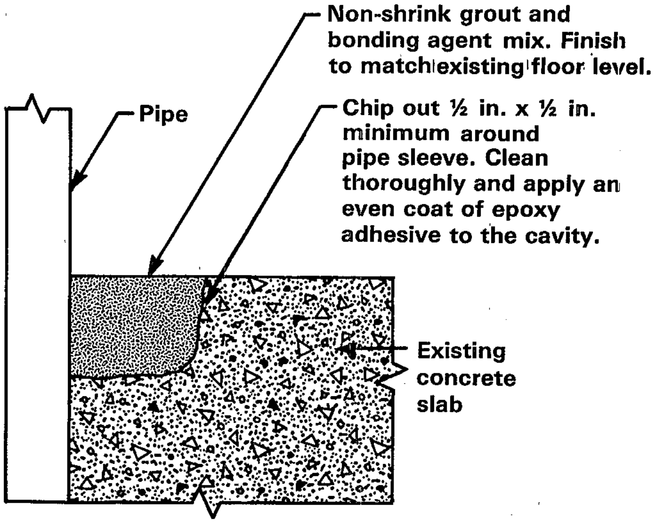
Clean joint thoroughly, and force flowable urethane into crack and chipped out joint. (Fill thoroughly with no air pockets)

Existing crack

Existing concrete block wall

Figure 8. Crack fill detail in concrete block wall.

The rate at which pliable sealants age depends on environmental factors such as temperature and relative humidity. This aging process ultimately decreases sealant ability to block out soil gases. The length of time to failure of the sealant depends on the composition of the sealant as well as the environmental variables. This information must be considered in the choice of sealant material. Table 13 presents the expected service life of some common sealants (SCBR83). All sealants are susceptible to failure due to mechanical stress. Pliable sealants such as silicone caulks are generally more tolerant than sealants such as paints and rigid foams.


Non-shrink grout and bonding agent mix. Finish to match existing floor level.

Pipe

Chip out ½ in. x ½ in. minimum around pipe sleeve. Clean thoroughly and apply an even coat of epoxy adhesive to the cavity.

Existing concrete slab

Figure 9. Pipe penetrations in slab.

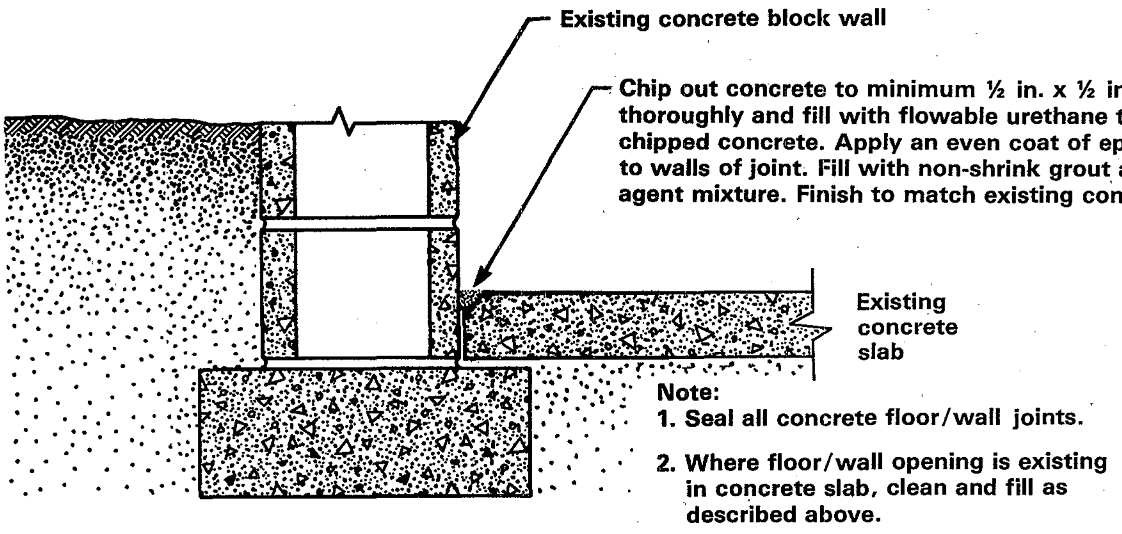


Figure 10. Floor and wall seal detail.

Table 13. Expected Service Life of Various Sealing Materials*

Type of Sealing Material	Documented Test Period, Years	Expected Service Life, Years
Polysulfide	16	22
Silicone rubber	8	15
Polyurethane (2-component)	7	10
Butyl rubber	13	15
Acrylic plastic	13	15
Acrylic polymer	7	15

*Assuming that the material is correctly produced, is fully processed, and is not subjected to excess loading within its area of application. The figures given for the calculated service lives can be considered the minimum, based on values from practical experience.

Reference: Swedish Council of Building Research (SCBR83)

Sealants are economical candidates for supplements to other radon reduction efforts, since many are already mass-produced for the homebuilding industry. In some circumstances where indoor radon levels need lowering only slightly, they may serve adequately by themselves. Sealants have been used to mitigate houses with indoor radon concentrations up to 70 pCi/L (Ho85, Ni85).

4.2.3 Confidence

The primary factors limiting confidence in the use of sealants are that they may not perform adequately (i.e., they may not produce a gastight seal to begin with or they may fail over time) and that other unidentified radon entry routes may overwhelm the reduction achieved by the sealant system. The former limitation has already been discussed in this section. Choice of the radon reduction efforts must take into consideration the house as a complete system, with consideration of all potential radon entry routes.

Sealant test results are available from a wide variety of sources including laboratory studies and field tests. Some results have been obtained from comparative studies, while others are from sealant-specific studies. Some results refer to infiltration measured through a wall, while others are composite measures of the effectiveness of household radon reduction projects. For example, the potential effectiveness of sealing as the sole means of reducing indoor radon concentration has been demonstrated to vary from 30 to 90 percent (Ni85, Sc83). This wide range of total reduction emphasizes the uncertainty of successful control with similar sealing efforts in apparently similar house situations. At present, test results for sealants must be examined critically in order to determine their relevance to a particular problem. Appendix A, in Tables A-1 through A-6, presents a summary of sealing and closure remedial actions taken as part of the Elliot Lake, Ontario, remediation effort. According to the Lawrence Berkeley Laboratory Study (Fi84):

- The work described in these tables was performed in two stages. Stage I involved a visual inspection and closing of obvious radon entry routes along with closing of other visible but less obvious entry routes that were indicated to be important in tests (the tests were not described). If the estimated annual average potential alpha energy concentration (PAEC) for the house was still greater than 0.02 WL after completion of Stage I measures, further work was undertaken in a Stage II procedure to identify and seal additional radon entry pathways. Note that the tabulated data are only from houses where the measures were successful (i.e., the estimated annual average PAEC was reduced to below 0.02 WL).

- An examination of the data in Tables A-1 through A-6 indicates that installation of water traps (between drain tile systems and the sump or floor drain) and repair or replacement of the sump can dramatically reduce the PAEC in many houses.
- In most houses for which data were tabulated, cracks and joints were sealed in conjunction with other measures; in the few houses where only cracks and joints were sealed, substantial reductions in PAEC were noted.
- The DSMA data (Tables A-1 through A-6) also show that a combination of sealing techniques is often effective for radon control. The various sealing techniques (in combination or separately) sometimes reduced the PAEC by greater than a factor of 10 and frequently by more than a factor of 3; similarly, large reductions would generally be difficult to achieve by ventilation or air cleaning. As noted above, however, the tabulated data do not include instances where sealing techniques failed. Numerous failures are noted in the literature and generally attributed to radon entry through alternative (often unidentified) locations, failure of sealants to adhere to surfaces, or future cracking of surfaces. In several references, the need for quality workmanship when implementing the various sealing measures was emphasized. The long-term effectiveness of the sealing-based measures has not been documented. Also, the available data are primarily from houses with basements; thus, the effectiveness of these sealing measures in houses with slab-on-grade foundations or crawl spaces is not extensively documented.

Current experience further demonstrates that little confidence should be placed on the sole use of sealants to exclude soil-gas-borne radon from a house. A homeowner should expect that sealing all noticeable cracks and openings will reduce an indoor radon problem by only about half, since anything short of total sealing will simply redistribute the soil gas flow toward the remaining openings.

4.2.4 Installation, Operation, and Maintenance

The goals of sealant installation are to identify all soil gas entry routes, adequately prepare the surface for sealant application, and apply the sealant as prescribed. There are no operation costs. Maintenance includes surveillance of, identifying, and resealing soil gas entry routes.

The first step in sealant installation is to identify and categorize each possible soil gas entry route. Table 14 is a list of soil-gas-borne radon entry routes through walls and floors into houses, categorized for sealant selection purposes.

Next, the sealant materials to be used must be selected from those available. Table 15 is a partial listing of available sealants by category, along with various considerations which relate to their usefulness (Tat87). The information in this table was obtained from sources including manufacturers' literature, laboratory research study reports, and field study reports and is not presumed to be totally inclusive. Work is in progress to develop and extend the information in this table. Considerations specific to a particular house can be weighed using the comparative summary information presented in this table. It should not be expected that any one sealant type will be adequate to seal an entire house against soil gas entry. Some sealants are designed for specific surfaces and conditions, and several types may be required for one house.

Films of radon-impermeable materials may be applied in large sheets or rolls to cracked or porous walls and other large open surface areas. Such applications must be supplemented by caulking or taping at the joints to provide an airtight barrier between the wall and the interior of the house.

Table 14. Soil-Gas-Borne Radon Entry Routes

Route	Category	Example
Block Walls	Pores	Pores in blocks
	Small Cracks	Hairline mortar joint cracks between blocks
	Large Cracks	Large cracks (larger than $1/16$ in. width) Settling cracks
	Design Openings	Expansion joints in floor slab Utility openings through floor Wall and floor joints in footings Open top blocks in basement walls
Concrete Floors	Pores	Porous concrete
	Small Cracks	Hairline cracks in floor slab
	Large Cracks	Large cracks or breaks in floor slab
	Design Openings	Expansion joints in floor slab Utility openings through floor Wall and floor joints in footings

Table 15. Sealant Information

Sealant Name	Sealant Type	Safety Concerns	Application Effectiveness (%)	Cost	Sealant Manufacturer	Information Source
Small Cracks						
Fomofill	One component, bead caulk	—	—	$11/1cf	Fomo Products, Inc.	ATCON86
Geocel Construction 1200	Caulk, silicone	Nontoxic, water-based solvent	—	$2/tube	Geocel Corp.	Ha87 Ma87 Se87
Geocel Construction 2000	Copolymer caulk	Ventilation required during installation	—	$2.50/tube	Geocel Corp.	Ha87 Ma87 Se87
Geocel SPEC 3000	Caulk, urethane	Use respirators w/ organic vapor cartridges	—	$3/tube	Geocel Corp.	Ha87
Sikatop	Nonshrink grout w/binder	—	—	—	Sika Chemical Corp.	Ha87
Sikadur	Nonshrink grout w/binder	—	—	—	—	Ha87
Silastic	Silicone caulk	—	—	—	Wright/Dow Corning	Ha87 ATCON86
Insta-Seal Kit, I-S 550	One component, caulk bead	Ventilation required during installation		$79/2.2cf	Insta-Foam Products, Inc.	Ha87 ATCON86
Handi-Foam, Model I-160	One component, caulk bead	—	—	$89/2.2cf	Fomo Products, Inc.	ATCON86
Large Cracks						
Versi-foam 1	Two component urethane foams	Ventilation required during installation	—	$22/1cf	Universal Foam System, Inc.	Ha87 ATCON86
Versi-foam 15	Two component urethane foams	Ventilation required during installation	—	$220/15cf	Universal Foam System, Inc.	Ha87 ATCON86
Froth Pak FP-180	Two component urethane foams	Ventilation required during installation		$254/15cf	Insta-Foam Products, Inc.	Ha87 ATCON86
Dow Corning Fire Stop Foam Kit #2001	Two component silicone liquid	—	—	1-2lb. kit: $12.75/1cf	Insta-Foam Products, Inc.	Ha87 ATCON86
Insta-Seal Kit, I-S 550	One component, caulk bead	Ventilation required during installation	—	$78/2.2cf	Insta-Foam Products, Inc.	Ha87 ATCON86
Handi-Foam, Model I-160	One component, caulk bead	—	—	$89/2.2cf	Fomo Products, Inc.	ATCON86
Froth Pak Kit FP-9.5	Two component, spray foam	—	—	—	Insta-Foam Products, Inc.	ATCON86
Fomofill	One component, bead caulk	—	—	$11/1cf	Fomo Products, Inc.	ATCON86
Geocel Construction 1200	Caulk, silicone	Nontoxic, water-based solvent	—	$2/tube	Geocel Corp.	Ha87 Ma87 Se87
Geocel Construction 2000	Copolymer caulk	Ventilation required during installation	—	$2.50/tube	Geocel Corp.	Ha87 Ma87 Se87
Geocel SPEC 3000	Caulk, urethane	Use respirators w/ organic vapor cartridges	—	$3/tube	Geocel Corp.	Ha87 Ma87 Se87
Tremco THC-900	Flowable urethane, two-part	Ventilation required during installation	—	$49/1.5 gal.	Tremco	Ha87 Ma87 Se87
Zonolite 3300	Spray foam and fire proofing	Check ventilation requirements	—	—	W. R. Grace and Co.	Ha86
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.	Ma87 Se87
Pores						
Foil-Ray	Reflective insulation	Flammable, non-toxic	99	$0.36/sq.ft tape–$8.50/roll	—	Ha87
Thiocol WD-6	Alkylpolysulfide copolymer (0.102 cm thickness)	Non-hazardous; choking fumes when burned; wear masks, gloves, shield; avoid inhalation	90	—	Thiokol Corp.	Ha87 Ha86
Rock Coat 82-3	P.V.C. copolymer solution (0.127 cm thickness)	Fire hazard, exhaust; wear goggles, gloves	26	—	Halltech, Inc.	Ha86

Table 15 (continued)

Sealant Name	Sealant Type	Safety Concerns	Application Effectiveness (%)	Cost	Sealant Manufacturer	Information Source
Pores (continued)						
Rositron II	Two component furan	—	97	$6.75/gal. ($0.33/sq.ft)	Ventron Corp.	Fr75
HydrEpoxy 156	—	—	94	$7.30/gal. ($0.19/sq.ft)	Acme Chemicals & Insulation Co.	Fr75
HydrEpoxy 300	Two component, water-based epoxy	Self-extinguishing	85	$6.37/gal. ($0.31/sq.ft.	Acme Chemicals & Insulation Co.	Fr75
Aerospray 70	One component	Self-extinguishing	99	$2.96/gal.	American Cyanamid	Fr75
Blockbond	Surface bonding cement w/binder	Check ventilation requirements	—	—	—	Ha87
Shurewall	Surface bonding cement w/binder	Check ventilation requirements	—	—	—	Ha87
Acryl 60	Surface bonding cement w/binder	Check ventilation requirements	—	—	Standard Dry Wall Products	Ha87
Trocal, etc.	Sheeting: polymer, Al-mylar, PVC, polyethylene	—	—	—	Dynamit Nobel of America, Inc.	Ha87
—	Polyethylene terephthalate (0.009 cm thickness)	—	99	—	—	Ha86
Polyester	One component, medium viscosity, unsaturated polyester	Self-extinguishing	95	$2.11/gal. ($0.13/sq.ft.)	Essex Chemical Corp.	Fr75
Saran Latex XD4624	Experimental Saran Latex	—	89	$2.72/gal. ($0.12sq.ft.)	Dow Chemical Co.	Fr75
Design Openings						
Versi-foam 1	Two component urethane foams	Ventilation required during installation	—	$22/1cf	Universal Foam System, Inc.	Ha87 ATCON86
Versi-foam 15	Two component urethane foams	Ventilation required during installation	—	$220/15cf	Universal Foam System, Inc.	Ha87 ATCON86
Froth Pak FP-180	Two component urethane foams	Ventilation required during installation	—	$254/15cf	Insta-Foam Products, Inc.	Ha87 ATCON86
Froth Pak Kit FP-9.5	Two component, spray foam	—	—	—	Insta-Foam Products, Inc.	ATCON86 Ha87
Vulkem	Flowable urethane, 1 part	Ventilation required during installation	—	$10/qt. tube		Ma87 Se87
Zonolite 3300	Spray foam and fire proofing	Check ventilation requirements	—	—	W. R. Grace and Co.	Ha87

NOTE: Inclusion of a sealant in this table should not be construed as an endorsement by EPA of this 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.

Caulking materials are most useful where most surfaces are believed to be impermeable to soil gases. The caulking is then used to seal small or large cracks, joints, or other discontinuities between gas-tight surfaces. In this case, preparation of the existing surface is crucial to the success of the radon reduction effort. All cracks must be enlarged so that proper surface preparation and adequate sealant penetration ensure a good bond with the sealant for a very long period of time. Refer to Figures 7, 8, 9, and 10.

Coatings are most useful where a large surface is believed to be porous to soil gases. Liquid applications, such as epoxy sealants and waterproof paints, are useful for surfaces such as basement walls and floors. Cracks in the surfaces, however, should first be treated with a caulking material as described above to prevent leakage. Coatings are generally more brittle than caulks: they will rupture with small relative motions of their substrates. For this reason, their expected lifetimes tend to be short.

Once candidate sealants have been identified, commercial sources must be located. Table 16 lists sources alphabetically for the sealants listed in Table 15 (Tat87). These sources should be contacted initially for current information, since new sealants (and new applications for old sealants) are being developed rapidly. After this information is evaluated, selection of the sealants to be applied can be completed.

Once sealants have been selected, surface preparation can begin. When paints, caulks, etc., are to be applied, cracks must be widened down to a sufficient depth, so that sufficient surface area around the crack is exposed to ensure a strong bonding. The necessary width varies with sealant composition and viscosity and is specified in the application instructions.

Depending on the type of sealant, further surface preparation will be required. Some epoxy-type sealants require that one component be applied to the surface and the other added for final curing. Some single component sealants require preparation of the surface by applying certain chemicals. As with mechanical preparation, this depends on the sealant to be applied. Surface preparation will require close attention to areas in which more than one category of entry route is to be treated and in which more than one sealant is to be used.

Sealants must be applied according to the manufacturer's instructions. This may be as simple as skilled use of a caulking gun. Applications may, however, require special tools and machinery, as well as skilled personnel.

In order to prolong the effectiveness of the applied sealants, it is helpful to plan for their long-term protection. For example, any puncture in a film applied to a wall will degrade its effectiveness. Paneling could be applied, as long as the nail/staple holes are securely sealed. Caulk strips can be protected from routine traffic patterns.

Sealant applications should be inspected regularly to check that they have not failed from either mechanical causes or degradation.

4.2.5 Estimate of Costs

Many sealing systems can be installed for a material cost of $100 or less. More extensive efforts may cost as much as $500 (Sc83). Additional costs for surface preparation may be necessary for certain sealants. Labor costs will depend on the surface conditions involved, and the mechanical and chemical preparations necessary. In rare instances, these may be the only costs involved.

Table 16. Manufacturer/Supplier Information

Manufacturer	Mailing Address	City	State	Zip	Phone
Acme Chemicals & Insulation Co.	166 Chapel Street	New Haven	CT	06513	(203) 562-2171
American Cyanamid	One Cyanamid Plaza	Wayne	NJ	07470	(201) 831-2000
Dow Chemical Co.	2020-T Dow Center	Midland	MI	48640	(517) 636-1000
Dow Corning Corporation	P. O. Box 0994	Midland	MI	48640	1-800-447-4700
Essex Chemical Corporation	1401 Broad Street	Clifton	NJ	07015	(201) 773-6300
Fomo Products, Inc.	1090 Jacoby Road, P.O.Box 4261	Akron	OH	44321	(216) 753-4585
Geocel Corporation	Box 398	Elkhart	IN	46515	(219) 264-0645
Halltech, Inc.	465 Coronation Drive	West Hill	Ontario	MIE 2K2	(416) 284-6111
Insta-Foam Products, Inc.	1500 Cedarwood Drive	Joliet	IL	60435	1-800-435-9359
Sika Chemical Corporation	P. O. Box 297T	Lyndhurst	NJ	07071	(201) 933-8800
Thiokol Corporation	Box 8296, 930 Lower Ferry	Trenton	NJ	08650	(609) 396-4001
Tremco	10701 Shaker Boulevard	Cleveland	OH	44104	(216) 292-5000
Universal Foam System, Inc.	Box 548, 60001 S. Penn.	Cudahy	WI	53110	(414) 744-6066
Ventron Corporation	150-T Andover Street	Danvers	MA	01923	(617) 774-3100

NOTE: Inclusion of a manufacturer on this list should not be construed as an endorsement by EPA of the manufacturer or the manufacturer's products. This table is not represented as a complete listing of suitable manufacturers. This table is intended only as a partial listing of some vendors known to be marketing sealants.

Section 5

Soil Ventilation

5.1 Overall Considerations for Soil Ventilation

The general principle of soil ventilation is to draw or blow the soil gas away from the house before it can enter. Most commonly, fans are used: a) to draw suction on the soil around the foundation in an attempt to suck the soil gas out of the soil and to vent it away from the house; or b) to blow outdoor air into the soil, creating a "pressure bubble" underneath the house which forces the soil gas away. When fans are employed to ventilate soil in either manner, the approach is referred to as active soil ventilation. The techniques that have been used for active soil ventilation are discussed in the subsequent sections.

It currently appears that some form of active soil ventilation will often need to be part of the mitigation approach for any house where reductions above 80 percent are required. Active soil ventilation is the approach which has most consistently demonstrated very high radon reductions with practical capital and year-round operating costs.

If an active soil ventilation system is operated with the fan in suction, it will be effective only if it is able to maintain soil gas pressure lower than the air pressure inside the house near all of the major soil gas entry routes (as listed in Table 4). Under this condition, if there is any gas movement through those potential entry routes, it should be house air flowing out rather than soil gas flowing in. If the fan is operated in pressure, blowing outdoor air into the soil, it will be effective only if it can maintain air pressure sufficiently high near the entry routes so that soil gas will be forced away. Soil ventilation systems in pressure might also work, in part, by diluting the soil gas with outdoor air before it can enter the house.

To achieve such effective treatment of all of the potential entry routes, the active soil ventilation system requires a suitable combination of the following factors.

- ventilation points located sufficiently close to the entry routes.
- adequate permeability in whatever is being ventilated (the soil and crushed rock underneath the slab, or the void network inside hollow-block foundation walls). With good permeability, ventilation effects will extend to entry routes remote from the ventilation points (i.e., there will be a good extension of the pressure field induced by the fan). Good permeability reduces the need to locate points close to all entry routes.
- fans sufficiently powerful to develop adequate static pressure at the gas flows that are encountered in the system piping. Fans developing adequate suction (or pressure), where the piping enters the slab, wall, or soil, increase the likelihood that the suction (or pressure) will be distributed through the soil or wall voids remote from the ventilation points.
- system piping with a sufficiently large cross-sectional area. The pressure loss in the piping system will be significantly less when the cross-sectional area of the piping is larger. Thus, if the piping is larger, more of the fan's capacity will be productively used in developing suction (or pressure) on the soil, and less will be consumed in simply moving gas through the piping system.
- closure of major openings in the slab and walls. If such openings are not adequately closed, indoor or outdoor air will leak into the suction system through these openings (or air being blown into the soil by a fan in pressure will leak into the house). Fan capacity will be consumed by these leaks, and the fan's ability to maintain the desired pressure field around all entry routes will be reduced.

These factors will be repeatedly addressed in the subsequent discussions of the individual active soil ventilation approaches.

Soil ventilation can be attempted without the use of a fan. Systems without fans are referred to as *passive* soil ventilation systems. Passive systems involve a vertical pipe (or "stack") which rises up through the house, connecting to the soil ventilation points at its lower end and penetrating the roof with its upper end. The intent is that a natural suction will be created at the ventilation points. This natural suction results from the low pressures created at the upper end of the pipe when winds pass over the roofline, and from upward air movement in the pipe caused by buoyant forces when the temperature in the pipe is higher than that outdoors (the same thermal stack effect which exists in the house). Passive systems have the advantage of eliminating fan maintenance and fan noise. However, the amount of suction that they can draw is very limited, and will be essentially zero on days when there is no wind and when it is warm outdoors. As a result, the performance of passive systems can be unpredictable and variable. Consequently, while passive systems are discussed briefly in Section 5.6, the focus of this chapter is on active, fan-assisted soil ventilation.

5.2 Drain Tile Soil Ventilation (Active)

5.2.1 Principle of Operation

Perforated plastic or porous clay drain tiles surround part or all of some houses in the vicinity of the footings. These drain tiles are pipes which are intended to collect water and drain it away from the foundation. Drain tiles will generally be located right beside or just above the perimeter footings, either on the side away from the house (in which case they are referred to as "exterior" drain tiles), or on the side under the house (in which case they might be referred to as "interior" drain tiles or, if the house has a slab, as "sub-slab" drain tiles). Sometimes the interior tiles are not located beside the footings, but extend underneath the slab in different patterns. The water collected in the drain tiles is routed to an above-grade discharge away from the house (if the lot is sufficiently sloped), to a dry well away from the house, or to a sump inside the house (from which the water is pumped to an above-grade discharge).

Drain tiles are located right beside two of the major soil gas entry routes: the joint between the perimeter foundation wall and the concrete slab inside the house; and the perimeter footing region where soil gas can enter the void network inside block foundation walls. Suction on these drain tiles using a fan can be effective in drawing soil gas away from these potential major entry routes, preventing soil gas movement up through the wall/floor joint and up into the void network inside block walls. If the permeability is sufficiently high in the soil and crushed rock under the slab, and in the soil under the footings and beside the foundation wall, there is a good chance that suction on the tiles can extend underneath the entire slab (and along the below-grade face of the foundation wall). The chances of achieving effective treatment of the major entry routes, and of treating the entire slab, are improved when the tiles form a complete loop around the perimeter of the house. Drain tiles provide a convenient, in-place network that enables suction to be easily and effectively drawn over a wide area, particularly where it is usually needed the most.

Drain tile suction, where the tiles drain to an above-grade discharge, is illustrated in Figure 11. A comparable system, where the tiles drain to an internal sump, is shown in Figure 12. In both cases, the drain tiles illustrated are exterior tiles.

Drain tile suction should be one of the first measures considered for any house that has a reasonably extensive drain tile network in place, especially if high levels of radon reduction are needed. The primary advantage of drain tile suction is that it can be very effective. Furthermore, it can be one of the least expensive and least obtrusive of the active soil ventilation techniques if the entire installation is outdoors, as when the tiles drain to an exterior above-grade discharge or dry well. The primary disadvantage of drain tile suction is that many houses do not have a complete drain tile loop, although even a partial loop can be sufficient in some cases.

Pressurization of the drain tiles might also be considered. However, all of the drain tile ventilation experience of which EPA is aware involves use of the fan in suction.

5.2.2 Applicability

Drain tile suction will be most applicable under the following conditions.

- houses which already have drain tiles in place. In theory, drain tiles could be retrofitted around an existing house that did not have them initially. However, in most cases, there will probably be more economical approaches for reducing indoor radon in houses without pre-existing drain tiles.
- houses requiring either high or low degrees of radon reduction. Drain tile suction systems have demonstrated reductions as high as 99 percent in some cases. Thus, this technique can be used in houses requiring high degrees of reduction. However, drain tile suction can, under some circumstances, be installed at a fairly low cost — perhaps as low as $200 to $300 (for the fan, piping, and other materials) in the simpler cases where homeowners can reasonably install the system themselves. With costs this low, this technique might also be considered where only limited degrees of reduction are needed.
- houses having drain tile loops which completely surround the perimeter and which are not clogged with silt. As discussed in the next section, best year-round radon reduction performance is most consistently seen with this technique when the drain tiles form a complete loop around the perimeter. If some portion of the perimeter footing does not include drain tiles beside it — or if the tiles are damaged or blocked with silt — that portion of the

Note:
1. Closure of major slab openings is important.

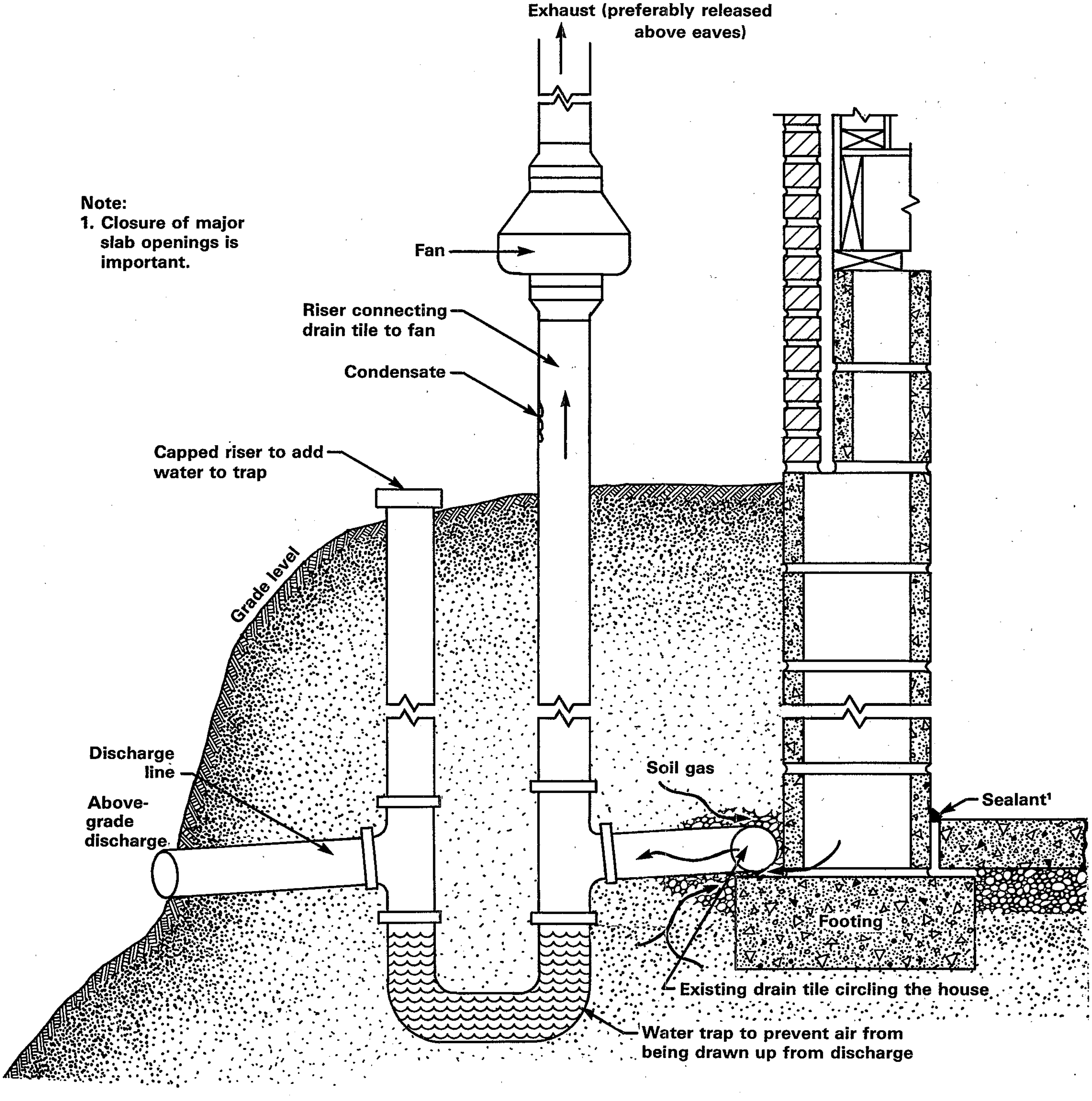


Figure 11. Drain tile ventilation where tile drains to an above-grade discharge.

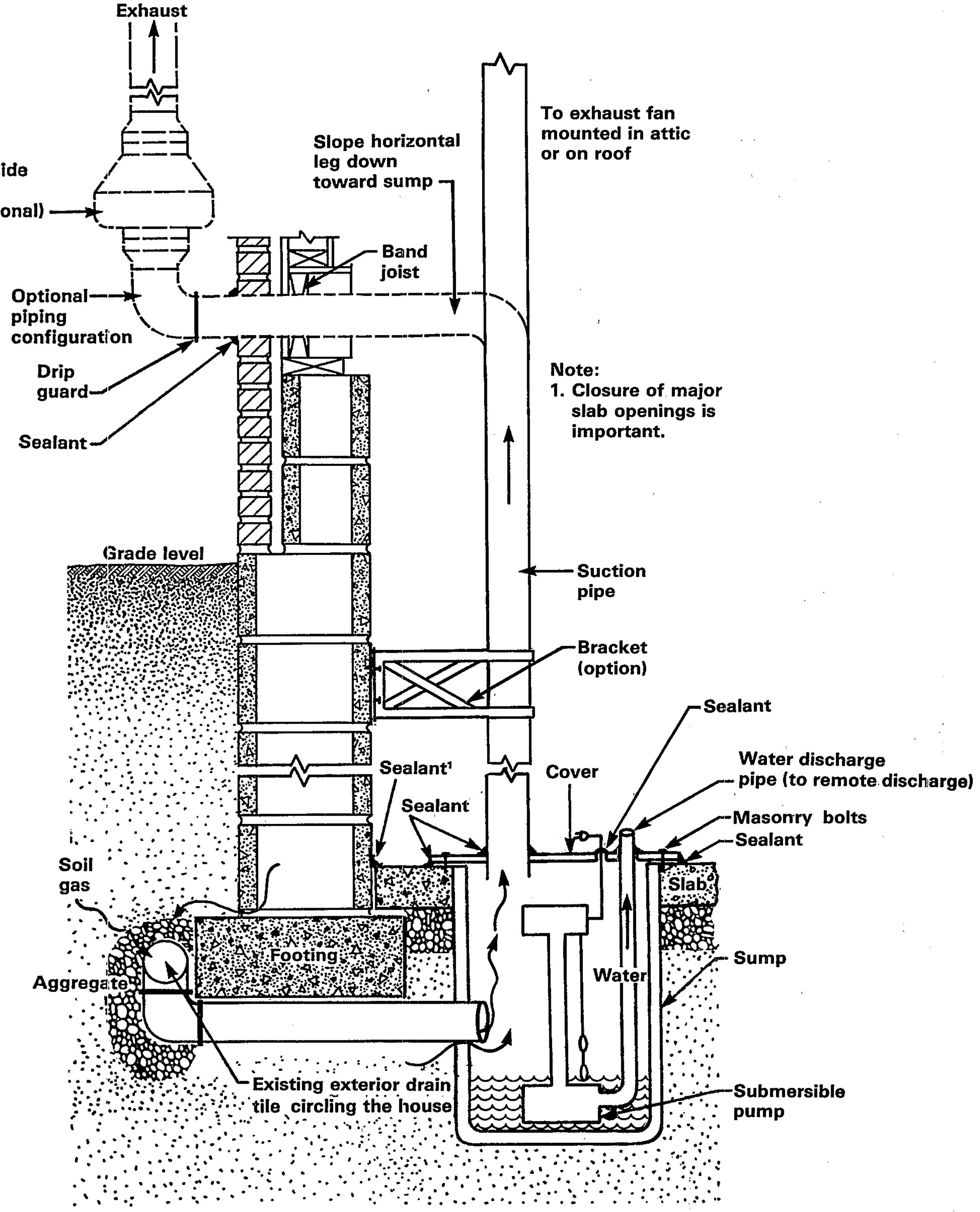


Figure 12. Drain tile ventilation where tile drains to sump.

perimeter might not be effectively treated. However, the results also show that — even where a complete drain tile loop does not exist — moderate to high reductions can sometimes still be achieved. Drain tile suction will be most applicable to houses with partial loops when: a) there is some reasonable length of tile located near the most important potential entry routes; b) the sub-slab and soil permeabilities are good, to improve the likelihood that suction will extend to sections of the slab not having tiles; and c) only moderate radon reductions are needed. The major difficulty in pre-mitigation assessment where drain tile suction is being considered will often be in determining the extent of the drain tile system.

- houses without potential major soil gas entry routes remote from the perimeter walls. While suction on the perimeter drain tiles appears often to extend underneath the entire floor slab — and while entry routes are remote from the perimeter tiles might thus be treated fairly well — the system will experience a greater challenge when entry routes are remote from the drain tiles. Examples of such remote entry routes include: cold joints or cracks in the middle of the slab; block fireplace structures in the middle of the slab which penetrate the slab and rest on footings underneath the slab; and interior load-bearing walls (especially hollow-block walls) which penetrate the slab. EPA's data suggest that — if the perimeter loop is complete, if the sub-slab permeability is good and if the fan performance is satisfactory — drain tile suction systems can produce significant reductions of indoor radon in houses with such interior entry routes. However, the risk of reduced performance is increased.
- houses where the lower level is highly finished living space. If the drain tile suction system can be installed entirely outside the house (or in an unfinished section inside the house where the sump is located), the drain tile system could be cheaper and/or less obtrusive than other approaches that could necessitate modifications in the finished sections.
- houses having concrete slabs, with best performance to be expected when the footings (and drain tiles) are well below grade. If the drain tiles are around a house with an earth-floored basement or crawl space, or are close to grade level, there is an increased chance that outdoor or indoor air will be drawn down through the soil and into the drain tiles by the suction system, thus preventing the suction from effectively extending through the soil. Most of the experience to date with drain tile suction has been in houses having basements with concrete slabs. Drain tile suction might perform effectively in other types of substructures, but data are not available to confirm the performances that might be routinely expected in these other substructures.
- houses where the drain tiles do not become flooded. Flooding would be likely to occur only when the tiles discharge to an exterior dry well which does not drain adequately. If the drain tiles become blocked with water, the suction being drawn by the fan will not be distributed around the tile loop. If the tiles flood, it will sometimes be apparent in the form of extensive water around the foundation during wet weather.

In some cases, there might be some uncertainty whether a given house meets some of the criteria listed above. In particular, it might be uncertain whether the drain tiles form a complete loop or whether some of the tiles are silted shut. In such cases, judgment must be used. If the drain tiles are reasonably likely to go around three sides of the house, or perhaps even less, the advantages of the drain tile suction approach might make it cost effective to try it before attempting a more expensive one, especially if only moderate radon reductions are needed (50 to 85 percent).

Drain tile suction will likely achieve best results most easily where the permeability of the aggregate and soil under the slab (and that of the soil under the footings) is good. The permeability under the slab is important since it determines the extent to which the fan-induced pressure field will extend under the slab, remote from the drain tiles. The permeability of the undisturbed soil under the footings can be important in determining how well suction on exterior tiles will extend to the interior face of the footing (and hence underneath the slab). For interior tiles, the soil permeability can determine how well the suction extends to the exterior face of the footings and the foundation wall. Drain tile suction seems generally applicable even when the permeability is not good. However, when the permeability is not good, radon reduction performance will potentially be reduced (especially for partial tile loops), and more powerful fans will be needed.

5.2.3 Confidence

A number of mitigators have reported experience with drain tile suction systems. The experience of some of these mitigators is summarized below.

The EPA has tested drain tile suction in eight houses in Pennsylvania, where the tiles drain to an above-grade discharge as in Figure 11 (He87b). All houses had basements with hollow-block foundation walls. Five of the houses had exterior drain tile loops which extended essentially all the way around the house. The other three had exterior loops which were not complete, with tiles absent from one or more sides of the house. The initial radon levels in these eight houses ranged from 11 to 230 pCi/L. The results of this testing, as determined by 2 to 4 days of continuous (hourly) radon measurements before and after mitigation, are summarized below.

- Of the five houses with essentially complete loops, four were reduced to average radon levels below 4 pCi/L, generally reflecting radon reductions well in excess of 90 percent (as high as 99 percent in one case). Of these four houses with averages below 4 pCi/L, only one exhibited any individual hourly measurements higher than 4 pCi/L over 4 days of hourly readings.
- The fifth house with a complete loop averaged 7 pCi/L with the drain tile system in operation, representing 97 percent reduction.
- The house having some hourly readings above 4 pCi/L had a hollow-block structure which penetrated the center of the basement slab, resting on footings under the slab, supporting a fireplace on the floor above. The house averaging 7 pCi/L had an interior block wall penetrating the slab. None of the other three houses had such major slab penetrations remote from the perimeter walls.
- All five houses had fans which maintained from 0.7 to 1.3 in. WC suction in the riser from the drain tiles.
- Of the three houses having only partial drain tile loops, the one having a high-suction fan (1 in. WC suction in the riser) achieved 88 percent reduction (falling from 94 to 12 pCi/L).
- The other two houses with partial loops were tested with lower-suction fans (0.15 and 0.4 in. WC in the riser). The reductions in these houses were 74 and 37 percent, respectively.

These results suggest that drain tile suction, of the type illustrated in Figure 11, can give high reductions (often above 90 percent) when a complete drain tile loop surrounds the house. System performance can apparently be reduced somewhat when there is a major soil gas entry route through the slab at a point remote from the perimeter walls, where the tiles are located. However, even with such remote entry routes, reductions above 90 percent were achieved, suggesting that the ventilation effects from the perimeter tiles must be extending under the slab to at least partially treat these potential interior entry routes. Even where only a partial drain tile loop exists, fairly high reductions can sometimes be achieved if a fan is used which can maintain sufficient suction. With full or partial tile loops, performance will be improved when the sub-slab permeability is good, where the fan maintains high suction, and when major slab openings inside the house are closed. With partial loops, the extent and location of the tiles are also important.

The EPA has also tested drain tile suction in three block basement houses in Pennsylvania where the tiles drain to an interior sump, as in Figure 12 (He87b). The extent of the drain tiles draining into the sumps of these houses was uncertain in all three cases. The tiles were probably only partial. The results are summarized below.

- In the one house with a high-suction fan (maintaining 0.5 in. WC suction in the sump), a reduction of 96 percent was observed (reducing levels from 47 to 2 pCi/L). This house also included a crawl space, which was lined and vented (as discussed in Section 5.5) in conjunction with the basement sump suction.
- In the remaining two houses, lower-suction fans (maintaining 0.1 to 0.3 in. WC in the sump), reductions were 43 and zero percent, respectively. The reductions in the house achieving 43 percent could likely have been increased by using a higher-suction fan. The tiles in the house achieving no reduction were probably very limited in extent.

These results with sump suction are generally consistent with the results where the tiles drain to an above-grade discharge. Where the tiles form only a partial loop, high reductions can sometimes still be achieved when a high-suction fan is used, depending on the extent of the tiles and the sub-slab permeability. Some diagnostic effort to assess the extent of the tiles entering the sump would seem to be well-advised before a sump suction system is installed.

In another EPA project in New Jersey, drain tile suction was tested in two split-level houses having a basement with block foundation walls and an adjoining slab-on-grade wing (Mi87). In each house, the tiles drained into a sump inside the basement. From probing the tiles where they entered the sump, each house appeared to have two drain tile loops — one around the outside of the basement footing, and the other around the inside of the footing. A good layer of crushed rock existed under the slabs. In addition to suction on the sumps in the basements of these houses, the mitigation effort also included separate suction underneath the slab of the adjoining slab-on-grade. High suction fans, comparable to the ones used in the Pennsylvania testing, were employed. Radon reductions of 99.7 and 99.8 percent were obtained in the two houses (identified as Houses C30A and C39A in Reference Mi87) which had had pre-mitigation concentrations of 2,250 and 1,500 pCi/L, respectively. These results are based on charcoal canister measurements. While it is not possible to separate the individual effects of the basement sump/drain tile suction and the separate sub-slab suction under the adjoining slab, it is apparent — in view of the very high overall reductions obtained — that the sump suction must have been very effective in treating the basement wings of these houses. The apparently complete double loops of drain tiles, and the very good sub-slab permeability in these two houses, represent ideal conditions for drain tile suction.

Sump suction was also tested in a third New Jersey house having a basement with block foundation walls, with no adjoining slab on grade (House C32D in reference Mi87). Again, it appeared that both an interior and an exterior drain tile loop drained into the sump. Initial reductions with the sump suction system appeared to be about 50 percent, based on several days of continuous radon measurements in the fall. Pressure field measurements under the slab confirmed that suction was not extending to the side of the house opposite the sump hole, explaining the reduced performance. This result appears to illustrate the potential effect of incomplete drain tile loops and/or of insufficient or interrupted sub-slab permeability.

A number of private radon mitigation firms have had experience with drain tile suction. For example, one mitigator has installed a number of drain tile suction systems in moderately elevated basement houses in the Midwest, where apparently complete loops drain into sumps inside the basement. This mitigator reports that initial radon levels of up to 17 pCi/L can be reduced well below 4 pCi/L through suction on the sump (Re87).

Other investigators have also tested drain tile ventilation where the tiles drain to a sump inside the basement. Four houses with such a sump ventilation system were tested in one study (Ni85). One house had a poured concrete basement, another had a concrete block basement, a third had a combination poured concrete basement plus crawl space, and the fourth had a combination block basement plus crawl space. The drain tiles for the last house were known not to extend entirely around the perimeter. The extent of the tiles in the other three houses was not reported. Drain tile/sump ventilation was applied to each house in combination with crack sealing and closure of major wall openings. In the partial crawl-space house, the crawl space was also isolated and vented. Radon reductions of from 70 to over 95 percent were observed in these four houses. The radon levels remained subject to peaks during basement depressurization unless major cracks and openings in the walls and floor (including the wall/floor joint) were sealed (Ni85).

In another study, 80 percent radon reduction was achieved by the use of suction on a partial exterior drain tile system draining away from the structure in a house with poured concrete walls (Sa84).

Active suction on drain tile systems was installed in a number of houses as part of remedial work in several mining communities in Canada. These suction systems, which included drain tiles draining away from the house and also those draining to an interior sump, were reportedly effective. In some of these Canadian results (Ar82), radon reductions of 60 to 80 percent are reported with partial drain tile loops in block basement houses. The details regarding these particular installations are not known (e.g., extent of the drain tiles). In addition, other steps (such as source removal and covering exposed soil and rock) were commonly implemented in conjunction with the drain tile suction, so that the effects of the suction system alone cannot always be separated out.

In view of the above results, the confidence level in the performance of the drain tile suction approach is considered to be moderate to high, if there is a reasonable likelihood that a complete loop of drain tiles exists. The major causes of uncertainty in the performance of this approach are: a) uncertainty regarding the actual extent and location of the tiles in any given house, and the condition of the tiles (e.g., whether they are blocked with silt); b) uncertainty regarding sub-slab permeability, and the consequent ability of the drain tile suction to extend to interior soil gas entry routes remote from the tiles; and c) the lack of long-term (multi-year) experience on the performance of these systems. Some of these uncertainties can be reduced by appropriate diagnostics. If there is not a complete drain tile loop (or if the extent of the tiles is uncertain), then confidence is reduced to no better than moderate. However, significant reductions are sometimes possible with the partial loop, depending on the extent of the tiles and the permeability under the slab.

5.2.4 Design and Installation

5.2.4.1 Installations Where Tiles Drain to an Above-Grade Discharge or Dry Well

Figure 11 shows a drain tile suction system where the tiles drain to an above-grade discharge, and where the tiles are located around the exterior face of the footings. A similar configuration could be considered if the tiles drained to a dry well.

The circle beside the footing in Figure 11 represents the cross-section of a drain tile which, ideally, would form a continuous loop around the entire perimeter of the house. The pipe running from that circle to the above-grade discharge represents the discharge line which taps off from the loop and directs the water collected by the tiles away from the foundation. For drain tile suction to be cost-effective, it will generally be necessary that the drain tile, and the line running to the discharge, already be in place. The drain tile suction system consists of the water trap and the riser(s) (which are inserted into the existing line to the discharge) and the fan. The water trap is required to ensure that the fan effectively draws suction on the drain tiles. Without the trap, the fan would simply draw outside air up from the above-grade discharge point. The capped riser on the left in Figure 11 enables the homeowner to check the water level in the trap and to add water as necessary during dry weather.

Some drain tile systems have more than one discharge line. For example, it is not uncommon for the tiles to be laid in the configuration of a "C," looping around three sides of the house, with both legs of the "C" coming above grade on the downhill (fourth) side as two discharge lines. In such cases, a water trap (but not a fan) must also be installed in the second discharge line, to prevent outdoor air from entering the system through that line.

Pre-mitigation diagnostic testing. Different types of pre-mitigation diagnostics can be considered. Among those which could be particularly pertinent for drain tile suction systems are the following.

- Visual inspection, including:
  - —limited digging around the foundation to assess the extent of the drain tiles and the location of the discharge line.
  - —examination of house construction drawings, if available, since they might indicate the extent of the drain tile system. Also, the homeowner (if present during construction) or the builder might recall the extent of the tiles.
  - —inspection of potential entry routes remote from the perimeter walls, and possible smoke stick testing to evaluate the extent of soil gas influx at those interior routes. (Grab radon measurements in those potential entry routes might aid in assessing their importance.) If this inspection suggests that there is a potentially major interior entry route, then it might be necessary to treat that route separately from the drain tile suction system (perhaps as a second mitigation phase, after the drain tile system has been installed).
- Measurement of sub-slab permeability. Reasonably high permeability increases the likelihood that suction on the perimeter tiles will extend under the slab to treat interior routes, or that suction on a partial drain tile loop will effectively treat the entire slab.

Selecting location for trap and risers. The drain tile suction system is generally installed in the discharge line that leads from the drain tile loop to the above-grade discharge or dry well. The water trap and capped riser *must* be in the discharge line, *not* in the drain tile loop itself. The riser with the fan can be in the discharge line, as shown in Figure 11, or in the tile loop. It is usually most convenient and least expensive to include the fan riser at the same location as the trap, in the discharge line.

The first step is to locate the discharge line, and to dig down to expose the line at the point where the trap and riser are to be installed. Where the pipe discharges above grade, the position of the discharge line can initially be estimated by locating the point at which the line comes above grade, and then visually tracing the likely path of the line from that point back to the house.

The ventilation system can be installed at any point in the discharge line. The advantages of installing the system at a point remote from the house are: a) the risk is reduced or eliminated that high-radon soil gas, exhausted into the yard by the fan, will be carried back into the house; b) the fan noise reaching the house is reduced; c) there can sometimes be less visual impact if the installation is farther from the house (perhaps surrounded by plantings); d) less digging might be required, because the discharge line might be closer to grade level at a remote point; and e) moisture in the exhausted soil gas plume will be less likely to condense and freeze on the house during the winter, or create mildew problems in warm weather. On the other hand, if the system is remote from the house, the long length of discharge line between the fan and the drain tile loop would result in an increased pressure drop through the piping. This pressure loss would make the fan less effective in maintaining suction in the loop around the house, and could thus reduce the system's performance. At the low soil gas flows typically encountered in drain tile suction systems, this pressure loss should not be unduly large over reasonable distances unless the discharge line is partially silted shut or broken between the fan and the house. A greater disadvantage of remote location of the system could result when the discharge line is perforated plastic or porous clay pipe. For such lines, remote location would result in an increased amount of the fan capacity's being consumed in sucking soil gas and outdoor air into the discharge line at points away from the house, where it would not help reduce radon levels in the house. Another disadvantage of remote location of the system is that a long length of electric cable would be required to supply the fan motor with power from the house. Further, the trap must be at a point sufficiently deep underground to keep the water in the trap from freezing during winter, which would prevent proper drainage. The logical distance of the ventilation system from the house will be a site-specific decision but, in many cases, a reasonable distance would be up to 20 ft. Where the discharge line is perforated pipe, the distance would preferably be less.

As mentioned previously, if a drain tile system has two above-grade discharge points, it will be necessary to have a water trap and a capped riser for water addition (but not a fan) in the second discharge line also.

Installation of trap and riser(s). To install the trap and riser(s) after the proper point in the discharge line is exposed, the discharge line must be severed and a section removed so that the trap/riser assembly can be inserted. The trap and riser(s) must be airtight, not perforated or porous like the drain tiles. In addition, all piping connections must be airtight, so that fan capacity is not consumed by air leakage into this piping. In the EPA installations, the trap and riser(s) consisted of 4-in. diameter plastic sewer pipe, a logical choice because the discharge line is commonly about that size. If an in-line fan is used which is designed for mounting on 6-in. pipe, as in the EPA testing, one could also consider using 6-in. plastic pipe for the riser which supports the fan. The larger pipe would offer the advantage of reduced pressure loss in this riser (relative to 4-in. pipe).

The trap can be purchased as a unit or assembled from elbows and tees cemented together. How the trap is fabricated is not crucial as long as it prevents outside air from being drawn up from the above-grade discharge. Where the plastic trap connects to the existing drain tile on either side of the trap, the plastic pipe and the drain tile must be firmly connected (for example, by a clamp over a rubber sleeve). There should be no break that permits silting or otherwise prevents effective suction from being drawn on the drain tile loop.

The riser which supports the fan must be on the house side of the trap. This riser should protrude some reasonable distance above grade level (perhaps 2 to 3 ft) to provide clearance for the fan, and access for fan maintenance.

Although the riser shown on the opposite side of the trap from the fan is optional, it would facilitate addition of water to the trap during prolonged dry weather. Were the trap ever to dry out, the ventilation system would become ineffective, since the fan would then just be drawing outside air up from the discharge. This second riser should extend above ground only far enough for convenient access and should always be capped except when being used to inspect the water level or to add water.

After the trap and risers are installed, the hole should be filled in to cover the trap and the tiles.

If the drain tile loop includes two discharge lines, the trap and fan system shown in Figure 11 is installed in only one of the lines. A second trap (and capped riser) would also have to be installed on the second line, to prevent air flow into the system through that line.

Fan selection and mounting. Any fan can be used which will maintain good suction at the soil gas flows encountered. In the EPA testing in Pennsylvania (He87b), where sub-slab and soil permeabilities were generally not high, best performance was obtained when at least 0.5 in. WC suction was maintained. (Suctions greater than 1 in. WC were sometimes achieved.) Typical soil gas flows at these suctions were 40 to 150 cfm. Actual fan requirements will depend on the site (including sub-slab permeability and air leakage into the system). If the permeability of the sub-slab aggregate and the surrounding soil is fairly high, lower suctions might be sufficient. In general, the greater the suction a fan can sustain at a given flow, the better the chance of high radon reductions.

The fans most frequently used in the EPA testing were 0.05-hp, rated at 270 cfm at zero static pressure, and capable of developing over 1 in. WC static pressure before stalling. These fans cost approximately $100 apiece. Again, smaller fans might be sufficient where the permeability is high.

Whatever fan is used, it should preferably be mounted directly on the vertical riser, without any piping elbows and without any low spots in the fan housing where water could accumulate. Any elbows in the pipe would increase the pressure loss, thus reducing the suction that the fan could maintain on the tiles. Since soil gas moisture will always be condensing in the fan and piping during cold weather, it is crucial that the fan be mounted such that this moisture will drain out of the fan housing and back down the riser. Otherwise, fan performance and lifetime will be greatly reduced.

Figure 11 illustrates the typical fan configuration used in the EPA testing. The fan was designed with a plastic housing which provided effective weather protection, and which was suitable for in-line mounting in 6-in. diameter pipe. Thus, the figure shows the vertical 4-in. riser fitted with a 4-to-6-in. adaptor, with the fan mounted vertically after the adaptor. Mounting the fan vertically on the riser avoids all bends in the gas flow, and permits the condensed moisture to flow down the riser. Other configurations and fan designs can be considered which would accomplish these same objectives.

The fan should be mounted tightly on the riser. Any gaps in the connections between the fan and the pipe should be caulked or otherwise sealed. If the fitting is not airtight on the suction side of the fan, the fan will simply draw outside air through itself and will not draw effective suction on the drain tiles.

The figure shows a section of vertical pipe extending above the fan, so that the exhaust is actually discharged at some height above the fan. The concern is that the high-radon soil gas — which can contain from several hundred to several thousand pCi/L of radon — should be released at a height which will ensure substantial dilution with outdoor air before potentially being inhaled by anyone in the vicinity, and before potentially entering the house around windows. If the fan is remote from the house, structural considerations will probably limit the height of this vertical exhaust pipe to no more than a few feet — enough to place the exhaust above head level —due to the absence of nearby structures against which to support this "stack." If the fan is close to the house, it is recommended that the exhaust pipe be extended up above the eaves, using brackets attached to the house to support the pipe. Extending the exhaust pipe above the eaves will help ensure that the exhausted soil gas does not enter the house through nearby windows.

This exhaust stack will create a back-pressure on the fan, which will reduce the suction that the fan can maintain on the drain tiles (and hence, potentially, the radon reduction performance of the system). The configuration of the fan exhaust for any given house will have to be selected considering trade-offs among performance, appearance, and cost. If a vertical exhaust pipe is installed, the least pressure loss would be incurred if the pipe diameter were the same as (or larger than) the fan exhaust port. This diameter was 6 in. for the fans used in the EPA testing. The aesthetic impact of a 6-in. stack mounted outside the house might be considered unacceptable by some homeowners. Figure 11 shows the exhaust as being a 4-in. pipe, connected to the exhaust port of the fan using a 6- to 4-in. adaptor. This configuration reduces the visual impact of the pipe somewhat, but creates a significant pressure loss as the gas passes through the reducer/adaptor.

One approach that has been used to reduce the visual impact is to use a false rain gutter downspout attached to the side of the house as the "exhaust pipe." Again, there will be pressure loss in any adaptor connecting the fan exhaust port to the bottom of the false downspout. This loss might be reduced by using a large cross-section downspout. Large back-pressures could sometimes necessitate a larger fan. Another option would be to conceal the exhaust pipe by means of exterior finish (e.g., a chase framed around the stack, covered with siding). This approach would add substantially to the cost of the installation. The least back-pressure of all, of course, would result if the vertical riser were eliminated altogether, and the fan discharged the soil gas at essentially grade level. This approach might be considered where the fan is remote from the house, or is on a side of the house having no windows or doors, and is in an area where people will not be spending extended periods of time (such as a patio or play area). A short exhaust riser with a 90° elbow directing the exhaust horizontally away from the house could aid in preventing the exhaust from leaking back into the house.

The ultimate discharge point should be protected with a screen to prevent leaves or other debris from clogging the discharge, and to prevent children or animals from reaching the blades (if there is no exhaust pipe). The exhaust should be sufficiently high above the roofline so that it does not get covered by snow. Entry of rainwater into the exhaust pipe is not a problem as long as water cannot accumulate in the fan housing.

Some mitigators recommended insulating the fan riser, the fan and the fan exhaust piping, to help prevent condensed moisture from freezing in the piping or the fan housing. Extensive ice formation would increase pressure loss in the piping, thus potentially reducing system performance. Ice in the fan housing could interfere with fan operation.

The fan that is used must be designed and constructed for long-term exterior use. The fan's electrical wiring should be according to code.

All experience to date with drain tile ventilation has been with the fan mounted to draw suction on the tiles. It is possible that, at least in some cases, radon might also be reduced if the fan were reversed to blow outdoor air down into the tiles, forcing soil gas away from the foundation. One advantage of such a pressurization approach is that it avoids concerns about the exhaust of high-radon soil gas through the fan. However, the lack of data on the radon reduction performance of such an approach makes it impossible to give guidance at this time regarding how often, and to what degree, the drain tile pressurization approach will be effective. One potential concern, in the absence of data, is that pressurization of the soil in the vicinity of the tiles might force soil gas up into the house at an increased rate through some entry routes. Accordingly, in this document, the drain tile ventilation fan is always shown drawing suction.

Closure of major slab openings. To the extent that there are cracks or other openings in the concrete slab of the house, the drain tile suction system would be expected to draw house air down through these openings. Such movement of the house air through these openings is a result of a successful active soil ventilation (suction) system — where soil gas pressure is maintained lower than the pressure inside the house. If the slab openings are fairly small (e.g., hairline cracks), the amount of house air leakage out through these openings will be minor, and will probably not seriously reduce the radon reduction performance of the system. But if the openings are large — such as French drains, unpaved segments of the house, large cracks, or holes in the concrete exposing soil or rock — large amounts of house air might leak into the drain tile suction system. In these cases, the large amount of house air leakage into the system could prevent the system from maintaining adequate suction, and radon reduction performance would be negatively affected. If house air leakage into the system is great enough, it could also contribute to back-drafting of combustion appliances.

Therefore, closure of major slab openings is an important part of the drain tile suction system. Slab closure techniques are discussed in Section 4. Where practical, large openings such as unused French drains, holes in the slab, and unpaved areas should be closed with concrete or mortar. Where openings of moderate size are not easily accessible, it might be convenient to use foam, although concrete/mortar is preferable wherever possible. For smaller openings, such as cracks with a distinct gap, grout, flowable polyurethane caulk, or asphaltic sealant can be considered. These should be worked down into the crack as completely as possible. If a French drain is present which is clearly necessary for water drainage purposes, it must not be mortared totally closed. In such cases, the drain can be closed as illustrated in Figure 6, which blocks soil gas entry while still providing a channel that allows water that enters beneath the backer rod to drain away. If water enters through the face of the block wall above the French drain, and thus flows down into the drain from above, the channel above the urethane caulk must direct this water to a small sump hole with a trapped cover, installed for this purpose at some point around the perimeter.

In closing the openings, of course, the maximum benefit for the drain tile suction system would result if the openings were sealed gastight, so that no house air at all could move down through the openings. However, such absolute sealing of openings can be difficult to achieve initially and to maintain over the years, and is not necessary for this purpose. It will probably not reduce the performance of the drain tile system significantly if minor hairline cracks develop around the perimeter of the closed opening, so long as the cracks do not open and are not extensive.

Instrumentation to measure suction. Effective sustained performance of the drain tile suction system depends on its ability to maintain a sustained level of suction in the drain tiles. Various potential occurrences could cause this suction to be lost, despite continued, apparently normal, operation of the fan. Such occurrences could include drying out of the water trap over prolonged dry weather, rupture of the seal where the fan connects to the riser, failure over time of the closure effort on some major slab opening, and flooding of the drain tiles during wet weather. The first three examples listed above could result in substantial outdoor or indoor air leakage into the system, potentially causing fan suction to fall dramatically. The last example would probably cause fan suction to increase, because gas flow to the fan would be largely cut off. In any of these cases, the radon reduction performance could be reduced, sometimes dramatically, but the homeowner might be unaware because the fan could seem to be operating normally.

To help address this potential problem, mitigators should consider installing a suitable pressure gauge or a manometer in the riser, so that the homeowner would have a continuous indication of whether the fan suction is remaining in the "normal" range for that house. The normal range for a house would be determined by pressure measurements in the riser during post-mitigation diagnostic testing, as discussed later. Gauges can even be equipped with an alarm that illuminates a light or makes a noise if the suction shifts outside the normal range. Since the riser would be outdoors with this type of drain tile suction system, any pressure measurement device mounted on the riser would have to be protected from weather and physical abuse. Some mitigators recommend that the homeowner should be provided with an unmounted pressure gauge and instructions on how to use it. A resealable sampling port would be installed in the riser for the homeowner's use. This approach avoids rusting or other wear on the instrument over time, but requires diligence by the homeowner in continuing to make these measurements.

Post-mitigation diagnostic testing. The types of diagnostic testing that might most commonly be considered after the mitigation system is installed are summarized below.

- Radon measurements in the house. A several-day measurement (charcoal canister or continuous monitor) is suggested to provide a rapid indication of whether the system is working. An alpha-track measurement over the winter is then recommended to confirm sustained good performance under challenging conditions.

- Gas flow, pressure, and grab radon measurements in the riser between the fan and the drain tiles. These measurements are to confirm that the system is operating properly. Low suction, high flow, and low radon level would indicate a major leak of outdoor air into the system. High suction and unusually low flow might suggest, for example, that the riser is plugged, or that the drain tiles are flooded or otherwise plugged near the riser.

- Smoke tracer testing. A smoke source, such as a chemical smoke stick or an ignited punk stick, could be used near openings in the slab (e.g., near the wall/floor joint, if it has not been caulked). If the smoke is drawn into the crack, the drain tile system is successfully maintaining suction under the slab at that point. If flow is unambiguously up through the crack, that portion of the slab is not being treated. Holes could be drilled in the slab to permit more rigorous smoke testing at selected points; these holes would have to be filled in after the tests were completed. Smoke testing can also be used to check for leaks in the system piping (e.g., where the fan attaches to the riser).

- Measurement of suction field under slab. Small test holes could be drilled at selected points around the slab, and quantitative pressure measurements made (measuring the difference between basement and sub-slab pressures). This approach would quantify where the desired level of suction is being maintained under the slab, and where (if anywhere) the suction is inadequate. Preferably, the sub-slab pressure should be at least 0.015 in. WC lower than the basement pressure at every point. This type of testing would generally be done only if the system had not reduced radon levels sufficiently. If sub-slab suctions were inadequate in some places, alternative mitigation approaches would have to be considered (e.g., supplementing the drain tile suction with sub-slab suction points where needed, as discussed in Section 5.3).

- Testing of combustion appliances for back-drafting. A drain tile suction system would not necessarily be expected to suck enough air out of the house (e.g., down through slab cracks) to cause back-drafting. However, one should be alert to this possibility. In some cases, back-drafting can be obvious (as when a fireplace fails to draw properly and smoke enters the house). In other cases, flow measurements in the flue of the combustion appliance will be necessary to ensure that back-drafting is not occurring. If it is occurring, it will be necessary to close some of the slab openings to reduce house air outflow, and/or to provide a supplemental source of combustion air.

5.2.4.2 Installations Where Tiles Drain to an Internal Sump

Figure 12 shows a drain tile suction system where the tiles drain to a sump inside the basement. The figure shows the tiles around the exterior face of the footings, but the tiles could be beside the interior face instead. The sump is shown as a crock installed in a hole through the slab; other sump configurations are possible. Sumps connected to drain tiles will normally have a sump pump to pump the collected water to a discharge away from the house.

The fact that a house has a sump hole does not necessarily mean that it has drain tiles discharging into the sump. Some houses have a sump hole with no drain tiles, with the sump intended to collect water which runs into it from on top of the slab, or perhaps from a French drain system. If no drain tiles drain into the sump, then suction on the sump would not be considered "drain tile suction," and distribution of the suction field by in-place drain tiles will not occur. Suction on a sump hole having no tiles can still be a logical technique to attempt in many circumstances, and is discussed further in Section 5.3 as a variation of "sub-slab suction." But in the present section, it is assumed that the sump hole has tiles draining into it.

When a sump is covered in the manner illustrated in Figure 12, it is recommended that the sump pump be replaced by a submersible pump, if such a pump is not already present. Otherwise, enclosure of the pump inside the covered sump could result in rusting of the pump motor.

Pre-mitigation diagnostic testing. The pre-mitigation diagnostic testing that can be considered for the interior sump variation of drain tile suction is similar to that discussed in Section 5.2.4.1 for the variation involving exterior discharge. The sump variation provides reasonably convenient access to the tiles where they enter the sump. Therefore, one additional diagnostic test that can be considered with this variation is visual inspection through the tile opening in the sump, to judge the location and extent of the tile loop. One tool that can be used in this situation is a plumber's "snake," which can be inserted into the tiles from the opening in the sump in order to probe the extent of the tile system, at least in the vicinity of the sump.

Capping the sump. For effective suction to be drawn on the sump, the sump must be capped with an airtight cover. Figure 12 shows a flat cover, large enough to enclose the sump hole and extend over a small part of the slab. This cover can be fabricated out of sheet metal, although some mitigators have used alternative materials, such as plywood. Because of the necessary penetrations through the cover — including the water discharge line and the pump electrical wiring — it is often convenient to fabricate the cover in two pieces which fit together with openings for the water line and wiring. The periphery of the cover must be firmly attached to the surrounding slab (e.g., using masonry bolts). For an airtight seal between the cover and the slab, a bead of caulk or other sealant should be placed on the slab around the periphery of the cover before it is screwed in place. Any seam in the cover (if it is fabricated in two pieces) and all penetrations (for the suction pipe, the water discharge, and the pump wiring) must be sealed to make the penetrations airtight.

The cover design shown in Figure 12 assumes that water enters the sump only through the drain tiles — i.e., that water does not flow also into the sump from on top of the slab. However, in some sumps, water does also enter from on top of the slab. In those cases, the sump cover must be designed to provide an airtight barrier that still allows water to flow through. Figure 13 illustrates one possible cover design for accomplishing this objective (Br87, Bro87b, Sc87e). A recessed sheet metal cover containing a water trap allows water from on top of the slab to drain into the sump, while suction can still be drawn on the sump.

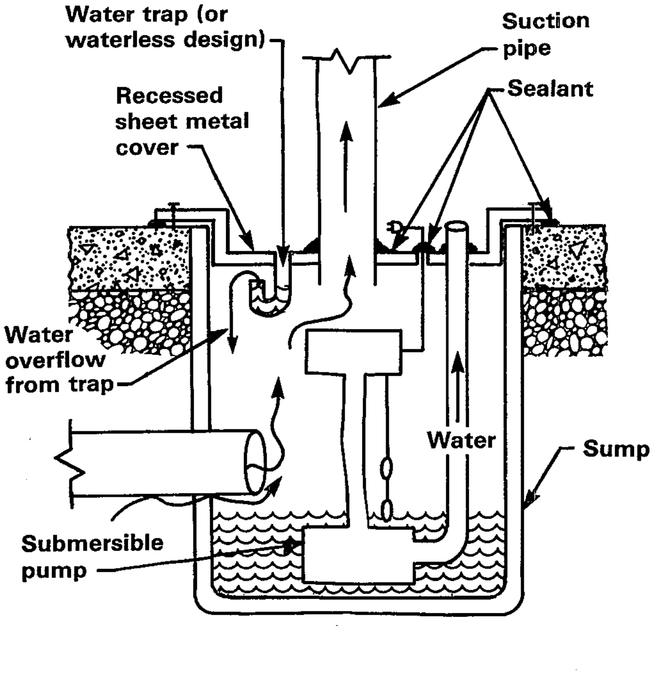


Figure 13. Possible design for a sump cover when water might enter sump from the top.

If a sump cover of the type shown in Figure 13 is used, it is crucial that the trap remain full of water. If the trap dried out, the cover would no longer be airtight, and suction would be lost. Small traps can dry out fairly quickly, and would require that the homeowner pour water into them frequently (perhaps weekly or monthly) during periods when water did not flow into the sump cover naturally. Some mitigators recommend that house plumbing be modified to direct a small amount of water into the sump cover continually, ensuring that the trap remains full without constant homeowner attention. Designs have also been proposed for a trap which will not create a loss of suction if it dries out, as illustrated in Figure 5. However, even such "waterless" traps can require maintenance (in particular, ensuring that debris in the trap is not preventing the ball from seating properly).

Installation of suction pipe. The suction pipe penetrates the sump cover at a convenient point, and extends up to a point where it penetrates the house shell to exhaust the soil gas drawn from the drain tiles. Two alternative piping configurations are illustrated in Figure 12. In one, the piping extends up through the house, penetrating through the roof and exhausting the soil gas at the roofline. In the second, the piping penetrates the house wall through the band joist (or at some other location near grade level) and extends up outside the house, preferably terminating above the eaves. With either configuration, the high-radon soil gas is exhausted where it cannot enter the house before being substantially diluted by outdoor air. For the alternative with the pipe rising up inside the house, this objective is accomplished with minimal visual impact outside the house. However, bringing this stack up through the house can add significantly to the cost of the installation.

The piping is depicted in Figures 12 and 13 as being 4-in. diameter plastic pipe, a reasonable size to provide reasonably low pressure drops through the pipe at the soil gas flows normally encountered, and to be reasonably practical for penetration through the 2 X 8-in. band joist (if the option of penetrating the house wall is selected). Other pipe sizes can also be considered. The larger the pipe diameter, the lower the gas velocity in the pipe, and hence the lower the pressure drop through the piping. Thus, larger piping will enable a given fan to more effectively maintain suction on the sump, where it is needed, by reducing pressure losses in the piping. For example, if a fan with 6-in. connections is being used — and if the pipe is extending up inside the house (so that the appearance of a 6-in. stack outdoors is not a concern) — then 6-in. pipe could be used, reducing the piping pressure loss (relative to 4-in. pipe). However, at the relatively low soil gas flows usually observed in sump suction systems, pipe as large as 6 in. is generally not necessary to reduce pressure losses so long as the fan used has sufficient performance. Pipe smaller in diameter than 4-in. (e.g., 2-in.) might also be considered, to reduce the visual impact of the piping. However, the smaller pipe would result in a greater pressure loss. Depending upon the flow rate of soil gas (and hence the amount of pressure drop), this additional pressure loss could potentially reduce system performance or necessitate a more powerful fan.

In addition to piping size, other factors which can increase pressure loss in the piping are the number of elbows and the length of piping. Each elbow creates additional pressure loss; long piping runs also contribute to pressure loss. Thus, the piping should be designed with a minimum number of elbows, and with the piping run as short as possible.

If the piping is taken up inside the house, through the floors and through the attic and roof, it will be desirable to penetrate the upper floors at points where the pipe has minimal visual impact on these floors. For example, the pipe could pass up through an upstairs closet. In general, it would also be desirable for the piping to penetrate the roof on the rear slope of the roof (by making a horizontal jog in the attic, if necessary) to minimize visual impact. If the effort required to bring the piping up through the house results in long lengths of piping with numerous elbows, a higher-performance fan might be required.

The weight of the piping will have to be supported in some manner. To underscore this requirement, Figure 12 shows a bracket mounted on the basement wall supporting the pipe. Other methods of support might prove more practical in individual cases. If the pipe goes up through the house, it could be supported in the attic and/or at each floor penetration. If the pipe goes out the side wall, the horizontal leg inside the house might be supported by clamps attaching it to the floor joists.

It is important that horizontal legs be sloped slightly, toward the sump. In this way, soil gas moisture, which will be condensing in the pipes during cold weather, will drain back to the sump. In no case should horizontal legs be sloped *away* from the sump; such a slope would permit water to accumulate in the low ends, partially blocking the pipe and increasing the pressure drop.

Joints between sections of piping must be sealed tightly with cement (and caulk if necessary). Pressure fitting is insufficient to ensure an airtight seal. If the piping joints are not well sealed on the suction side of the fan, house air (or outdoor air) could leak into the piping at the joints, causing a loss of suction and poorer radon reductions.

Fan selection and mounting. Fan selection criteria for sump suction are the same as those given in Section 5.2.4.1. Best performance in the EPA testing was achieved when the fan maintained at least 0.5 in. WC (and perhaps as high as 1 in. WC) *in the sump* at the soil gas flows encountered (typically 40 to 150 cfm). These figures depend on sub-slab permeability and air leakage into the system, among other factors. If the fan is mounted remote from the sump (e.g., in the attic), the fan must be sized to account for the pressure drop in the connecting piping, so that sufficient suction in the sump can be maintained. Less powerful fans might be considered if the sub-slab and soil permeabilities are high.

The optimum location for mounting the fan on the piping is always outdoors. If the fan is inside the house, with an exhaust pipe directing the fan exhaust outdoors, there is a risk. If any leaks occur at any time in the fan housing, in the connection between the fan and the exhaust pipe, or in any joints in the exhaust piping, high-radon soil gas being sucked out of the drain tiles by the fan would be blown through these leaks directly into the house. Therefore, where the suction pipe goes up inside the house, the fan would ideally be mounted vertically on the roof, at the end of the suction pipe. Some mitigators prefer to put the fan in the attic, with a short length of exhaust pipe extending from the fan through the roof. This approach is less expensive and visually less obtrusive than roof mounting. With attic mounting, if leaks did occur, their effect on radon levels in the living areas of the house would probably be minimal. The attic is normally ventilated, and the net flow of house air is from the living area into the attic. In no case should the fan be mounted into the piping in the basement or living area. Even if substantial care is taken initially in sealing all joints in the exhaust piping, the fan housing or exhaust joints might begin to leak over time, and the leaks could go unnoticed by the homeowner for an extended period.

If the suction pipe penetrates through the side wall near grade level, it is recommended that the pipe make a 90° upward bend outside the house so that the fan can be mounted vertically, as shown in Figure 12. The vertical mounting will enable condensed soil gas moisture and rain water to drain into the sump, without accumulating in the fan housing. With sidewall penetration in this manner, it is important to caulk carefully around the exterior face where the pipe penetrates the wall, and perhaps to install a drip guard around the horizontal pipe just outside the wall. These steps will prevent rainwater from running down the outside of the pipe and through the wall penetration, potentially causing water damage to the band joist and to other wooden members inside the house. A vertical exhaust riser is shown above the fan in the sidewall option in Figure 12, to exhaust the soil gas at a position where it will not be inhaled or enter the house. The considerations in raising this riser above the eaves — or in otherwise directing it so that it will not be inhaled or enter the house — have been discussed previously, in Section 5.2.4.1.

The fan must be mounted on the piping with an airtight seal, to avoid air leakage and suction loss.

As discussed previously, the fan shown here is mounted to draw suction on the sump. There is currently no experience with the effects of pressurizing the drain tiles.

Closure of major slab openings. As discussed in Section 5.2.4.1, major slab openings must be closed to help ensure effective extension of the drain tile suction underneath the slab.

Instrumentation to measure suction. As discussed in Section 5.2.4.1, a pressure gauge or a manometer should be installed in the suction piping above the sump (inside the house) to provide a continuous indication of whether the fan suction is remaining in the "normal" range for that house. Such continuous pressure measurement can alert homeowners to potential malfunctions in the system which would not otherwise be apparent (e.g., from changes in sound and vibration of the fan).

Post-mitigation diagnostic testing. The types of post-mitigation diagnostic testing that might most commonly be considered are the same as those listed in Section 5.2.4.1.

5.2.5 Operation and Maintenance

The operating requirements for either of the two drain tile suction variations consist of regular inspections by the homeowner to ensure that:

- the fan is operating properly (e.g., is not broken or iced up).
- the suction in the piping is within the normal range.
- all system seals are still intact (e.g., at all suction and exhaust piping joints, and at the connections between the fan and the piping). In the case of sump suction, seals to be checked also include those between the sump cover and the slab, around any penetrations of the cover, and where the piping penetrates the house shell.
- the traps are full of water (for installations of the type illustrated in Figures 11 and 13). A trap of the type in Figure 11 should probably be checked at least monthly if the weather has been dry. A trap of the type shown in Figure 13 might have to be checked weekly.
- all slab closures remain intact.

Maintenance would include any required routine maintenance to the fan motor (e.g., oiling), replacement of the fan as needed, addition of water to the trap, repair of any broken seals, and re-closure of any major slab openings where the original closure has failed. If the pressure gauge indicates that the suction is not in the normal range, and if the above maintenance activities do not correct the situation, the homeowner should measure radon in the house and possibly call a mitigation professional.

5.2.6 Estimate of Costs

Costs can vary widely, depending upon the specific characteristics of the house, the finish around the installation, the amount of diagnostics that are conducted, and the guarantee (if any) offered by the mitigator, among other factors. For a system of the type illustrated in Figure 11, installed by a contractor, a homeowner might have to pay about $700 to $1,500 for design and installation. This cost would depend upon the depth of the drain tile discharge line (since much of the cost is for the manual labor involved in digging down to expose part of this line), and upon the nature of the exhaust pipe installed above the fan. Installation of exterior finish to conceal an exhaust pipe up to the roofline would increase these costs.

For a system of the type illustrated in Figure 12, the design and installation cost might typically be between $800 and $2,500. The cost would depend largely upon: the suction piping configuration (i.e., through the side wall or up through the house); the difficulty involved in bringing the pipe up through the house; the location of the fan (e.g., in the attic or on the roof); and, for the side wall configuration, the nature of the exhaust pipe above the fan.

Some homeowners might be able to install a drain tile suction system themselves (particularly of the type shown in Figure 11, where no work inside the house is required). In this case, the cost would be limited to that of the materials — the fan, the plastic piping, and some incidentals. The materials cost alone would probably not exceed $300.

In sump suction systems, an additional installation cost could be the replacement of the sump pump with a submersible pump (to avoid motor deterioration), if such a pump is not already present.

5.3 Sub-Slab Soil Ventilation (Active)

5.3.1 Principle of Operation

In active sub-slab ventilation, a fan is used to either suck or force soil gas away from the foundation by means of individual suction (or pressurization) pipes which are inserted into the region under the concrete slab. The pipes can be inserted vertically downward through the slab from inside the house, as illustrated in Figure 14, or can be inserted horizontally through a foundation wall at a level beneath the slab, as in Figure 15. The intent of the system is to create a low-pressure (or high-pressure) region underneath the entire slab. Depending upon the permeability of the surrounding soil, this pressure field can extend beyond the immediate sub-slab area to the exterior face of the footings. This pressure field, if effective, would prevent soil gas from entering the house through cracks in the slab. It could prevent the soil gas from entering the void network inside hollow-block foundation walls in the region around the footings. Sometimes, the treatment can extend under the footings or through block walls to inhibit soil gas entry into the house through openings in the below-grade foundation wall. If the sub-slab ventilation fan is operated in suction, the system can be pictured as using the crushed rock that is often under the slab as a large collector, into which the soil gas in the vicinity of the house is drawn and then exhausted outdoors.

The central issues with sub-slab ventilation are the number of ventilation points needed, where they must be placed, and the static pressure needed in the ventilation pipes in order to effectively treat all soil gas entry routes. These factors will be determined largely by the permeability distribution under the slab — i.e., the ease with which suction (or pressure) at one point can extend to other parts of the slab and to the surrounding soil. Other considerations influencing the number, location, and pressure of the ventilation points are the location and nature of the entry routes, and the presence of unclosed openings in the slab or walls as discussed in Section 5.1.

In concept, a sub-slab ventilation system can be operated either: a) with the fan in suction, to reduce soil gas pressure lower than the pressure in the house, drawing soil gas away from entry routes; or b) with the fan in pressure, blowing outdoor air into the soil, creating a high-pressure region which can dilute the soil gas and force it away. Some investigators have reported very good results with the system operated in pressure under some conditions (Tu86). Pressurization offers certain advantages over suction. In particular, it avoids the release of a high-radon soil gas exhaust stream. But, in the absence of data, there is concern that, in some cases, pressurization might result in an increase of soil gas influx through some entry routes. Almost all experience to date has been with the system operated in suction.

The drain tile suction approach described in Section 5.2 is essentially a variation of sub-slab suction, especially where the drain tiles surround the inside of the footings under the slab. The principle of operation is the same: to establish an effective suction field around the house in order to draw away the soil gas. Some of the sub-slab suction variations considered for new construction (Section 9) and for passive systems (Section 5.6) involve the use of perforated pipe or tiles laid underneath the slab, similar to drain tile systems. However, in this section, the term "sub-slab ventilation" is used only to refer to where individual non-perforated pipes are inserted into the sub-slab region, as in Figures 14 and 15.

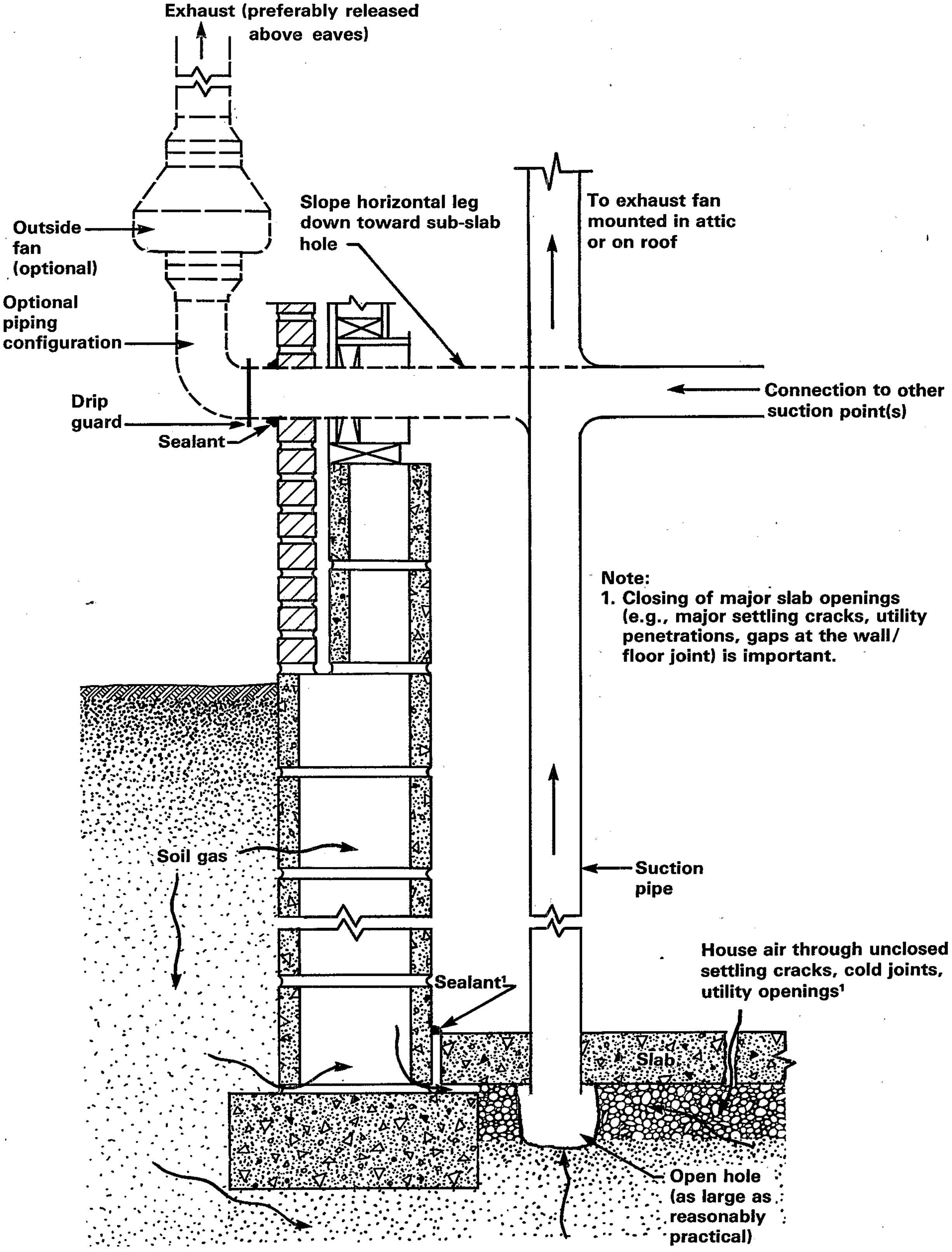
Another variation of sub-slab suction can be envisioned for houses having French drains. The French drain — which will generally have to be closed in some manner anyway, as part of any sub-slab suction system — could be used as ready-made access to the sub-slab region. In this variation, the French drain would be enclosed as illustrated in Figure 6, or with a baseboard duct such as that in Figure 19 (except without the holes drilled through the block wall). Suction would then be drawn on the enclosed French drain. Such a system, in addition to treating the sub-slab, might provide better treatment of block wall cavities than will the other sub-slab suction approaches.

Sub-slab suction has been one of the more widely applied and effective approaches used by the radon mitigation community in treating high-radon houses. Where drain tile suction is not an option, sub-slab ventilation should be the next technique considered in houses for which it is applicable.

5.3.2 Applicability

Sub-slab ventilation will be most applicable under the following conditions.

- Houses having a concrete floor slab in all or part of the house (i.e., substructures with basements, slabs below grade, slabs on grade, and paved crawl spaces). Sub-slab ventilation will probably not be applicable in earth-floored basements or crawl spaces unless the floor is first paved or covered with a gastight cover such as plastic sheeting. In houses with uncovered earthen floors, a large amount of basement or crawl-space air could leak into the suction system through the exposed earth, potentially preventing the system from establishing an effective pressure field in the soil.
- Houses having good permeability underneath all of the slab (i.e., permitting reasonably easy movement of gas under the entire slab). Good permeability will permit the ventilation effects of a limited number of suction points (perhaps only one) to extend effectively under the entire slab. Slabs having limited permeability under all or part of the slab will require a greater number of ventilation pipes. The pipes will have to be more carefully located, and/or other



Note:

1. Closing of major slab openings (e.g., major settling cracks, utility penetrations, gaps at the wall/floor joint) is important.

Figure 14. Sub-slab suction using pipes inserted down through slab.

Note:

1. Closing of major slab openings (e.g., major settling cracks, utility penetrations, gaps at the wall/ floor joint) is important.

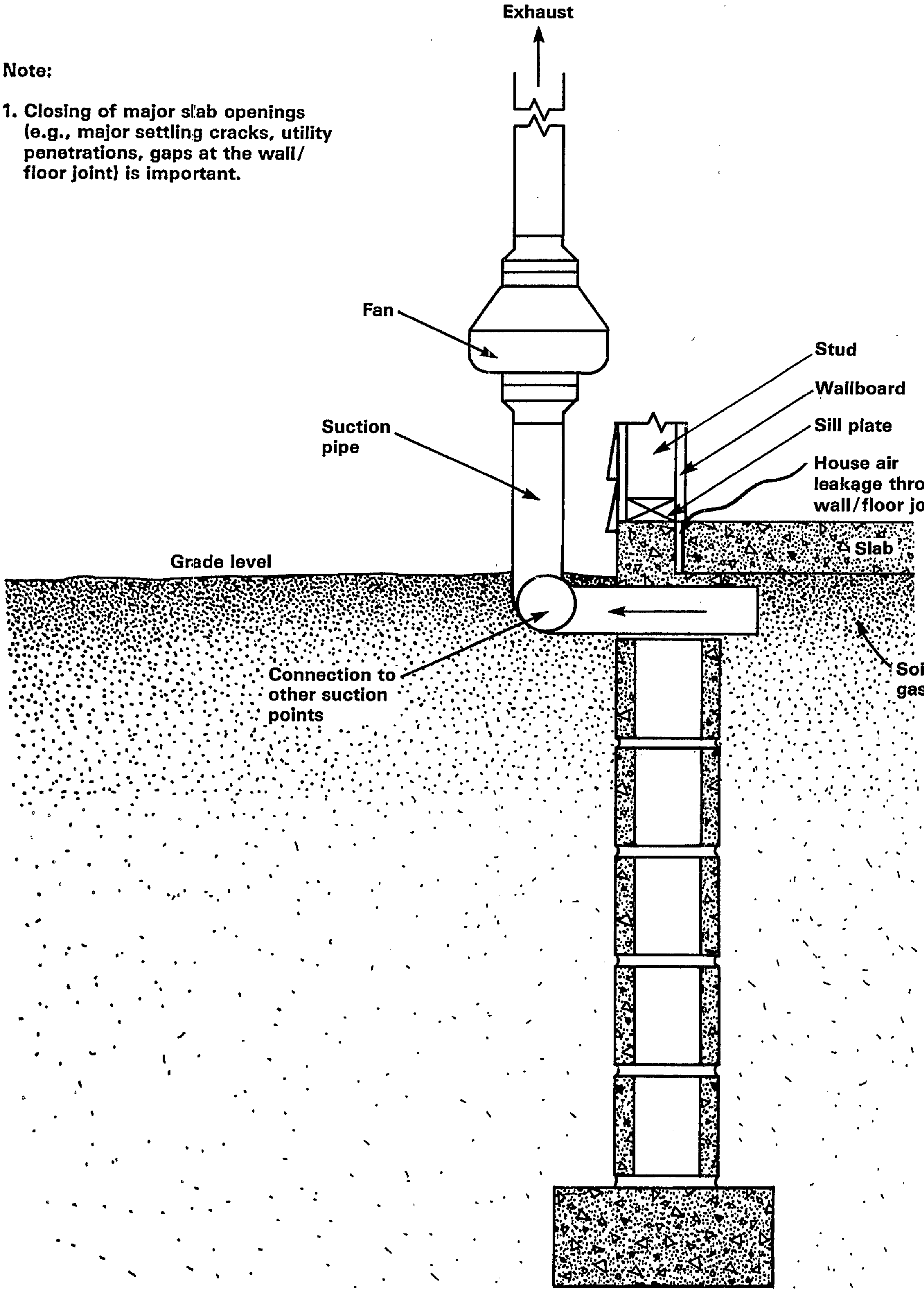


Figure 15. Sub-slab suction using pipes inserted through foundation wall from outside.

provisions (such as larger sub-slab holes and larger fans) will be needed to help increase the suction/ pressure in the pipes. Even with these extra efforts, performance might be reduced. Good sub-slab permeability will generally result when there is a reasonable depth of clean, coarse aggregate (crushed rock) under the entire slab which is not interrupted anywhere (e.g., by concrete which settled into the aggregate when the slab was poured, or by segments of undisturbed soil or bedrock which were not excavated). If the soil underneath the house is sufficiently porous, adequate permeability might exist even if there is not a well-defined aggregate layer, but best radon reductions have most consistently been achieved when there is a good layer of clean, coarse aggregate. Worst-case houses where the slab is poured directly on rock or impermeable soil can still be candidates for sub-slab ventilation, but will probably require special considerations in the design of the system, as discussed later. It is emphasized that the permeability *under the slab* is of primary concern. Even if the surrounding soil and rock away from the house have a low permeability, sub-slab ventilation would be expected to give good performance if a layer of aggregate provides good permeability directly under the slab.

- Houses with moderate to high initial radon concentrations, above about 15 to 20 pCi/L. Sub-slab ventilation is capable of achieving the very high reductions needed in houses having high radon levels. But the cost of these systems (usually at least $1,000 for contractor installations) is sufficiently high that other less expensive alternative approaches, perhaps capable of lesser radon reductions, might sometimes be more economical in houses with only slightly elevated initial radon levels. However, even in houses with only slightly elevated levels, sub-slab ventilation will sometimes be a desirable alternative.

- For basement houses, houses where at least a portion of the slab area is not finished, so that ventilation pipes can be installed without the expense of removing and re-installing wall and floor finish. If sub-slab ventilation is the only logical choice in a house with a fully finished basement, then the added expense will have to be accepted. In slab-on-grade and slab-below-grade houses, the finish over the slab is of less concern, because it is often possible to insert vent pipes from outside the house, horizontally through the foundation wall below the slab, with reasonably limited excavation. Under these conditions, it might be less expensive (and sometimes aesthetically preferable) to insert the sub-slab pipes from outside rather than modifying the interior finish to insert them from inside.

- Houses with any type of foundation walls, including hollow-block and fieldstone walls as well as poured concrete walls. If the sub-slab region is sufficiently permeable, and if the sub-slab ventilation points are properly located, sub-slab treatment sometimes appears sufficient to prevent soil gas from entering the void network inside hollow-block walls. In addition, if the soil under the footings and beside the foundation wall is sufficiently permeable, it appears that the sub-slab-induced pressure field can extend beyond the sub-slab region itself, potentially treating entry routes on the exterior face of the foundation walls. With hollow-block foundation walls, the sub-slab pressure field might extend into the wall voids if communication is sufficient, potentially drawing out any soil gas which does enter the voids through the exterior face. Thus, wall-related soil gas entry routes can often be treated, at least partially, by sub-slab systems; sub-slab treatment is not limited to slab-related entry routes alone. As a result, sub-slab ventilation can be considered even when the foundation walls contain entry routes, such as the void network in hollow-block walls, cracks in poured concrete walls, and chinks in fieldstone walls.

  Sometimes wall-related entry routes will not be adequately treated by sub-slab ventilation. Such cases can result, for example, when soil permeability under the footings is poor, or when there is insufficient communication between the sub-slab and the block wall void network. In these cases, the sub-slab system might have to be supplemented by some form of wall treatment.

- In houses having French drains, the sub-slab suction variation can be considered involving enclosure of, and suction on, the French drain.

As indicated above, and as emphasized in subsequent discussion, some reasonable sub-slab permeability will likely be necessary if sub-slab ventilation is to give good performance with a reasonable number of ventilation points. Since the sub-slab system is one of the best-demonstrated approaches for getting the very high reductions needed in high-level houses, there is incentive to try to make sub-slab systems work even in houses having poor sub-slab permeability. The discussion in Section 5.3.4 addresses the steps that can be taken in such houses. Experience in applying sub-slab ventilation where permeability is poor is limited, so that there are not currently firm guidelines for how sub-slab ventilation systems should be designed in such cases. Nor is it clear whether there are conditions so unfavorable that this approach should be dismissed altogether as an option.

If a house has very high initial radon levels resulting from soil gas, sub-slab ventilation should be one of the control approaches considered. In high-radon cases where sub-slab ventilation cannot be made to give adequate performance with a reasonable number of ventilation pipes, the alternatives that can be considered include:

- tearing out the slab and removing some of the underlying soil and rock, laying drain tiles inside the footings, putting down a layer of aggregate, covering with a liner, and re-pouring the slab. Suction would then be drawn on the drain tiles. (Alternatively, the drain tiles could be omitted, and sub-slab suction pipes installed as in Figure 14.) This approach would probably ensure the best results, but it would be expensive.
- attempting other mitigation approaches, such as house pressurization, block-wall ventilation, or year-around house ventilation, as applicable.
- constructing a false floor over the existing slab, and ventilating the space between the new floor and the slab. (False walls can also be installed.) There are almost no data on the performance of this approach.

5.3.3 Confidence

Active sub-slab suction has been one of the more widely used radon reduction techniques, both by researchers and by commercial radon diagnosticians. Sub-slab suction systems have been installed in at least 350 houses (mostly in the United States, but also including installations in Canada and Sweden). In fact, the actual number is probably far higher; there is no national record maintained of the installations made by commercial mitigators. The results from the various installations are not always directly comparable, because different installers sometimes use different radon measurement approaches for evaluating the performance of the installations. But essentially all sources report radon reductions of at least 80 to 90 percent, with reductions as high as 95 to 99+ percent being reported for some houses (Ch79, Vi79, Er84, Ni85, Br86, Br87, Bro86, Bro87b, Sc86a, Tu86, Fi87, He87a, He87b, Ma87, Mi87, Os87a, Sa87a, Se87, Si87). Commercial diagnosticians/mitigators using the most current knowledge and techniques generally indicate that, where sub-slab suction is employed, this approach reduces radon levels below 4 pCi/L in at least 90 percent of the houses. The exceptions are often houses where the sub-slab permeability is insufficient. In documented cases where reductions with sub-slab suction have been less than 80 to 90 percent, the reasons have generally included inadequate sub-slab permeability, improper location of the suction pipes, insufficient fan capability, and/or inadequate closure of slab openings (Ni85, He87a, Os87a).

EPA has tested sub-slab suction in 23 houses in Pennsylvania (He87a, He87b). These include 14 houses having basements with block foundation walls, 5 houses having basements with poured concrete walls, and 4 houses with poured concrete basements having an adjoining slab on grade. Initial radon levels in these houses were generally greater than 40 pCi/L, with the level in one house being 1,205 pCi/L. Among the conclusions apparent from this testing are the following.

- In basement houses having no adjoining slab on grade, sub-slab suction reduced radon levels to 4-5 pCi/L or less (generally representing reductions of 90 to 99 percent) in every house (block or poured concrete) where:
  - —there were three or more suction points, placed near the foundation walls. One house had seven points.
  - —a high-suction fan was used, maintaining at least 0.7 in. WC suction in the pipe near its penetration through the slab.
  - —reasonable efforts were made to close major slab and wall openings.

  Some of these houses were known to have limited sub-slab permeability, due to the nature (or absence) of aggregate visible through the slab holes drilled to insert the pipes. No special effort was made to enlarge the hole under the slab where the pipe was inserted. The number of pipes in these houses corresponded to one pipe for each 160 to 400 ft^2 of basement floor area.
- In three basement houses thought to have reasonable permeability, reductions of 94 to 99 percent were achieved with only one to two suction pipes (one pipe per 620 to 1,000 ft^2), when a high suction fan was used.
- In two basement houses thought to have reasonable (though not necessarily high) permeability, 80 to 85 percent reductions were achieved using two suction points (one point per 500 to 680 ft^2) and a moderate-suction fan (0.3 in. WC).
- In two basement houses having known poor permeability, limited reductions (16 to 45 per-

cent) were obtained using two suction points and a moderate-suction fan.

- The reductions achieved in basement houses with block foundation walls were generally comparable to the reductions in basement houses with poured concrete walls when high-suction fans and comparable numbers of suction points were used.
- In four houses having basements with poured concrete foundation walls and having an adjoining slab on grade, sub-slab suction in the basement only was sufficient by itself in one house to reduce levels below 4 pCi/L (99 percent reduction). In a second house, suction in the basement appeared sufficient only to reduce radon levels on the adjoining slab, but basement levels remained slightly elevated (8 pCi/L, 92 percent reduction), suggesting that the basement was still not being adequately treated. In the remaining two houses, sub-slab suction in the basement was supplemented by two suction pipes inserted under the adjoining slab, inserted horizontally through the stub wall from inside the basement. In one of those houses, levels were reduced below 4 pCi/L (99 percent reduction). In the other house, levels on the adjoining slab were reduced below 4 pCi/L, suggesting that the slab on grade was being adequately treated; however, the basement was still slightly elevated (9 pCi/L, 74 percent reduction), suggesting that the basement was not being adequately treated. In all four houses, a high-suction fan was used maintaining 0.5 to 1 in. WC suction in the pipes. There were four to six suction pipes in each basement, representing one pipe for each 110 to 230 ft^2 of basement slab area.

These results suggest that, in basement houses, one or two suction points can be sufficient for reductions well above 90 percent if sub-slab permeability is good and if a sufficiently powerful fan is used. If permeability is not good, more suction points are required to achieve 90 percent reduction, and placement of the pipes near the foundation walls appears to help. Houses with hollow-block foundation walls do not represent a distinctly more difficult case for sub-slab suction compared to houses with poured concrete walls, despite the increased potential for wall-related soil gas entry routes in block walls. Basement houses with adjoining slabs on grade can sometimes be reduced to acceptable levels by treating only the basement, although treatment of the adjoining slab will sometimes also be necessary.

In another EPA project in New Jersey (Mi87, Os87a), variations of sub-slab suction were tested in slab-on-grade, slab-below-grade, basement, and combined basement/slab-on-grade houses having block foundation walls. Initial radon levels ranged from about 400 to 1,350 pCi/L. Two of the combined basement/slab-on-grade houses included vertical suction pipes through the slab in the basement (as in Figure 14), plus suction on abandoned forced-air HVAC ducts that existed under the adjoining slab on grade (Houses C8A and C46A in Reference Mi87). Reductions of 99 percent were achieved in these two houses using a high-suction fan, based upon charcoal canister measurements. Initial efforts on one of the slab-below-grade houses (C48B), using a vertical pipe through the central region of the slab from inside the house, reportedly gave insufficient reductions due to inadequate sub-slab permeability. Performance was improved by widening and capping the perimeter wall/floor joint (in effect, creating a capped French drain as depicted in Figure 6). Suction was drawn on this enclosed perimeter channel as well as on the central pipe. Reductions of 99 percent were obtained using this approach. In two other slab-below-grade houses, identical to the first, 99 percent reductions were obtained using: a) sub-slab suction with one pipe penetrating horizontally through the foundation wall from outdoors (as in Figure 15); plus b) block wall ventilation (Section 5.4), with two suction pipes penetrating into the wall voids from outdoors (Os87a). These results on the slab-below-grade houses tend to confirm that, where permeability is poor, sub-slab suction points might most effectively be placed around the perimeter (i.e., near the major entry routes and in the region where permeability is likely to be highest). Also, with poor permeability, suction on wall voids as well as on the sub-slab can sometimes be a logical approach.

In addition to the work in House C48B above (Br87, Mi87), the sub-slab suction variation involving enclosure and depressurization of a French drain has also been tested in three other New Jersey houses (Hu87, Ma87, Se87). Two of these houses also included one vertical suction pipe through the slab (as in Figure 14) in addition to the French drain suction. Reductions of over 90 percent were obtained in these two houses (Se87). Results are not yet available from the third house. These results are too limited to confirm the effectiveness of the "enclosed French drain" approach.

In some cases with houses having block foundation walls, it might be found that the sub-slab suction system is not adequately treating the walls. This situation would be identified through post-mitigation diagnostic testing as described in Section 5.3.4. In such cases, it might be necessary to ventilate the wall voids (Section 5.4) as well as the sub-slab. Some investigators have tested combined sub-slab plus wall suction, usually achieving reductions greater than 90 percent (He87a, Os87a, Ma87). However, it has not yet been clearly shown how often, and under what conditions, the addition of wall ventilation to a sub-slab suction system will be preferred over the alternative of adding more sub-slab suction points (or of otherwise increasing the capability of the sub-slab system itself).

The preceding discussion of sub-slab ventilation performance has been addressing the case where the system is operated in *suction.* Almost all experience to date has been with the system in suction. Some researchers (Tu86) have tested installations in *pressure,* with the fan mounted to blow outdoor air into the soil. Testing in three houses in eastern Washington State (two poured concrete split-levels, one fieldstone basement) yielded radon reductions of 91, 94, and 98 percent through sub-slab pressurization. Interestingly, the reductions with pressurization in this study were superior to those in the same houses with suction, which were only 42, 76, and 93 percent, respectively. It is noted that the soil around these houses is a highly porous glacial till, and that only one of the houses had aggregate under the concrete slab (the other two had the slab directly on top of the soil). These factors could have influenced both the performance of the pressurization system, and the relative performance of pressurization versus suction. For example, in less permeable soil, there could be an increased risk that pressurization might force soil gas up into the house at an increased rate through some entry routes. When sub-slab pressurization was tested in five houses in New Jersey (Se87), radon reductions were consistently much poorer than they had been when the same five sub-slab ventilation systems were operated in suction.

In view of the extensive experience and widely favorable results, the confidence in sub-slab suction is considered moderate to high. Confidence is high if suitable pre-mitigation diagnostics are conducted to confirm that sub-slab permeability is good (or if it is known that several inches of crushed rock underlies the slab), and if the system is designed as described in Section 5.3.4. Confidence is moderate if the sub-slab permeability is poor or unknown, and/or if the fan is too small or if slab openings are not adequately sealed. Confidence in sub-slab pressurization cannot be classified at present, because the data base on pressurization systems is so limited. However, it appears to offer potential.

5.3.4 Design and Installation

Figure 14 illustrates a typical configuration for a sub-slab suction system with the suction pipe(s) penetrating vertically downward through the slab *from inside* the house. Some variation of this configuration is commonly used whenever the system is being installed in a house with a basement, so that getting under the slab from outside the house is impractical. With slab-on-grade and perhaps slab-below-grade houses, where it is practical to excavate by the foundation wall outside the house to a level below the slab, one can consider horizontal penetration of the foundation wall from outside, as illustrated in Figure 15. The decision on whether to enter the sub-slab from indoors or outdoors in slab-on-grade and slab-below-grade houses will depend upon, among other things, the extent of interior wall and floor finish.

5.3.4.1 Pre-mitigation Diagnostic Testing

The pre-mitigation diagnostics which can be of particular value in the selection and design of sub-slab ventilation systems include the following.

- Visual Inspection—Among the factors to be noted during the visual inspection would be:
    - — location and nature of potential entry routes (e.g., the size of the wall/floor joint, the presence of large cold joints in the slab or of interior load-bearing walls which penetrate the slab, and other slab and wall openings). This information is important in helping select suction pipe locations, and in determining the amount of slab and wall closure that is needed.
    - — available potential locations for pipe installation (e.g., unfinished portions of the house, open unused sump pits that might be used as a ready-made slab penetration for a pipe). If there are no unfinished portions, where do the most cost-effective pipe locations appear to be — are there locations where the removal/replacement costs for floor/wall finish will be minimized, or can the pipes be located outdoors? Should an alternative to sub-slab suction be considered? Are there features which would simplify the installation of a pipe up through the house, such as a utility chase, or such as a closet on the floor above?
    - — is there any evidence that at least a partial drain tile loop exists, so that drain tile suction might be an option?

Of course, other features which can be noted during a visual inspection (Section 2.4), such as house features contributing to the stack effect, will also be of interest.

- Measurement of Sub-Slab Permeability—One of the potentially most valuable diagnostic tests that can be considered in the design of the sub-slab system, is the determination of sub-slab permeability. See item 8 in Section 2.4. Different diagnosticians assess sub-slab permeability using different approaches. One particularly quantitative approach (Sa87a) is described in Section 2.4. This technique measures the extension of the pressure field under the slab, which is determined by the permeability. A less quantitative approach would be to drill through the slab at several points to enable a visual inspection of the condition of the aggregate; several inches of clean, coarse aggregate everywhere would suggest that permeability is probably good. Good permeability generally enables good radon reductions to be achieved with fewer suction points, and with greater flexibility in the location of the points.

Poor sub-slab permeability does not necessarily mean that sub-slab ventilation is not applicable. However, the sub-slab system would have to be designed taking the poor permeability into account, as discussed later in this section. In worst-case houses, where the slab is poured directly on underlying bedrock, permeability testing might show no extension of the suction field at all between the 80 in. WC suction hole and nearby test holes. Perhaps in some such extreme cases an alternative radon reduction approach might have to be considered, as a supplement to (or as a replacement for) sub-slab ventilation. However, sub-slab suction has been made to give good reductions even in some worst-case houses.

- Grab-Sample Radon Measurements—Spot radon measurements on samples taken from under concrete slabs, from inside block foundation walls, or from accessible entry routes (item 3 in Section 2.4) can sometimes aid in identifying regions of the slab having particularly high underlying radon levels. The location of sub-slab suction points can then be selected with a bias toward these "hot spots." If test holes are drilled through the slab for quantitative pressure field extension measurements, as discussed above, gas samples can conveniently be drawn from under the slab through these holes. The sub-slab values at the various points can be compared to identify "hot" segments of the slab. Holes can be drilled into wall voids of block walls to enable sampling of the gas in the cavities; alternatively, samples could be drawn through existing openings, if available. Comparison of results from different walls can suggest the potentially most important walls. The sub-slab suction points can then be positioned favoring the "hot" slab segments and walls. However, the less elevated regions cannot be ignored; they can still be important radon sources.

5.3.4.2 Selection of Number and Location of Suction Points

The number and location of suction points will be determined by sub-slab permeability, the location of potential major soil gas entry routes, and homeowner considerations.

If the diagnostic testing has included mapping of sub-slab permeability, then the number and location of the suction points will be suggested by those diagnostic results. In general, if the permeability is found to be good, then only one or two suction points will often be adequate, unless the house is very large or unless there are slab openings which cannot be effectively closed. If it is known that several inches of uninterrupted clean, coarse aggregate lies under the slab, only one or two points will probably be needed, even in the absence of permeability measurements. Good, uninterrupted aggregate is most likely to exist when the original homeowner has seen the aggregate put down during construction, or when the builder can confirm its presence, and when there is a plastic liner between the aggregate and the slab which prevents wet concrete from settling through the crushed rock. But even under these conditions, it can still be desirable to visually inspect the aggregate through test holes through the slab, to ensure that it does not contain excessive fines or dirt which could reduce its permeability.

As discussed in Section 5.3.3, EPA and commercial mitigators have observed very high reductions with one or two suction points in basements larger than 1,250 ft^2, when permeability is good. In some of the EPA testing (He87a, He87b), one point per 600 to 1,000 ft^2 of basement area was sufficient under these favorable conditions. One suction point has reportedly been sufficient to treat as much as 1,800 ft^2 (Br87).

If permeability is good, the location of the suction points can be fairly flexible. Figure 14 shows the suction pipe mounted near a perimeter wall, to ensure good treatment of the wall/floor joint and the footing region, and to get it out of the way of the homeowner. However, placement near the wall is not necessary if permeability is good. It would generally be good practice to place the points closer to what would be expected to be the most important entry routes. For example, if the front wall is fully below grade in a basement and the rear wall is completely above grade, it would be logical to place the point(s) nearer to the front. Or if there is a cold joint in the slab or an interior load-bearing wall in the basement, one of the points should favor those potential sources. If pre-mitigation diagnostic testing has included radon grab sampling to identify "hot spots," the grab sample results would suggest which parts of the slab or which walls the sub-slab pipes should be biased toward. With good permeability, the location of the point(s) often can be selected for convenience. For example, if part of the house over the slab is unfinished — such as a utility room, furnace room, or attached garage —

then it would be logical to place the points in these unfinished areas. (However, if there is more than one point, it would be desirable not to place all points in one unfinished part of the slab. The points should generally be distributed as uniformly as possible.) If there is an unused sump pit which can serve as a ready-made slab penetration for one of the suction pipes, this pit might be selected as one location. (In this case, it is assumed that the sump pit has no drain tiles draining into it. If it is a sump with drain tiles, then suction on this sump would be considered drain tile suction, as discussed in Section 5.2.) Of course, it is desirable to place the pipes where they will be of least inconvenience to the homeowner — e.g., near other already-existing obstructions in the room, perhaps near walls. If the riser from the suction pipes is to go up inside the house to a fan mounted in the attic or on the roof, then it would be convenient to locate an individual suction point under, for example, a closet on the floor above, to simplify extending the exhaust pipe up through the house.

If the suction pipes are to be inserted through the foundation wall from outside, as in Figure 15, the location of the wall penetration(s) would be selected based upon: aesthetics (for example, in the back of the house, away from the street); ease of access; the desire to have reasonable spacing between points, if there is more than one; and the location of "hot spots," if diagnostic testing has included radon measurements under the slab and inside block walls. While experience with this wall penetration approach on near-grade slabs is limited, it would be reasonable to place at least one point under the slab at its deepest point below grade, in an effort to reduce the infiltration of outdoor air down through the soil and into the system. The open end of the horizontal pipe should be immediately beneath the slab, in an effort to take advantage of any air spaces or increased porosity that might be available there (due to, for example, soil settling or aggregate if present). One approach for terminating the pipe just below the slab is to make the penetration through the foundation wall just below the slab, as illustrated in Figure 15. However, with block foundation walls, the block just below the slab can sometimes be solid. In these cases, it could be more convenient to make the penetration through a hollow block in the course of blocks one level below the solid blocks. If this is done, the hole under the slab (where the horizontal pipe will terminate) should be expanded upward to the underside of the slab. The pipe itself should still be installed horizontally; i.e., it should not be angled upward under the slab to reach the underside. Such angling would create a low point in the pipe where condensed soil gas moisture could accumulate, potentially blocking the pipe.

One or two suction points, with flexibility in where they are placed, can be sufficient only when the permeability under the slab is good. When the permeability is not good, more suction points will likely be needed, and there will be more restrictions on their locations.

When the permeability is limited, three, four, or even more suction points can sometimes be needed to reduce winter radon concentrations consistently below 4 pCi/L, even with high-suction fans. In some of the EPA testing (He87a, He87b) in houses known to have limited sub-slab permeability, one suction point was required for every 160 to 400 ft^2 of basement area to reduce winter concentrations to the vicinity of 4 pCi/L or less in high-radon houses. As many as seven suction points were used in one house. The number of suction points needed might be reduced by excavating a sufficiently large hole under the slab where the pipe is inserted, as discussed later (see Figure 16). Such excavation will reduce pressure losses where the soil gas enters the pipe, and thus enable the suction being drawn by the fan to more effectively extend under the slab. It is reported that one mitigator consistently achieves 4 pCi/L in houses with poor permeability using no more than one suction pipe for every 300 ft^2, by excavating holes of 36-in. diameter under the slab at each pipe.

Location of the suction points will become more important when the permeability is not good. It will likely be important that suction points be placed near many of the major entry routes, since the suction field would not be expected to extend very far from the suction pipe. Major entry routes to consider include: the perimeter wall/floor joint; the footing region (for houses with block walls); interior load-bearing walls which penetrate the slab; and other major openings which cannot be closed. In the EPA study in Pennsylvania (He87a, He87b), at least one point was placed near each perimeter wall and each load-bearing interior wall, just far enough out from the wall to avoid hitting the footing. Where possible, the pipe was placed approximately in the middle of each wall. If the wall were more than about 25 ft long, two pipes were generally placed along the wall, usually about equidistant from each other and from the ends of the wall. This placement, illustrated in Figure 14, was selected in an effort to ensure that the wall/floor joint and the footing region (and, it is hoped, the entire sub-slab) were adequately treated. Another advantage to placing the pipes near the foundation walls is that permeability is likely to be best there. Even if much of the slab is poured on undisturbed impermeable soil or bedrock, some excavation and backfilling almost certainly would have taken place around the footings. Placement of pipes near the walls has the further advantage of getting *them out* of the way of the homeowner. As discussed in Section 5.3.3, placement of a sufficient number of pipes along the walls did consistently reduce high-radon houses with poor sub-slab permeability to 4-5 pCi/L or less during winter measurements. If the suction pipes are installed with a sufficiently large hole excavated under the slab (Figure 16), the need to locate points right beside major entry routes (e.g., beside the walls) might be reduced.

In some cases, the sub-slab permeability might be poor under only parts of the slab, and good elsewhere. For example, the aggregate might not be uniform, with some parts of the slab having little or no aggregate. Or sometimes the aggregate layer might be interrupted, so that the suction field will not effectively extend into one part of the sub-slab from adjoining areas. In such cases, it will be necessary to place at least one suction point in each segment of the slab that is thus isolated, if that segment contains potential soil gas entry routes.

Where horizontal penetration through the foundation wall from outdoors is employed, as in Figure 15, suction points will most conveniently be near the perimeter walls regardless of the sub-slab permeability. Augering horizontally under the slab for more than a foot or two adds complexity and increases the risk of hitting sub-slab utility lines.

In cases where a French drain is enclosed and depressurized, the "suction point" will be the entire basement perimeter. This approach places the suction right at one of the major entry routes, namely, the wall/floor joint.

If the house has more than one level with a slab — for example, a basement with an adjoining slab-on-grade — the design of the sub-slab suction system will depend upon the sub-slab communication between the two levels. If communication is good, it will sometimes be sufficient to install suction points on only one level, with the suction effects extending to the adjoining level. In such a house, the pipes would be installed in the most convenient level — for example, in an unfinished basement, rather than in an adjoining finished slab-on-grade. In this example, the number and location of the suction points in the basement would be selected based upon permeability measurements or mitigator judgment. However, it would be logical to place at least one of the suction points in the basement near the joint with the adjoining slab, in an effort to ensure treatment of the adjoining slab.

In many houses with bi-level slabs, it appears that each level will require some treatment of its own. The aggregate under the two levels will not form a continuous layer, well-connected at the contact point between the levels. In these houses, the number and locations of the suction points will have to be selected for each level. One option for placing suction pipes under the slab of the upper level would be to insert them horizontally through the stub wall between the lower and upper levels. For example, pipes could be inserted horizontally through the stub wall under the adjoining slab on grade, from inside the basement. This approach is analogous to that shown in Figure 15, except that the horizontal pipe would be penetrating the foundation wall from inside the lower level rather than from outdoors. The potential advantage of penetrating the stub wall in this manner is that it permits sub-slab treatment of the upper level without the aesthetic impact of outdoor pipes (Figure 15) and without vertical pipes inside the finished upper level (Figure 14). In addition, it permits the piping treating the upper level to be easily tied in with the piping treating the lower level. Of course, if the upper slab requires a suction point on a side away from the common wall with the lower level, this stub wall penetration will not be sufficient.

5.3.4.3 Installation of Suction Pipes into Slab

For the configuration in Figure 14, holes must be made in the slab at the points where the suction pipes are to be installed.

There are several ways of making these holes. If an unused sump pit containing exposed soil or aggregate is present, it can be used to provide ready-made access to the aggregate under the slab. The pit is covered with an airtight cover, and the suction pipe penetrates this cover, similar to the arrangement depicted in Figure 12 and described in Section 5.2.4.2. The difference is that, in this case, there are no drain tiles, there is probably no sump pump, and the sump crock shown in Figure 12 is absent. Before sealing the sump pit, it might be well to dig around the pit with a trowel, to confirm that there is good communication with the surrounding soil and aggregate. For example, cases have been observed where sumps which appeared to have soil at the bottom were in fact fully concrete-lined, with a layer of soil concealing the concrete at the bottom. If the sump receives water from on top of the slab, a cover of the type shown in Figure 13 would be needed.

If pipes must be installed where there is no sump pit, the easiest and neatest way to make a hole in the slab is with a coring drill. Such a drill (with a diamond bit) can be used to cut through the slab and remove a core of the concrete of the same diameter as the outside diameter of the intended suction pipe (e.g., 4-1/2 in.). This approach leaves the adjoining slab intact. Coring drills are usually continuously cooled with water during use, and a sand dike is typically constructed around the drilling area to contain the water. Thus, any carpeting would have to be removed. Coring drills (and operators) can generally be hired from local construction firms. Alternatively, with additional time, a homeowner could make a fairly neat hole through the slab using small tools. A 4-in. circular pattern of small (1/4- to 1-in.) holes can be drilled through the slab using a masonry drill, and the circular hole can then be chipped out using a medium-sized rotary hammer with a chisel action (Sa87b).

An approach for making a larger hole in the slab calls for using a jackhammer. Electrically driven hammers can be rented by a homeowner, but these are not always powerful enough to break through the concrete. More powerful compressed-air hammers and experienced operators might be needed. The hole created in the slab by a jackhammer might typically be 1 to 2 ft square. Alternatively, a large hole can be cut using a diamond saw.

Figure 14 depicts an open hole excavated in the aggregate and soil under the slab beneath the hole in the concrete. The purpose of this sub-slab hole is to reduce the pressure loss in the system. The soil gas — moving through the soil from all directions toward the suction point — sustains a significant pressure drop as it accelerates from its relatively low velocity in the soil at some distance from the pipe (perhaps only a few feet per minute), to the velocity in the pipe (perhaps 50 to 200 ft/min, or even higher). The hole reduces this pressure drop because the pressure drop sustained in accelerating the soil gas through free air (that is, the hole) is much less than the drop sustained in accelerating it through a porous medium (such as soil or aggregate). The benefits of having this hole under the slab increase as the porosity of the soil/aggregate decreases. That is, the hole is more important when the soil under the slab is less permeable, and is less important when there is a good layer of highly permeable aggregate. The larger the sub-slab hole is in diameter, the greater will be the amount of the acceleration that will occur in the hole (rather than in the soil), and hence the greater will be the benefits of reduced pressure loss.

Various mitigators use various criteria regarding this sub-slab hole. If there is a good layer of aggregate (and if a high-suction fan is being used with relatively limited pressure loss in the piping), it is probably not really necessary to have a sub-slab hole. However, system performance could be improved somewhat by making the hole, so that it is recommended that the hole be included in any event as a matter of course. If the slab hole is a capped sump, the sub-slab hole is provided automatically. If the slab hole is prepared with a coring drill, it will be necessary to work through the cored hole with appropriate tools to expand the hole under the slab to the maximum diameter practical.

Where sub-slab permeability is poor, the importance of the sub-slab hole can be so great that a special effort should be considered to make the hole as large as practical. To provide the necessary access to the sub-slab, the opening through the slab must be roughly 12 to 18 in. square (or in diameter), made with a jackhammer. The hole under the slab can then reasonably be excavated with a diameter of 24 to 48 in. The suction pipe is then installed, and the concrete slab restored. Rather than filling this hole with coarse aggregate, it is suggested that, for maximum effect, the hole be left as an unfilled void. One approach for doing this is illustrated in Figure 16, although options can be considered. In the illustrated approach, the horizontal dimension of the sub-slab hole is somewhat less than the dimension of the hole that has been jackhammered in the slab. Thus, there is a lip of undisturbed aggregate and soil around the slab hole which can support a piece of plywood or sheet metal, which would prevent wet concrete from falling into the hole when the slab is restored. Ultimately, the weight of the dry concrete covering the hole would be supported by the original slab, if the sides of the opening through the slab have been jackhammered at an angle, as shown in Figure 16. The new concrete would also be supported by the undisturbed lip. Another alternative for supporting the wet concrete, rather than using a metal or plywood cover, would be to fill the hole with clean, coarse aggregate. However, this will increase the soil gas pressure drop through the hole. Whenever permeability is poor, it is recommended that the hole be left unfilled in order to maximize the benefit of reduced pressure loss.

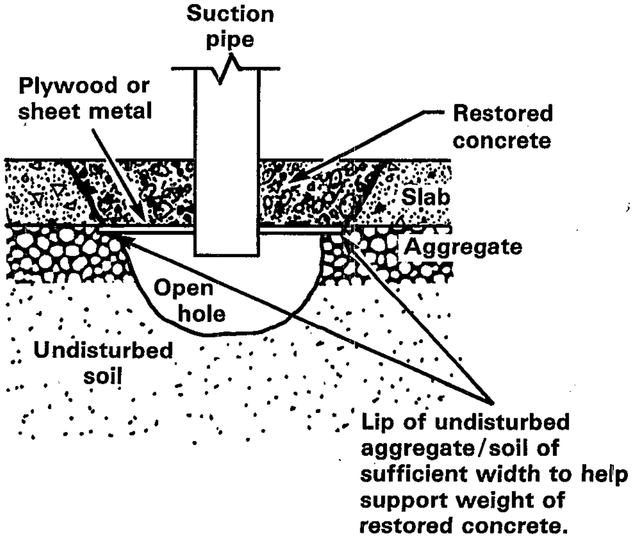


Figure 16. One method for creating open hole under sub-slab suction point when slab hole has been created by jackhammer.

The time and cost involved in installing a suction pipe in this manner will be greater than if the pipe were installed with a coring drill and with only a small sub-slab hole. However, in houses with poor permeability, the large-hole approach can reduce the number of suction pipes needed, which can have aesthetic and cost advantages, and it might improve performance. Efforts are underway to further assess the "jackhammer/large-hole" approach, and to better compare the tradeoffs between this approach and the "coring drill/small hole" approach for poor permeability houses.

Whenever the opening through the hole is made using a jackhammer, it is recommended that a sub-slab hole be excavated as large as practical, even if the permeability is not poor. The hole can only help system performance, and the increased access to the sub-slab that the jackhammered opening provides should be taken advantage of. If the permeability is good, filling the hole with clean, coarse aggregate will simplify restoring the slab.

In houses where sub-slab permeability is good, the diagnostic approach discussed in Item 8 of Section 2.4 for determining the pressure field extension (Sa87a) can give quantitative information. Under these conditions, the diagnostic test takes into account the size of the anticipated sub-slab hole. As discussed in Section 2.4, the distance between the vacuum cleaner suction point and the measurement point, which is perhaps 8 in. away, is the radius of the anticipated hole under the slab.

After the hole through the slab and any hole under the slab have been prepared, a vertical plastic pipe must be mounted in the hole. If the hole is a covered sump pit, the mounting is performed as described in Section 5.2.4.2 (and as shown in Figure 12). The seam in the sump cover around the perimeter of the suction pipe, where the pipe penetrates the cover, must be well sealed with caulk or other sealant, so that house air is not sucked down into the sump.

If the slab hole is prepared using a coring drill to the same dimensions as the pipe, as in Figure 14, the pipe is inserted into the hole such that the bottom of the pipe ends no more than an inch or two below the underside of the slab. If a sub-slab hole is not dug, the bottom of the pipe should not extend below the sub-slab aggregate; the open end of the pipe should be embedded in the permeable aggregate layer. The vertical pipe will need some support from above to hold it in place. The crack between the pipe perimeter and the concrete must be sealed with caulk or asphaltic sealant. Care should be taken to force the caulk down into the crack. If the gap between the pipe and the concrete is large enough, it might initially be plugged using backer rod, with additional sealant on top. If this crack is not sealed well, house air will leak through it into the suction system, reducing system effectiveness.

If a hole has been jackhammered through the slab and a sub-slab hole excavated, as in Figure 16, then, as discussed previously, a sheet metal or plywood cover must be mounted over the sub-slab hole and over the surrounding lip of undisturbed aggregate. This cover is required so that the new concrete will not fill the hole and will not settle down through (and block) the exposed aggregate. The suction pipe, supported from above, is mounted in a hole through the sheet metal or plywood. As an added precaution, to reduce leakage of house air down through cracks around the boundary of the restored concrete, it would be advisable to liberally apply a sealant (such as asphaltic sealant) around the seams between the pipe and the cover, and between the cover and the side of the concrete hole. If the sub-slab hole is filled with aggregate, the exposed aggregate should be covered by some material (for example, polyethylene liner, building felt) to prevent plugging of the aggregate with wet concrete when the slab hole is repaired. The suction pipe would penetrate this liner, and seams should be sealed. The last step in this process is to pour new concrete in the slab hole to restore the slab. Some investigators propose that the broken surface of the original slab, around the sides of the hole, be cleaned and coated with an epoxy adhesive to help ensure airtight adhesion between the old and new concrete. Before the adhesive has dried, the hole is filled with concrete and leveled to match the existing slab.

The above discussion has addressed the case where the pipes are inserted vertically down through the slab. If the pipes are to be inserted horizontally through a foundation wall, as in Figure 15, then a coring drill is a feasible tool to make the penetrations when there is sufficient work space. Sufficient space will most commonly be available when the penetration is from inside the basement, through a stub wall under an adjoining slab on a higher level. When the hole is being made from outside, at or below grade level, the coring drill can sometimes still be applicable. Another option includes the use of a power drill to make small holes through the foundation wall in the desired circular pattern, and the use of a hand chisel (for hollow-block walls) or a rotary hammer with chisel action to chip out the hole. An auger would then be used to excavate the hole for the suction pipe under the slab. With any of these approaches, the hole through the wall should be made with the same dimensions as the plastic suction pipe that is to be used.

As with the vertical pipe approach, it would be advantageous to excavate a hole in the soil under the slab where the horizontal pipe will end, in order to reduce the pressure drop. This hole might be created by appropriate manipulation of the auger, or perhaps by hand. As discussed previously, if the wall penetration is through the second course of hollow blocks below the slab (to avoid a course of solid blocks immediately below the slab), the hole under the slab should extend up to the underside of the slab. The horizontal pipe should not be angled upward in this hole, to avoid having a low point where water can accumulate.

The distance that the horizontal pipe should be inserted under the slab will depend upon the particular house. In many houses, the pipe might be inserted only a foot or two. This short distance will not only simplify installation, but it also will likely give best treatment of the wall/floor joint and of entry routes associated with block foundation walls. If treatment remote from the foundation walls is required, it might be possible to auger horizontally farther under the slab, if it were known that no sub-slab utility lines were in the intended path. This approach has not been tested.

After the horizontal pipe has been inserted, it should be rodded out if necessary to ensure that it did not become plugged with soil and rock during insertion. The seam between the pipe perimeter and the foundation wall should be sealed, to ensure that outdoor air (or house air, for stub wall installations) does not get sucked through this crack into the suction system.

5.3.4.4 Design of Piping Network

The one or more sub-slab suction pipes will need to be joined together in some logical fashion, and connected to a fan. Usually, the amount of soil gas flow drawn by sub-slab systems is sufficiently low that it is not necessary to use more than one fan for the entire system, unless the suction points are so widely separated that it is simpler to use two fans than to try to connect the piping.

In general, all piping should be plastic (for example, PVC sewer pipe), both from the standpoint of durability and of leak resistance. Flexible air hose (such as clothes drier hose) has not always provided sufficiently gastight joints, and can sometimes sag to create a site for condensate accumulation. It also tears easily. All sections of piping must be carefully joined together with cement to ensure an airtight joint. Caulking of the joints would help ensure that house air leakage into the system will be prevented. Air leakage could greatly reduce the suction in the system.

The size of the piping should be selected to reduce the pressure drop in the pipe while maintaining a reasonable aesthetic appearance. The larger the diameter of the pipe, the lower the gas velocity in the pipe, and consequently the lower the pressure drop. Thus, one should generally use the largest reasonable pipe, so that more of the given fan's suction capability will be used in drawing suction on the sub-slab, and less in moving gas through the pipe. The pressure loss as a function of pipe diameter for a given assumed flow and piping configuration can be calculated to aid in pipe selection. In most of the EPA sub-slab suction testing, the vertical risers out of the slab have been 4-in.-diameter PVC pipe. On occasion, where long horizontal pipe runs are needed to connect risers from different parts of the slab, the horizontal collector might be a 6-in.-diameter pipe, with the 4-in. risers tapping in along the length of the collector. The flows in sub-slab suction systems are generally fairly low, sometimes no more than 50 cfm from the whole system, and perhaps less than 10 cfm in a single riser. Therefore, smaller pipe diameters (e.g., 2 in.) can sometimes be considered for aesthetic reasons with little penalty in increased pressure loss. Anyone considering the use of 2-in. pipe should calculate the pressure loss at different estimated flows to ensure that the loss can be tolerated. If a fan with 6-in. connections is being used, then a 6-in.-diameter pipe might be considered for the riser connecting the rest of the piping network to the fan (especially if this riser is inside the house, and thus less visible). However, at the relatively low flows typical in sub-slab systems, the pressure drop is sufficiently low that 6-in. pipe is usually not really necessary when piping runs are short and fan performance is good. The larger the pipe that can be tolerated aesthetically, the more effective a given fan will be in ventilating the sub-slab.

In addition to pipe diameter, other piping parameters which determine pressure loss are: bends and elbows in the piping; other flow obstructions, such as piping size reducers; and the length of piping. Elbows and other flow obstructions should be minimized, since each creates a pressure drop. The piping network should be designed to be as short as possible.

Where sub-slab permeability is good, the quantitative diagnostic approach for determining sub-slab pressure field extension (Sa87a) permits a calculation of the suction which is required in the sub-slab hole. For a given fan performance curve, one can calculate the pressure loss which can be tolerated in the piping if the required suction under the slab is to be maintained. The pipe diameter, piping length, and piping elbows can then be selected which would keep the calculated piping pressure drop within the tolerable value.

In basements with unfinished ceilings, where there is more than one interior suction point (either vertical slab pipes or horizontal stub wall pipes), the most common piping configuration is to extend each pipe up to the level of the floor joists at the basement ceiling. A central collection pipe is run laterally along the ceiling beneath the joists (or between the joists, if running parallel to them). All of the individual suction pipes are extended horizontally between the joists at the ceiling as necessary so that they can be teed into this central collector. At a logical place, a tee off this piping network connects the system to the fan.

As shown in Figure 14, the options for fan mounting in sub-slab suction systems are the same as those for sump/drain tile ventilation in Figure 12. The tee from the piping system can direct the piping up through the house to a fan mounted in the attic or on the roof. Alternatively, it can direct the piping out through the band joist, to a fan mounted beside the house. Even if there is only one sub-slab suction point, there might still need to be a horizontal run of piping along the basement ceiling. The horizontal run could be needed either to direct the pipe to a point where it can conveniently penetrate up through the upper floors to an attic fan (for example, going through an upstairs closet); or to take the pipe through the band joist at a convenient location to a fan beside the house. With exhaust through the roof, there might also have to be a horizontal leg in the attic to take the piping to a point where it can penetrate up through the roof on the rear slope.

The piping network can be supported by clamping horizontal legs to the floor joists. If the pipe rises through the house to a roof exhaust, it can also be supported in the attic or at the floor penetrations.

In houses where there is a finished ceiling over the slab, rather than exposed floor joists, and where there are interior slab suction points, alternative approaches can be considered. One alternative could be to take the riser from each suction point straight up through the house into the attic, and to make any necessary horizontal run in the attic to tee pipes together before penetrating the roof at one point with a single fan exhaust. Alternatively, each suction pipe could penetrate the band joist at the nearest point, although this would complicate subsequent teeing of the pipes together for a single fan. Or, interior horizontal piping could be concealed by a section of false ceiling, similar to what is sometimes done with HVAC ducts.

All horizontal piping legs must be inclined slightly toward the vertical pipes penetrating the slab, so that condensed moisture will drain away. Accumulated condensate would partially block the horizontal pipes at low spots, increasing pressure drop and potentially reducing performance. If there is an unavoidable low spot, a small hole might be drilled in the bottom of the horizontal pipe at the low point, and a small water trap connected to the hole. Water accumulated in the horizontal pipe would then drain out through the open end of the trap. However, if such a trap were installed, care would have to be taken during warm weather to ensure that the trap remains full of water. Some of the system suction would be lost by air leakage in through the trap if the trap were to dry out.

If the piping penetrates through the band joist, the exterior penetration should be well sealed, and a drip guard installed, so that rainwater running down the outside of the pipe does not enter the house and damage the band joist.

If the suction pipes penetrate horizontally through the foundation wall from outside, one logical approach could be to connect the individual pipes by a horizontal pipe that runs around the necessary part of the house at the level of the sub-slab pipes (that is, just below slab level). If the slab is below grade, the connecting pipe would be placed in a trench which would be filled in, totally concealing the pipe. This horizontal connecting pipe is represented by the circle on the piping elbow in Figure 15. This pipe would become visible only where a portion of the slab became slightly above grade due to the contour of the lot. A riser would tee off from this horizontal connecting pipe at a convenient point to permit mounting of the fan.

With any configuration, joints between sections of piping must be sealed tightly with cement (and caulk, if necessary). Otherwise, air can leak into the piping at these joints, significantly reducing system performance.

5.3.4.5 Selection and Mounting of Fans

The considerations in selecting and mounting the fans for sub-slab suction systems are exactly the same as those discussed for drain tile suction in Section 5.2.4.

As with drain tile suction systems, sub-slab suction systems have generally been observed to give best performance during the EPA testing in Pennsylvania when the selected fan is capable of maintaining a suction of at least 0.5 in. WC (preferably as high as 1 in. WC) in the pipes near their penetration through the slab. Typical soil gas flows encountered at these suctions were 40 to 150 cfm from the total system, often less than 10 cfm from a single suction pipe. The 0.05 hp, 270 cfm in-line fans described in the drain tile discussion have been commonly used in EPA sub-slab installations, and have been used by a number of private mitigators as well. The actual fan used at a given house and the actual fan requirements will depend upon the sub-slab permeability, the air leakage into the system, and the piping pressure losses, among other considerations. The permeabilities under many of the houses tested by EPA were not high. If the permeability of the sub-slab aggregate and the surrounding soil is high, less powerful fans might be sufficient.

The fan should always be mounted outdoors. It should be mounted on the rear slope of the roof, if the pipe goes up inside the house, or beside the house, if the pipe penetrates the band joist. When the pipe rises through the house, the fan can be mounted in the attic, with an exhaust pipe through the roof; this protects the fan from the weather and reduces installation cost, but creates a risk of soil gas release into the attic if an exhaust seal fails. The fan should be mounted vertically so that the condensed soil moisture will drain to the sub-slab, and not accumulate in the fan housing.

Fan exhaust should be above the roofline, and away from windows, to minimize exposure of persons inside or outside the house to the potentially high-radon exhaust. If the riser pipe from the sub-slab network goes up inside the house, the exhaust would be via a penetration through the rear slope of the roof. If the sub-slab piping penetrates the band joist and goes up outside the house, the exhaust should rise above the eaves. If a riser is not employed when the fan is mounted beside the house, the exhaust should be directed away from the house, in an area where people will not be spending extended periods of time. The ultimate fan discharge point should be protected with a screen as necessary to prevent debris from clogging the discharge and to prevent children and pets from reaching the blades. The exhaust should be sufficiently high above the roof so that it does not get covered by snow.

The fan must be mounted on the suction pipe with an airtight joint, using adequate piping cement and caulk as required. Any exhaust piping —that is, piping on the pressure side of the fan — should also be carefully sealed. If the fan housing is in more than one section, the seams between sections must be sealed. Otherwise, soil gas will be released through these unsealed joints (e.g., into the attic or beside the house) rather than just through the intended exhaust point above the roof.

The fan (and any exterior electrical wiring) must be designed for outdoor use.

If the fan and the fan exhaust stack are mounted outdoors, some mitigators recommend insulating the fan and the exhaust stack, to help prevent condensed moisture from freezing and blocking the piping and fan housing in the winter.

As discussed previously, the fan is shown in Figures 14 and 15 as being mounted to draw suction on the sub-slab, because this is the arrangement with which there is the greatest amount of experience. Future development work might provide guidelines for conditions under which the fan could be reversed, to blow outdoor air into the sub-slab. Sub-slab pressurization would avoid the concerns regarding the exhaust of high-radon soil gas which occurs when the fan is in suction. One concern with pressurization is that air blown under the slab at some points could increase the flow of soil gas into the house through certain entry routes. Another concern is possible freezing around the footings in cold climates.

5.3.4.6 Closure of Major Slab and Wall Openings

As discussed in Section 5.2.4.1, it is important that major openings in the slab be closed in order to reduce house air leakage into the system, helping ensure that suction is effectively maintained underneath the slab. In addition to closure of obvious major openings and cracks, the wall/floor joint might well be caulked if it is anything more than a hairline crack, because its length makes it a potentially significant source of house air leakage under the slab. If the wall/floor joint is a French drain, it should be closed as illustrated in Figure 6. Alternatively, if the drain is never used for water drainage, it could be mortared shut. Any sump pit not being used as part of the suction system should be capped with an airtight cover.

Closure of major wall openings is also advisable. Not only might wall closure help reduce air leakage into the sub-slab system, but — to the extent that the walls are not fully treated by the sub-slab system — it could help reduce soil gas entry through wall-related entry routes.

Another potential slab-related entry route is a floor drain, if the drain connects to the soil (for example, to drain tiles or to a septic system). A floor drain might not necessarily contribute to air leakage into the sub-slab system, but it can be a significant soil gas source. Soil gas from the drain tile or septic system can enter the house via the floor drain, with the influx possibly exacerbated by any slight house depressurization caused by the sub-slab suction system. If the floor drain is trapped, it should be ensured that the trap remains full of water. If it is not trapped, it is possible to buy a plastic trap that can be inserted into the existing drain (e.g., see Figure 5). Alternatively, the trap can be plugged using a rubber stopper that can be removed if ever the drain is needed. If the floor drain is trapped, but has a cleanout plug which bypasses the trap — sometimes present when the drain connects to a septic system, so that the drain line can be accessed for cleaning if necessary — the plug must be in place. If it is missing, it should be replaced (for example, with a rubber stopper).

5.3.4.7 Instrumentation to Measure Suction

As discussed in Section 5.2.4.1, it is recommended that a pressure gauge or a manometer be installed in the suction piping at some convenient point inside the house, to provide the homeowner with a continuous indication of whether the fan suction is remaining in the "normal" range for that house. Such continuous pressure measurement can alert homeowners to potential malfunctions in the system which would not otherwise be apparent. Alternatively, the homeowner could be provided with an unmounted gauge, with a resealable sampling port installed in the piping for the homeowner's use.

5.3.4.8 Post-Mitigation Diagnostics

Various post-mitigation diagnostic tests can aid in ensuring that the sub-slab ventilation system is operating properly, and in deciding upon appropriate system design changes if it is not. Some of the potentially most applicable diagnostic tests are listed below.

- *Radon measurements in the house.* One obvious diagnostic test is the measurement of radon levels in the house after mitigation, for comparison against pre-mitigation levels. For a rapid comparison, a measurement over a few days is probably the best option — for example, using a continuous monitor or charcoal canisters. If the system appears successful based upon this short-term test, a longer-term test — for example, an alpha-track detector over a winter — would be advised to confirm sustained good performance under challenging conditions.
- *Gas flow, pressure, and grab radon measurements in individual sub-slab suction pipes.* These measurements would show whether the system was maintaining the expected suction in the pipes, and whether the soil gas flows were reasonable. Low suction and low flows near the slab would suggest a leak in the piping somewhere between the slab and the fan. High flows, above perhaps 40 cfm in one slab pipe (especially if accompanied by low in-pipe radon concentrations), would suggest that house air or outdoor air was leaking into the system, and that some additional slab or wall closure might be in order. Very high suctions and low flows (below a few cfm) might suggest that that particular sub-slab pipe was sucking in an area with poor communication to the rest of the slab, or that the pipe was plugged. Any holes drilled in piping to permit this testing must be plugged when the testing is done.
- *Smoke tracer testing.* A smoke source, such as a chemical smoke stick or an ignited punk stick, could be held near remaining openings in the slab (for example, near the wall/floor joint, if it has not been caulked). If smoke flow is unambiguously down into the cracks everywhere while the sub-slab system is operating, then the system is maintaining good suction under the slab. If flow is unambiguously up in some location, then that portion of the slab is not being treated, and soil gas is still entering the house at that location. If the smoke flow is ambiguous (which will often be the case where only hairline cracks have not been closed), then this simple test is not helpful. Holes could be drilled in the slab to permit more rigorous smoke testing around the slab. These holes would have to be filled after the tests were completed.

  Smoke testing can also be used to check for leaks at joints in the system piping, or at any other seals (such as where the pipe penetrates the slab). Leaks would reveal themselves by causing the smoke to flow unambiguously into the joint or seal (if the system is in suction).
- *Measurement of suction field under slab.* Small test holes could be drilled around the slab, and quantitative pressure measurements made under the slab. This approach would confirm whether the desired level of suction was being maintained around the perimeter of the slab, and where (if anywhere) the suction was inadequate. It would also indicate any need for additional suction points, or a larger fan, or other pertinent system changes. If the quantitative pressure field extension measurements described in item 8 of Section 2.4 were made prior to mitigation, the test holes would already be in place. It would be logical to repeat the sub-slab pressure measurements with the sub-slab suction system operating, to determine if suction is extending to the remote test points as the pre-mitigation diagnostics may have predicted.
- *Testing of combustion appliances for back-drafting.* Sub-slab suction systems would not necessarily be expected to suck enough air out of the house to cause back-drafting, but one should be alert to this possibility. As discussed in Section 5.2.4.1, flow measurements in the flue of some combustion appliances can be necessary to ensure that back-drafting is not occurring. If it is occurring, efforts will be needed to close some of the slab openings through which house air is being sucked, and/or to provide a supplemental source of combustion air.

5.3.4.9 Removal of All or Part of Slab (Worst-Case)

All of the prior discussion of sub-slab ventilation has addressed the house where ventilation pipes are inserted under the existing slab. It is believed that such an approach can often be successful, even in houses with poor sub-slab permeability, if there are an adequate number of suction pipes suitably positioned, and so long as the fan can draw sufficient suction. Large sub-slab holes, as illustrated in Figure 16, and other efforts to reduce pressure loss in the system, can also aid in achieving effective treatment under slabs with poor sub-slab permeability.

While this approach with individual suction pipes under the slab can probably be made to work in most houses, in some houses it may not be sufficient. Data from houses with very poor permeability are too limited to enable guidelines at this time that could define a priori when a particular house cannot be treated using sub-slab ventilation, or what the most economical alternative in such houses might be. One alternative might be to employ block wall ventilation (Section 5.4) in conjunction with, or in place of, slab ventilation.

Where other soil ventilation approaches will not adequately reduce levels in houses with poor sub-slab permeability, the ultimate solution would be to tear out all or part of the existing slab, and to put down a good layer of clean, coarse aggregate before pouring a new slab. This approach would then enable highly effective sub-slab ventilation, almost ensuring very high soil gas radon reductions. The problem, of course, is that replacing the slab in this manner will be very expensive.

Such a comprehensive approach, where the entire slab is replaced, would include the following major steps.

- Jackhammer apart and remove the entire original slab.
- Excavate the underlying soil and rock around the entire floor area, to a reasonable depth (at least 4 in.). Jackhammer out any protruding rock if necessary to achieve a uniform depth.
- Lay a complete loop of 4-in. perforated drain tile around the inside of the footings. Place a tee in this loop which will permit a vertical suction pipe to be connected to the loop after the new slab is poured. Alternatively, one might delete the drain tile loop, and simply make provisions to install a vertical pipe through the new slab as in Figure 14. However, the drain tile loop would seem to be the safer bet. The tee would be placed where the vertical riser could conveniently penetrate the upper stories (for attic or roof mounting of the fan), or penetrate the band joist (for mounting the fan beside the house).
- Fill in the excavation with clean, coarse aggregate, to the level of the top of the footing.
- Lay a polyethylene vapor barrier over the aggregate and the top of the footing; joints in the barrier should be overlapped at least 8 in., and penetrations of the barrier by utilities should be sealed or taped. This barrier will prevent the wet concrete from settling through the aggregate when the new slab is poured, and will reduce house air leakage through slab cracks into the sub-slab suction system.
- Pour a new slab.
- Install a vertical suction pipe on the end of the tee protruding through the slab, and take this riser up through the house (or out through the band joist) to a fan, as described in Sections 5.2.4 and 5.3.4).

Alternatively, consider removing the slab only around the perimeter, in order to reduce expense and disruption inside the house. In this case, the excavation, the backfilling with aggregate, etc., would take place only around the perimeter. An interior perimeter drain tile would be laid, as above. This approach is illustrated in Figure 17. This partial replacement of the slab would ensure good treatment of the perimeter footing region, but could still leave the central area of the slab insufficiently treated.

There are as yet no data to confirm the radon reduction performance of such comprehensive slab-replacement approaches in existing worst-case houses. Where the entire slab is replaced, performance would be expected to be very good. Where only the perimeter of the slab is replaced, performance would likely depend upon to what extent radon entry had been through perimeter routes (such as the wall/floor joint) versus routes in the interior of the slab.

It is re-emphasized that slab removal is considered as a last resort. In most houses, it would be expected that a suitable radon reduction system could be designed which would not require slab removal.

5.3.5 Operation and Maintenance

The operating requirements for a sub-slab ventilation system consist of regular inspections by the homeowner to ensure that:

- the fan is operating properly.
- the suction in the piping is within the normal range, if a gauge or manometer has been installed. Smoke stick tests to confirm that the flow remains downward through slab cracks are also advised, to the extent that cracks suitable for smoke testing exist.
- all system seals are still intact (for example, where the pipes penetrate the slab and/or

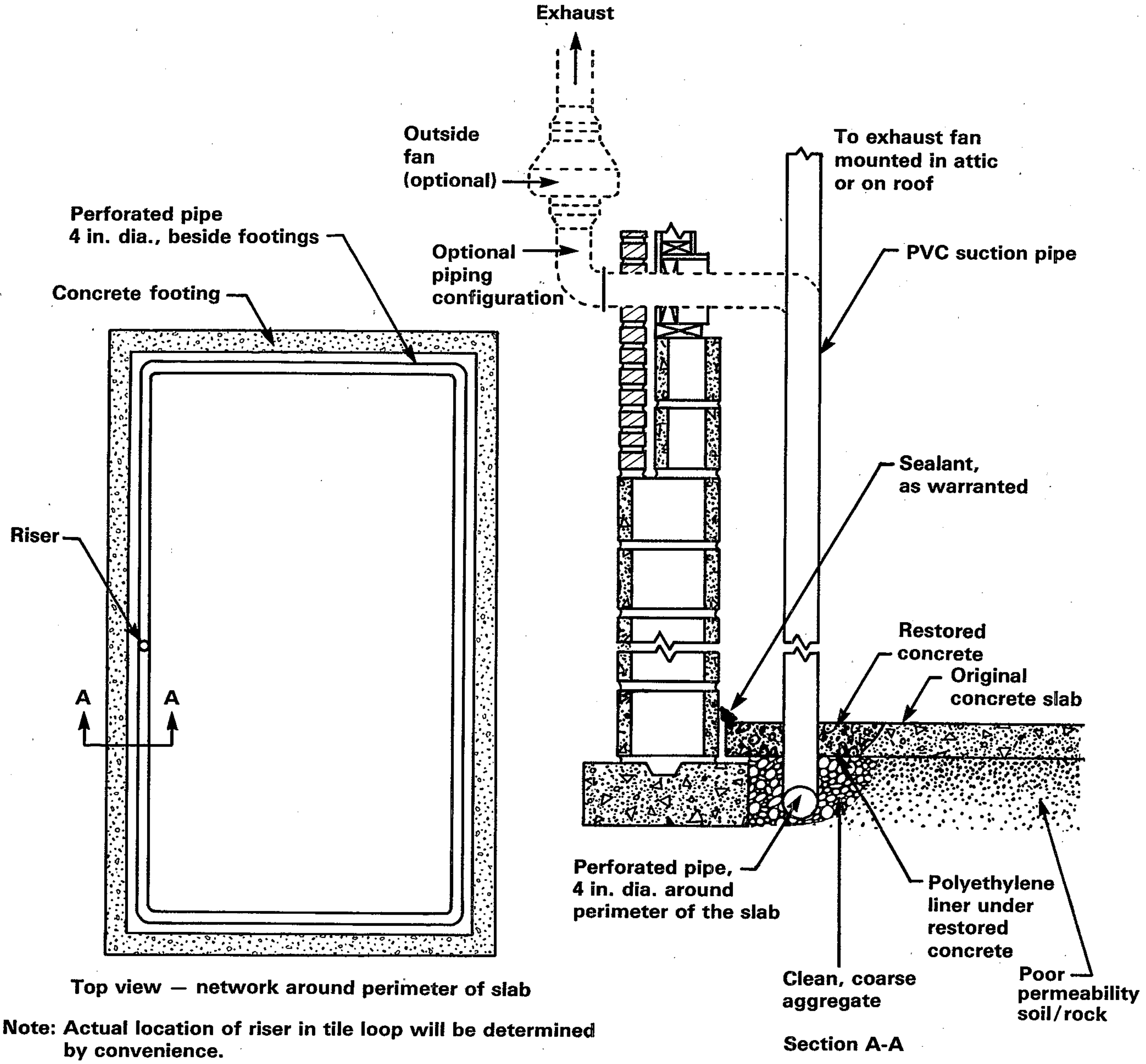


Figure 17. Retrofit of interior drain tiles under slab with poor sub-slab permeability (where only perimeter of original slab is torn up)

foundation walls, at all piping joints, and at the connection between the fan and the piping). Smoke testing would help indicate if leakage is occurring at these points. Any holes made in the slab or piping for diagnostic testing should be checked to ensure that the plugs remain intact.

- all slab and wall closures remain intact (and the integrity of any new concrete remains intact).

Maintenance would include any required routine maintenance to the fan motor (for example, oiling), replacement of the fan as needed, repair of any broken seals, and re-closure of any major slab openings where the original closure has failed. If the pressure gauge/manometer indicates that the suction is not in the normal range, and if the above maintenance activities do not correct the situation, the homeowner should measure the radon in the house and possibly contact a mitigation professional.

5.3.6 Estimate of Costs

Costs of sub-slab systems will vary widely, depending upon the characteristics of the house, the finish around the installation, and the diagnostic testing conducted, among other factors.

If an installation of the type shown in Figure 14 is made in an unfinished basement, if only one or two suction points are needed, and if the fan is mounted beside the house with no more than a simple exhaust riser above eave-level outside the house, the sub-slab system might be installed by a contractor for as little as $900 to $1,200 in the simplest case. If the riser from the sub-slab network is taken up through the house to a fan mounted in the attic or on the roof, the cost of contractor installation might typically be about $1,500 to $2,500, if no unusual difficulties are encountered. The increased cost for taking the pipe up inside the house is due primarily to the additional labor required. Site-specific complexities could increase these costs significantly. Among the complexities causing a cost increase could be:

- extra effort in sealing large slab and wall openings (for example, pouring a slab in an unpaved fruit cellar).
- high degrees of floor and wall finish over the slab or on the floors above, increasing the effort in modifying and restoring finish to install and conceal the pipes (the pipes into the slab, and the riser to the roof).
- steps required to address poor sub-slab permeability, such as an increased number of suction pipes and/or excavation of large sub-slab holes as in Figure 16.

The installed costs of the exterior sub-slab system (Figure 15) will generally be similar to those given above for the interior through-the-slab approach, except that cost impacts (caused by high degrees of interior finish, and by taking the riser up inside the house) are avoided. One factor influencing the cost of externally installed systems will be the amount of effort expended to conceal the outside riser (for example, by framing outside finish around the riser). The above costs include both labor and materials.

In the worst case, if the slab had to be torn up due to poor sub-slab permeability (as discussed at the end of Section 5.3.4), costs would rise dramatically. Such an extensive effort would cost at least several thousand dollars, with the cost becoming higher as the degree of finish over the slab increases.

Installation of a sub-slab suction system is not an easy "do-it-yourself" job, but some installations might be successfully completed by some homeowners with the necessary skills. In those cases, the installation cost would be limited to the cost of materials (perhaps about $300 for the fan, piping, and incidentals) plus the cost of hiring a coring drill or jackhammer operator. Costs of materials for refinishing around the installation, or for concealing the pipes, would be extra. A do-it-yourself installation might be most logically attempted when it is known that a good layer of crushed rock underlies the slab.

Operating costs would include the electricity to run the fan, and a heating penalty because some of the gas exhausted by the fan will be house air sucked down through the slab. Occasional replacement of the fan would also be a maintenance cost. As discussed in Section 5.2.6, the cost of electricity to run a 0.05 hp fan 365 days per year would be roughly $30 per year. Assuming that about half of the gas exhausted by the fan is house air that has leaked into the system — and considering the typical total gas flows observed in EPA's systems in Pennsylvania (He87b) — the sub-slab system might be expected to increase the house ventilation rate by roughly 40 cfm. (This figure will vary from house to house; some researchers have determined through tracer gas measurements that up to 100 cfm was being drawn out of some houses by the sub-slab suction system (Hu87).) The cost of heating 40 cfm of makeup outside air to house temperature throughout the cold season would be very roughly $100 per year in relatively cold climates, depending upon outdoor temperatures and fuel prices. If the house is air conditioned, the cost of cooling 40 cfm through the summer would be very roughly $20 per year, depending upon temperature and humidity. Thus, the total operating cost might be roughly $150 per year. There is not sufficient experience to reliably estimate the lifetime of the fans. A new fan of the type commonly used in the EPA test program would cost about $100 (not installed).

5.4 Ventilation of Block-Wall Void Network (Active)

5.4.1 Principle of Operation

When the foundation wall is constructed of hollow concrete blocks or cinder blocks, the interconnected void network inside the block wall can serve as a conduit for soil gas. Soil gas which enters the wall through mortar joint cracks, pores, and other openings in the exterior face of the blocks can move either vertically or laterally throughout the wall inside this void network. The soil gas can then be drawn into the house through any openings in the interior face, including any uncapped voids in the top course of block, holes around utility penetrations, mortar joint cracks, and the pores in the block itself.

The principle of block wall ventilation is to sweep the soil gas out of these voids by using a fan to draw suction on the void network, or to prevent soil gas from entering the voids by blowing outdoor air into the network and thus keeping it under pressure. Depending upon the communication between the wall voids and the sub-slab region, ventilation of the wall voids can also provide some treatment of the sub-slab, at least in the vicinity of the walls (for example, the wall/floor joint). Communication between the wall voids and the sub-slab can occur through mortar joint cracks, pores, and other openings in the block wall below the level of the slab. The extension of the pressure field out from the wall will also depend upon the permeability of the surrounding aggregate and soil. When the wall ventilation system is operated in suction, the void network might be pictured as a large collector into which the surrounding soil gas is drawn, and from which the soil gas is then exhausted outdoors. (Since the void network is also nominally lower in pressure than the house, house air also flows through unclosed wall openings into the voids and out through the fan exhaust.) When the system is operated in pressure, the void network is a plenum which permits the pressurizing air to be distributed around the perimeter of the foundation.

A key problem with wall void ventilation is that the numerous and often-concealed wall openings (including the pores) are very difficult to close adequately. Thus, despite efforts to close these openings, large amounts of house air and outdoor air will leak into the ventilation system through these openings, if it is operated in suction. If the system is in pressure, air being blown into the wall will leak out. Therefore, it can be difficult to maintain sufficient suction (or pressure) throughout the entire wall. Thus, high radon reductions can sometimes be difficult to achieve using wall ventilation alone. As an added concern, house air leakage into a wall suction system can sometimes depressurize the basement sufficiently to cause back-drafting of fireplaces and other combustion appliances. Where back-drafting occurs, an outside supply of combustion air must be provided, or else the wall ventilation system might be operated in pressure instead of suction. Basement depressurization resulting when the wall system is in suction can also increase soil gas influx through slab-related entry routes not being treated by the system, thus reducing net radon reduction performance.

In view of these concerns, ventilation of block wall voids is now looked upon as a technique which would be used largely as a supplement to sub-slab suction (or other mitigation techniques) in cases where sub-slab suction by itself is not sufficient to treat the wall-related entry routes. Houses with poor sub-slab permeability might sometimes be candidates for wall ventilation, if the slab is not badly cracked (i.e., if there are not significant slab-related entry routes).

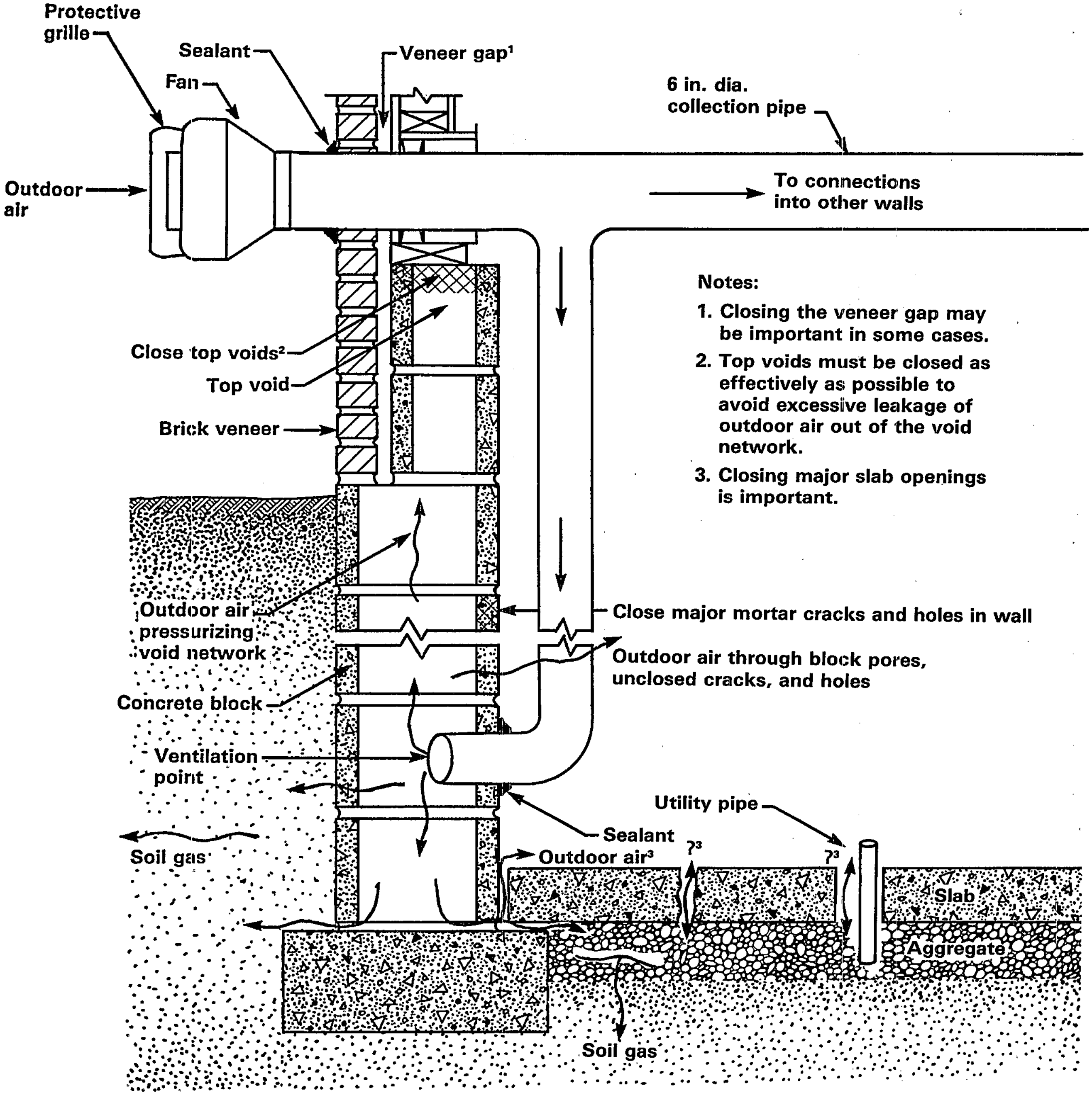
Two approaches have been considered for implementing block wall ventilation. One approach, referred to as the "individual pipe" approach, is illustrated in Figure 18. In this approach, one or two pipes are inserted into the void network in each wall to be treated and are connected to fans that draw suction on or ventilate the wall. The second approach (Figure 19) is referred to as the "baseboard duct" approach. In this case, a sheet metal "baseboard" is installed around the entire perimeter of the basement (including interior block walls), and covers the joint between the floor and the wall. Holes are drilled through the interior face of the block at intervals inside this baseboard, and the wall is ventilated by depressurizing or pressurizing the baseboard duct with fans. The baseboard duct approach offers potential advantages, in possibly producing a more uniform ventilation effect around the perimeter, better treating the sub-slab (especially if installed over a French drain), and in some cases being less obtrusive. However, it is more expensive than the individual pipe approach, due to the increased labor required for installation.

Regardless of which of these approaches is used, it is crucial that all large openings in the walls be closed. These openings include the voids in the top course of block (if the walls are not capped by a course of solid blocks), and large holes in the face of the wall (for example, around utility penetrations, chinks in the blocks, and mortar joints). There can also be large concealed openings, such as the gap between the interior block and any exterior brick veneer, and such as openings concealed within fireplace and chimney structures. The fans that can be realistically considered for this application will have trouble enough in maintaining suction/pressure throughout the void network even if the large accessible openings are well closed. If the openings are not closed, the chances of obtaining effective wall treatment are greatly reduced.

Figures 18 and 19 show the fans operating to pressurize the walls. This is done to emphasize the need to be alert to house depressurization effects that can commonly result with wall ventilation systems when the fans are operated in suction. As discussed in Section 5.4.4.1, operation in pressure might not always be desirable. In such cases, the fan would better remain in suction, with the depressurization effects being addressed by providing an outside source of combustion air for appliances.

5.4.2 Applicability

This technique applies only to houses having hollow-block foundation walls (concrete block or cin-



Notes:

1. Closing the veneer gap may be important in some cases.
2. Top voids must be closed as effectively as possible to avoid excessive leakage of outdoor air out of the void network.
3. Closing major slab openings is important.

Figure 18. Wall ventilation with individual pressurization points in each wall.

der block). Among block-wall houses, wall ventilation will generally be most applicable under the following conditions.

- Houses where diagnostic testing, and/or previous experience with a sub-slab suction system, indicates that wall-related entry routes will not be adequately treated by a sub-slab suction system alone. Thus, wall ventilation is needed as a supplement to, or in lieu of, sub-slab suction. For example, wall ventilation might be recommended if — despite a sub-slab suction point relatively near the block wall — radon levels inside the wall voids are still distinctly elevated.

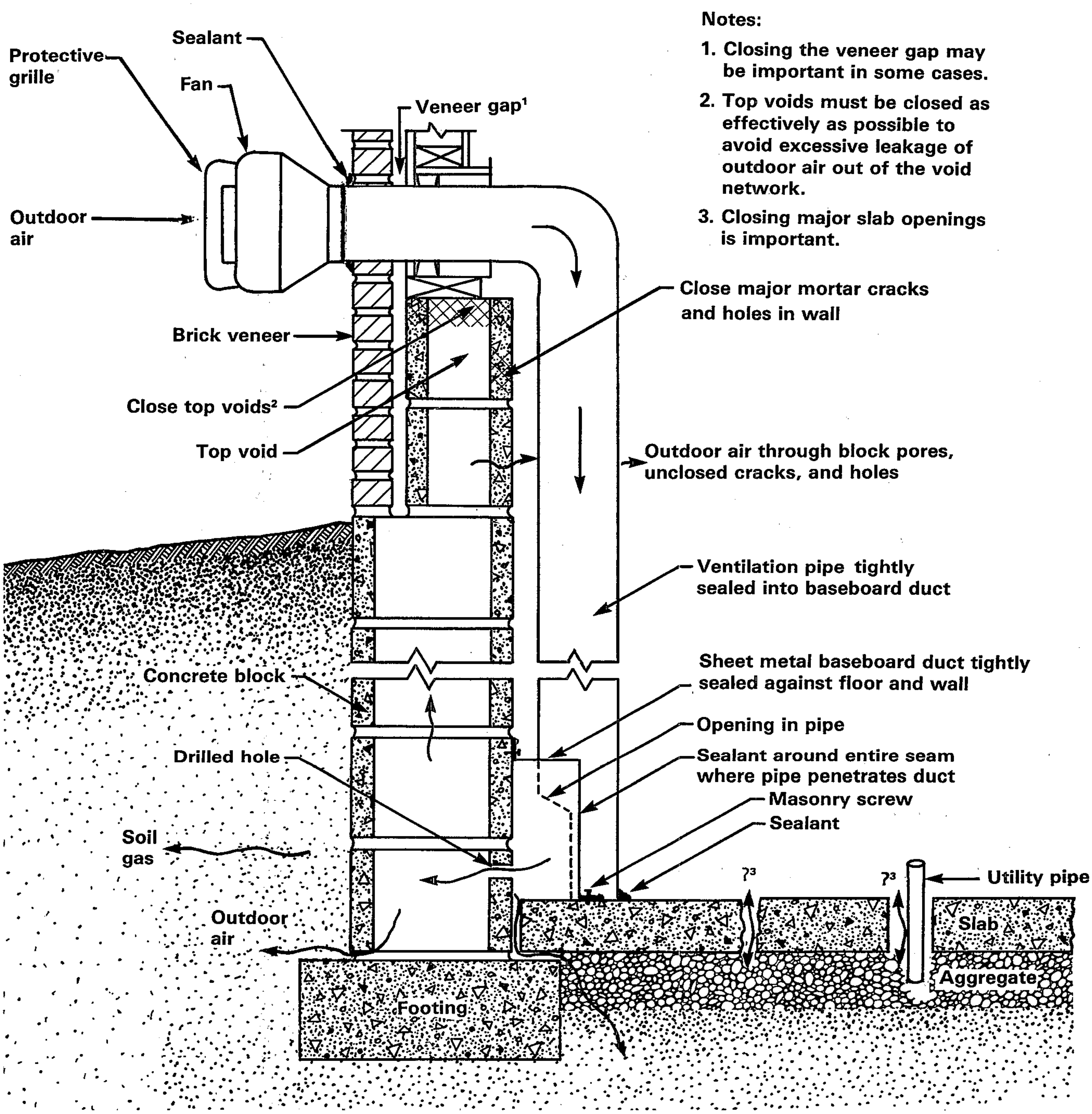


Figure 19. Wall ventilation with pressurized baseboard duct.

- Houses where there are no major openings in the block walls, or where the openings are accessible for reasonably convenient closure. This includes not only the perimeter walls, but also any interior block walls which penetrate the slab and rest on footings underneath the slab. Particularly amenable are houses where:

— a course of solid cap block closes the top of the walls all around. Or, if there is no solid cap block, the open voids in the top course are accessible for effective closure.

— there is no fireplace/chimney structure built into one of the walls, potentially concealing routes for air leakage and soil gas entry.

— there is no exterior brick veneer, concealing a gap between the veneer and the interior block or sheathing through which air might flow down into the void network (see Figure 20c).

— the block does not have particularly high porosity, since high porosity facilitates air flow through the face of the block. True cinder block is often highly porous. Concrete block, which is more common, will occasionally have higher-than-normal porosity when there is a reduced amount of cement present in the mix from which the blocks were fabricated. Particularly porous blocks are characterized by more sharply defined grains of aggregate on the surface, deeper pits between the grains, and a rougher texture. In less porous blocks, these features are more smoothed out by the concrete.

— the wall is reasonably integral, and does not contain an excessive number of wide mortar joint cracks or missing mortar. (All walls will have *some* hairline mortar joint cracks.)

Where there are major difficult-to-access wall openings, wall ventilation can sometimes still give good reductions. However, with such walls, the wall ventilation system will be more expensive, due to the need for added closure effort, additional fan capacity, additional ventilation points, and steps to minimize pressure loss in the system piping (larger diameter pipe, fewer elbows). With such an extensive wall ventilation system, approaches other than wall ventilation might become more economical.

- Houses where there are no obvious major slab-related soil gas entry routes remote from the wall. Some EPA data suggest that the ventilation effects inside a wall will not always extend effectively under the slab, even if the wall can be effectively closed. Thus, houses with badly cracked slabs, for example, would not be good candidates for wall ventilation, except in conjunction with sub-slab suction.
- Houses with 1- to 2-in. wide French drains around the perimeter wall/floor joint. Such houses could sometimes be logical choices for the baseboard duct variation of wall ventilation. The French drain will generally have to be covered in some manner in any event, definitely with any soil ventilation approach. Application of the baseboard duct approach provides this cover, while: a) taking advantage of this ready-made access under the slab to provide sub-slab treatment around the entire slab perimeter; and b) uniformly treating the wall voids close to the footing region. This approach with French drains is essentially a combination of sub-slab and wall void treatment.
- Houses of any substructure involving block foundation walls, where the walls extend up to form part of the living area, or where the voids open to the living area. This could include houses with basements, slabs below grade, slabs on grade, or certain crawlspace designs.
- Houses with moderate to high initial radon concentrations, above about 15 to 20 pCi/L. The cost of contractor-installed wall ventilation systems is sufficiently high that other less expensive approaches (capable of lesser radon reductions) might be more cost-effective in houses with only slightly elevated initial levels.

5.4.3 Confidence

Block wall ventilation has been shown to be very effective in houses suited to the approach (that is, houses which permit good closure of all major wall openings and which do not have major slab-related entry routes remote from the walls). Wall ventilation has also been made to perform well in less suitable houses, through the expenditure of the necessary effort to adequately close wall openings and to boost suction/pressure in the walls. However, EPA's experience has suggested that one cannot always reliably predict which houses will be truly suitable, and how much effort will be required to make the wall ventilation system give the desired reductions. Therefore, the confidence in this technique is felt to be no better than moderate.

EPA has tested wall ventilation in 11 block basement houses in Pennsylvania with initial radon levels ranging from 50 to 1200 pCi/L (He87a). Among the conclusions apparent from that study are the following.

- Individual-pipe wall ventilation systems were installed in five houses suited to this technique (open top voids readily accessible for closure, no fireplace, no brick veneer). High reductions (96 to 99 percent) were achieved in all but one, referred to as House 19. Wall closure was relatively simple in these five houses, and the radon reductions were thus achieved at a relatively moderate cost. In four of these houses, the fans were operated in suction; in the fifth, the fan was in pressure.
- In House 19, where the fan was in suction, reductions were limited despite effective clo-

sure of the walls, confirmed by smoke tracer testing showing that the walls were under suction everywhere. The slab in this house was badly cracked, and diagnostic testing confirmed that soil gas was entering the house through these cracks. Thus, it appears that effective wall ventilation, in a house amenable to effective wall closure, cannot be relied upon to treat slab-related entry routes remote from the walls.

- Individual-pipe wall ventilation systems were tested in three additional houses that offered a variety of difficulties in wall closure. These difficulties included inaccessible open top voids, a fireplace, and exterior brick veneer. Reductions above 90 percent were obtained in two of these houses, largely by increasing the number of ventilation points, increasing the fan capacity, and reducing the pressure losses in the system piping (larger-diameter pipe). These two houses had one or two fans in suction. But in the third house, which had the full range of complexities preventing effective wall closure, reductions were less than 50 percent with two fans in pressure.
- Three of the four houses tested using the baseboard duct variation achieved 97 to 98 percent radon reductions, confirming the potential of this approach. One of these three had a French drain. These three houses offered a variety of difficulties in wall closure — inaccessible top voids, a fireplace, exterior brick veneer, and unusually porous blocks. Efforts to close wall openings in one house were particularly extensive, including injection of foam to close the gap between the exterior brick veneer and the interior block or sheathing, and coating the entire face of the porous cinder block with waterproofing paint. Each of the houses had two fans in pressure, blowing into the duct. In some cases, access to the entire perimeter wall/floor joint was difficult or impractical due to obstructions against the wall (stairways, shower stalls, boilers, etc.).
- The fourth house on which the baseboard duct variation was tested was one (end) row house in a larger structure containing several units, with a French drain around the entire structure. Since the wall ventilation in the one unit could not treat the entire multi-house structure, this house is not felt to be a fair representation of the potential of baseboard duct ventilation in detached houses.

In view of the above results, it is apparent that wall ventilation can perform very well with reasonable effort in suitable houses, and can be made to perform well in some less well-suited houses if sufficient effort is expended. In some houses with particularly extensive wall openings or with badly cracked slabs, wall ventilation might not be practically applicable except perhaps in combination with other techniques. The baseboard duct variation appears to help achieve high performance in the more complex houses, but, with the limited data, the observed good performance of the baseboard variation might be due in part to the additional wall closure efforts in the houses with the baseboard systems.

Block wall ventilation was tested on one New Jersey house as part of a project funded by EPA and the U. S. Department of Energy (Se87). The house had a basement with an adjoining slab on grade. Two individual wall suction pipes were inserted into the stub wall in the basement, separating the two wings of the house. This system reduced radon levels from approximately 150 to about 3 pCi/L.

The results with sub-slab suction in houses with block foundation walls (Section 5.3.3) suggest that a well-designed sub-slab system can often effectively prevent soil gas entry into the house through the wall void network. However, the wall ventilation results presented above (especially from House 19) suggest that a well-designed wall ventilation system might not so often be expected to prevent soil gas entry through remote slab cracks. Accordingly, a logical approach in high-radon block basement houses would generally appear to be to install sub-slab suction initially, and to augment the sub-slab system with wall ventilation if the sub-slab system proved unable to treat the walls.

Limited data are available from houses where a sub-slab suction system has been tested with and without simultaneous wall suction (He87a). These limited data suggest that sometimes wall ventilation can be a beneficial supplement to a well-designed sub-slab system, and that sometimes wall ventilation is unnecessary. Currently, there are no clear guidelines for determining beforehand when wall ventilation will be a necessary supplement to sub-slab suction.

5.4.4 Design and Installation

5.4.4.1 Individual-Pipe Variation

Figure 18 illustrates ventilation of the wall void network by inserting a series of individual pipes into the wall cavities at various points.

In the design of a pipe-wall ventilation system, every block wall that rests on footings should have at least one vent pipe. This would, of course, include each of the exterior perimeter walls (even if one or more of these walls is not below grade). In addition, any interior block walls that penetrate the slab and rest on footings should be vented. These include walls dividing the basement into living areas, walls separating the basement from an attached garage, and walls separating the basement from an adjoining crawl space. If the crawl space is heated (that is, is essentially open to the basement or to other parts of the house), the block walls around the crawl space also must be vented. The concern with above-grade and interior walls arises because soil gas can enter the void network around the underground footings. Thus, any block wall that contacts footings can serve as a chimney for soil gas to flow into the house, even if the exterior face of the block does not appear to contact the soil.

Figure 18 shows the fans operating to pressurize the walls. This is done to emphasize the need to be alert to house depressurization effects that can result when the fans are operated in suction. Where wall ventilation is the sole mitigation measure employed — in which case significant fan capacity is applied to the walls — experience to date suggests that combustion appliance back-drafting and increased soil gas influx through slab cracks will be fairly common problems when the system is operated in suction. Operation in pressure is an approach that has been used successfully in avoiding these problems in several houses tested by EPA (He87a). However, as discussed in Section 5.3, there is concern (in the absence of data) that operation of active soil ventilation systems in pressure might sometimes significantly reduce net performance by forcing soil gas up into the house through some entry routes. Some limited data from sub-slab pressurization systems support this concern (Se87). Moisture condensation/freezing in the walls of the house during cold weather due to increased house ventilation, and freezing around the footings, are additional potential concerns with pressurization. The EPA data to date on wall pressurization systems have not revealed a house where performance has been significantly reduced by operation in pressure rather than suction. However, these data are limited to just a few houses, and the potential thus remains for problems to arise if operation in pressure is attempted in a broader range of houses. Accordingly, if a wall ventilation system is installed as the sole mitigation measure, the installer should be prepared to install an outside supply of combustion air if operation in suction causes back-drafting and if operation in pressure proves undesirable.

Where wall ventilation is only part of the overall mitigation system, the fan capacity applied to the walls is sometimes much less than where wall ventilation is used alone. For example, where wall ventilation is used in conjunction with sub-slab suction, it is common for the wall treatment to address only one or two walls, and for only a fraction of the total fan capacity to be applied to the walls. In these houses, the risk that house depressurization from the wall suction will be sufficient to cause back-drafting is reduced. However, it is still a threat.

Pre-mitigation diagnostic testing. One of the key pre-mitigation diagnostic procedures will be visual inspection. Among the factors of particular importance to be noted during the visual inspection would be:

- the nature and accessibility of major openings in the wall, and the presence of features potentially complicating wall closure (for example, open top voids rendered inaccessible by a sill plate, fireplace structures, exterior brick veneer, porous blocks).
- the nature of the slab cracks (or other slab-related entry routes) remote from the walls, which might not be treatable by wall ventilation.
- wall finish which might influence the location of ventilation points.

Another possible diagnostic test would be determination of the pressure field which can be established inside the block wall (item 9 in Section 2.4). This test could be analogous to the measurement of sub-slab pressure field extension, discussed in item 8 of that section. In the quantitative variation of this type of test, a fan (or an industrial vacuum cleaner) would be used to develop pressure (or suction) at a point in the wall, and the resulting pressures at other points in the wall would be measured. For this test to be meaningful, major wall openings should be closed before the tests are conducted. Otherwise, very limited extension of the pressure field would likely be measured, due to air leakage through the wall openings.

A third possible diagnostic test would be spot radon measurements on samples taken from inside some of the block cavities in the foundation walls. Comparison of the results from the various walls would suggest which walls are relatively "hotter," thus warranting emphasis in system design. Holes can be drilled into some of the block voids to enable sampling of the gas in the cavities. Alternatively, samples can be drawn through existing penetrations, if available. It is recommended that the samples be drawn from the second course of blocks above the floor slab (Tu87a).

Selection of number and location of suction points. Where wall ventilation is the only mitigation measure being installed, at least one ventilation pipe will generally be needed in each perimeter wall and in each interior block wall that penetrates the slab. At least one pipe per wall is necessary because there is no assurance that effective communication will be maintained between the voids in turning a corner. The mason who laid the block during construction could have applied the mortar and laid the block in a manner that would prevent the pressure effects in one wall from being effectively transmitted to the adjoining wall. For this same reason, if there is a discontinuity in a wall (formed by a pair of right-angle turns in the block), there should probably be at least two ventilation points in that wall, one on each side of the discontinuity. Because of air leakage and the resulting difficulty in maintaining the pressure field throughout the void network, the installations in the EPA testing (He87a) generally included a second ventilation pipe in a wall any time the wall was longer than about 25 ft. These two pipes would logically be installed roughly one-quarter of the wall length from each end of the wall. Where only one pipe is used in a wall, it is reasonable to locate it approximately in the linear center of the wall. If there is reason to believe that a particular wall could be subject to greater leakage (for example, due to a fireplace structure or to exterior brick veneer on that wall), an additional ventilation pipe in that wall would be advisable. If pressure field testing has been conducted as part of the pre-mitigation diagnostics, these diagnostic results might give a more quantitative indication of where the ventilation points should be in order to maintain the desired pressure/suction levels throughout the cavity network.

If radon measurements have been made on the gas inside the block voids, additional pipes might be placed in the "hot" walls. Walls which are less "hot," but which contain gas above 4 pCi/L, will still probably require at least one pipe. Such less elevated walls can be radon sources, even if they are not dramatically elevated. In addition, if the system is operated in pressure, untreated walls could become avenues through which the air being blown into the soil through the other walls could sweep soil gas into the house.

If the wall ventilation is a supplement to a sub-slab suction system, it can be sufficient to install pipes into only those walls which diagnostic testing suggests that the sub-slab system is not (or will not be) treating.

In terms of height, the ventilation points should be placed as close to the slab as possible, preferably in the first or second block above the slab. Placement close to the slab will generally help ensure treatment of the footing region (where most of the soil gas probably enters the void network), and treatment of the wall/floor joint and the sub-slab. Moreover, if the system is operating in suction, placement of suction points near the slab will mean that soil gas will not be drawn high up in the wall. Only the bottom foot of the wall, rather than the bottom several feet, will be used as the soil gas collector. The suctions that can be maintained in the void network are quite low (always less than 0.1 in. WC, and sometimes as low as 0.02 in. WC). Therefore, the pressure difference between the voids and the house may be subject to occasional reversal (for example, when the wind velocity changes, or when an appliance such as a clothes drier is turned on). If the house temporarily became lower in pressure than the voids, gas inside the blocks would be drawn into the house. If the voids were full of soil gas, drawn up from the soil by suction pipes high in the wall, it would be this soil gas that would enter the house during such pressure reversals.

The ventilation points may be located either inside or outside the basement. Figure 18 shows them inside the basement and connected to an outdoor fan. Inside installation is generally simpler and minimizes the piping visible outside the house. When a basement is finished (or for aesthetic purposes even in an unfinished basement), penetration of the blocks from outside the house may be preferred to avoid making holes in wallboard or paneling and putting a piping network inside the living area. With slab-on-grade houses, access to the block voids from outdoors should not be a problem. Outside installation would involve drilling halfway into the blocks from the outside rather than the inside and mounting the pipe outside, with limited excavation to expose the outer face of the block. When the walls are partially or largely below grade, outside mounting would require digging a well against the exterior basement wall to provide access, similar to a basement window well. However, if the system is to be operated in suction, this well would possibly be deeper than a window well, to get the pipes down as close to the slab as practical. If desired, such a well could be filled in after the piping was mounted and brought above grade. For interior walls, of course, the only option is to make the penetration inside the basement. The least obtrusive approach for making this penetration (and installing the piping) is a house-specific decision.

Installation of ventilation pipes into walls. After the points are selected where pipes are to be mounted in the walls, a hole is drilled or chiseled through one face of a block, into one of the cavities in that block. The hole would be drilled through one face, exposing the cavity (but not penetrating the opposing face). For ease in mounting and in subsequent sealing, this hole should be the same dimension as the outside diameter of the pipe that is to be installed.

The horizontal pipe is inserted partway into the cavity, as depicted in Figure 18. The gap between the block face and the pipe, around the pipe circumference, must then be well closed. Caulk or asphaltic sealant should be worked into the gap to form a good seal. If this gap is not sealed, air will leak through the gap, reducing the effectiveness of the ventilation system in the same manner as air leakage through any other major unclosed opening in the wall.

Design of piping network. The ventilation pipes must be connected together in some manner, and the piping network tied into one or more fans. Two fans might be needed in some cases due to the relatively large air flows into/out of the walls.

As discussed in Section 5.3.4, all piping should be plastic which is well-cemented (and perhaps caulked) at all joints to ensure a gastight seal.

The piping used most commonly for penetrating the walls in the EPA test houses was 4-in. diameter plastic pipe. It was felt that 4-in. pipe would result in reasonable gas velocities in the pipe, and hence reasonable pressure losses through the piping. Also, such piping is readily available and reasonably convenient to work with. Significant pressure drops can occur through the piping at the relatively high gas flows obtained in wall ventilation systems, typically from 100 to over 250 cfm in the piping system connected to any one fan. These pressure drops can be significantly reduced by using larger-diameter pipe. Reducing the pressure drop will make more of the fan pressure/suction capability available for establishing a pressure field in the walls, and will consume less in moving gas through the pipes. This is a particularly important consideration with wall ventilation systems, since air leakage through unclosed wall openings makes it difficult to maintain a good pressure field in the walls, and the fans can use all of the assistance they can get. Thus, 6-in. diameter pipe should be considered for as much of the piping network as possible. Smaller pipes (e.g., 2-in. diameter) have sometimes been used to penetrate the walls in combined sub-slab plus wall void suction systems, where only limited wall treatment was desired. However, the pressure drop through such narrow pipe will be so large at the gas flows encountered, that the resulting treatment of the wall would be expected to be very limited. Thus, if any meaningful degree of wall treatment is desired, it is suggested that piping no smaller than 4 in. be used.

Another consideration in reducing the pressure drop through the piping is that each elbow, size reducer, or other restriction in the piping will cause pressure loss. Thus, the number of elbows and other flow restrictions should be minimized. Pressure loss also increases with increasing length of the piping run, so that the run of piping should be as short as reasonably practical.

If the penetration into the wall is from inside the house, elbows can be used to bring the pipe legs (protruding horizontally from the bottom of the walls) vertically up to ceiling level, as shown in Figure 18. There, they can be tapped into a central collection pipe which handles the flow to (or from) each of the wall points. One possible configuration, used in a number of the EPA installations, involved a central 6-in. diameter collection pipe running the length of the basement, clamped to the floor joists of the floor above. There was no ceiling and the joists were exposed. The legs of 4-in. piping from each wall ventilation point tapped into this collector along its length. If the collector runs the length of the house, it will be perpendicular to the joists, and location of the collector beneath the joists will often be the preferred alternative. Wherever pipes run parallel to exposed joists, of course, the preferred approach would be to locate the piping up between the joists, to reduce its visibility.

If two fans are being used, there could be two collectors, one for each fan. Some number of the wall pipes would tap into each collector. Which wall pipes tap into a given collector in two-fan systems will be determined not only by logistics, but also by the amount of air flow expected in the various wall pipes. For instance, if a particular wall is expected to have a lot of air leakage (for example, due to a fireplace structure), one collector/fan might be dedicated to one or two points in that wall.

Each collector will have to be connected to a fan outdoors. When wall ventilation systems are operated in pressure, there will not be a high-radon fan exhaust. In those cases, there will not be the need to incur the cost and the pressure drop involved in mounting the fan in the attic or on the roof, as is the case for sump suction and sub-slab suction. Accordingly, since Figure 18 shows the fan in pressure, one end of the collector is shown penetrating the band joist, with the fan mounted horizontally directly on the collector just outside the house. The opposite end of the collector would be sealed. However, when the wall ventilation system is operated in suction, soil gas exhaust will be a concern. In suction cases, a vertical pipe will have to tap into the collector at a convenient point, and rise through the house to a fan mounted in the attic or on the roof. Alternatively, the collector can penetrate the band joist and, with an elbow, be connected to a vertically mounted fan with an exhaust stack which extends upward outside the house, preferably above the eaves. These exhaust pipe configurations for fans in suction are the same as those illustrated in Figures 12 and 14.

Figure 18 shows the 6-in. collector directly penetrating the 8-in. band joist. This should generally be possible. If the collector were narrowed to 4 in. before penetration, the 6- to 4-in. adaptor that would be required would create a significant pressure drop.

If the rooms over the slab are finished, it could sometimes be desirable to insert the pipes into the walls from outside the house. If the block penetration is outside, each exterior wall pipe could tap into a collection pipe which loops around the outside of the house. This exterior collection loop could connect to a fan at the rear of the house. Alternatively, there could be two fans, one near each of the rear corners. Each fan could connect to a collector which handles the wall pipes around half of the house. Again, reasonable pipe sizes could involve 4-in. wall pipes tapping into a collection loop of 6-in. piping. Much or all of this piping could be buried in a trench around the affected parts of the house, in order to hide the piping from view, with a riser coming above grade off the collection loop for mounting the fan. If the wall pipes have to be fairly far below grade, in order to get down near the slab, the collection loop might be shallower (just enough to get it out of sight), in order to reduce the excavation effort.

With either the interior or the exterior wall penetration approach, it will be desirable to locate the connectors to the fans so that the fans are positioned away from bedrooms, to minimize fan noise.

Where wall ventilation has been used in combination with sub-slab suction, both the wall points and the sub-slab points are often connected to a common fan. For example, in one configuration tested by EPA, horizontal suction pipes extending out of the walls were teed into the vertical pipes rising out of the slab, with the vertical pipes then connecting to a central collection pipe and a fan. This configuration is convenient in enabling the total system to be connected to a single fan, reducing fan costs and piping. However, when there are several wall suction points, this configuration results in a dramatic reduction in the suction possible under the slab, due to the large quantity of air flowing into the system from the walls. Even when steps were taken to reduce the flow out of the walls — such as reducing the wall pipe diameter to only 1 or 2 in., or installing a damper in the wall pipes — the loss of suction under the slab was significant. Such reduction of wall flows also reduces wall treatment, tending to defeat the purpose of having installed the wall pipes to begin with.

If only one or perhaps two walls are to be treated, connecting one or two wall points and the slab points to the same fan might often be satisfactory. The loss of suction under the slab might not be sufficient to prevent good sub-slab performance. Or where the sub-slab permeability is good, and/or where the walls are a major entry route, connecting the sub-slab points and multiple wall points together might prove satisfactory. However, in many cases where several walls must be treated as a supplement to sub-slab suction, better performance will probably result when the wall ventilation system has its own piping network and fan, separate from the sub-slab system.

Selection and mounting of fans. A variety of fans might be considered for wall ventilation systems. One reasonable choice is the 0.05 hp, 270 cfm in-line fan discussed in previous sections, which can be mounted to either pressurize or depressurize the walls. In the EPA testing (He87a) these fans typically provided between 0.02 and 0.10 in. WC static pressure in the wall pipes near their penetration through the blocks, at the air flows encountered (between about 100 and 250+ cfm per fan). Since there is some pressure loss between the horizontal pipe and the block cavity, the pressures actually being maintained in the void network are even lower than those in the pipes. Accordingly, fans with a different performance curve (permitting a higher static pressure or a greater flow) might help improve performance in some cases.

As discussed previously, consideration can be given to mounting the fans either to blow outdoor air into the wall voids, or to draw suction. Pressurization and depressurization have seemed to provide roughly comparable radon reduction performance in the relatively limited testing to date. Operation in pressure would avoid the threat of house depressurization (due to house air leakage into the walls and out the fan exhaust), and hence the chance of combustion appliance back-drafting. It would also avoid the concerns about exposure to high radon levels from the suction fan exhaust. However, as discussed, there is a risk that operation in pressure could sweep soil gas into the house at an increased rate through some entry routes in some cases, thus reducing performance. Thus, if a wall ventilation fan is mounted in pressure, the installer should be prepared to reverse the fan to suction (and to install an outside source of combustion air, if necessary) if pressure operation results in this potential problem.

In houses where the closing of potentially major wall openings is difficult, two (or more) fans might be necessary to accommodate the increased air leakage through the walls. Diagnostic testing (especially pressure field measurement in the walls), before or after the initial installation, could aid in determining the number and type of fans. If air leakage is so severe that more than one fan is needed, the likelihood is increased that the fans will have to be operated in pressure, or that outside air will have to be provided, in order to avoid combustion appliance back-drafting.

The fan(s) should always be mounted outdoors, especially if the system is operated in suction. If the fan were indoors and if leaks developed in the piping between the fan and outdoors, then — if the fan is in suction —high-radon gas from the wall voids would be blown into the house through these leaks. If an indoor fan is in pressure, the impacts of leaks in the intake piping leading to the fan would consist of some house depressurization (and consequently possible increased soil gas influx and combustion appliance back-drafting), because the fan would draw some air out of the house (and blow it into the walls).

The fan must be mounted on the collection pipe (or on the extension off the collection pipe) with an airtight joint, using adequate piping cement and caulk as required to prevent air from leaking into the system at that joint. Otherwise, the static pressure that the fan can maintain in the system will be reduced.

If the fan is in pressure, so that high-radon exhaust is not a concern, the fan can be mounted beside the house, as shown in Figure 18. This will minimize pressure loss and facilitate subsequent maintenance. The fan depicted in the figure is an in-line duct fan designed for mounting on a 6-in. pipe. Hence, it is shown mounted directly on the 6-in. collector pipe. Alternatively, a comparable in-line wall fan could be used when the system is in pressure. A wall fan would connect to the 6-in. collector like the duct fan, but it would be designed for mounting by screwing its housing into the side of the house.

If the fan is in suction, then the high-radon exhaust is a concern, and it would be necessary to mount the fan in one of the configurations illustrated in Figures 12 and 14 for sump suction and sub-slab suction. The fan could be mounted in the attic or on the roof, or vertically beside the house with a stack exhausting above the eaves. Although gas from the wall voids is diluted by air leakage, relative to soil gas drawn directly from the sub-slab, the radon levels in the voids with the fan in suction can sometimes be as high as several hundred to over 1,000 pCi/L, depending on a number of factors (such as soil gas radon levels). Thus, exhausting the gas in a manner to minimize exposure is important when the fan is in suction.

Since it will not be certain beforehand whether the fan should be in pressure or suction, the initial fan connection to the central collection pipe would advisably be temporary. The fan could be mounted in a temporary frame at grade level outside the house, connected to the collector by hose or piping which exits the house, for example, through a basement window. If pressure operation gives good performance in this temporary configuration, then a hole can be drilled through the band joist for the collector pipe, and the fan permanently mounted. If it appears that operation in suction is preferred, then the option of raising a stack up through the house to a fan in the attic or on the roof can be considered.

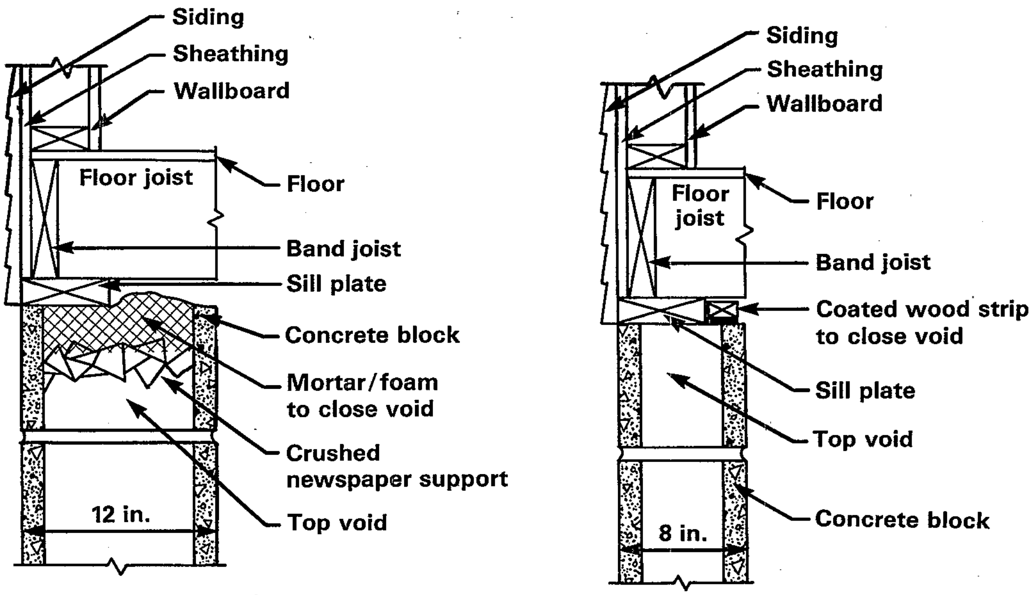
If the fan is in suction, the fan should always be mounted vertically so that condensed moisture from the soil gas will not accumulate in the fan housing, reducing performance and shortening fan life. Also, any horizontal piping should be slightly inclined downward from the fan, to avoid accumulation of condensed moisture in low spots in the piping. However, when the fan is in pressure, the fan will have only outdoor air passing through it, and the threat of moisture condensation in the fan is avoided. Thus, in pressure cases, the fan can be mounted horizontally, as shown in Figure 18.

The fan intake (for pressurization) or exhaust (for suction) should be protected in some manner to prevent debris from clogging the discharge and to prevent children and pets from reaching the blades. Wall-mounted fans commonly have a housing which provides the necessary protection. Protective grilles can be purchased for duct fans. The fan (and any exterior electrical wiring) must be designed for outdoor use.

Closure of major wall and slab openings. As discussed previously, major wall openings must be closed to reduce air leakage through the wall, if wall ventilation systems are to be able to achieve good performance with a reasonable number of fans and suction points.

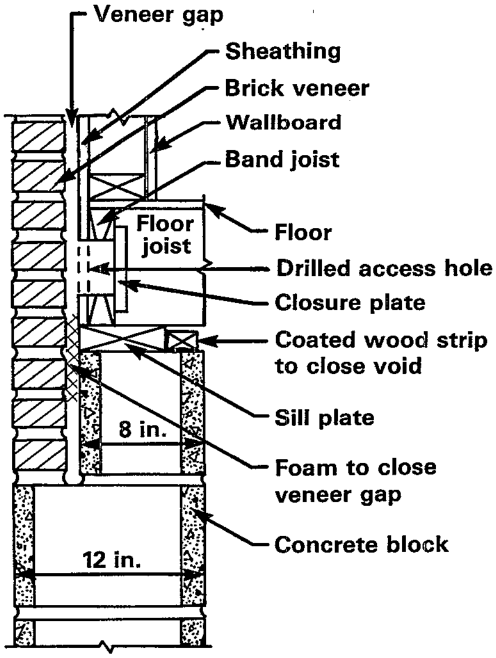
Top voids. If there is not a course of solid cap block on top of all ventilated block walls, then the open voids in the top course of block will be a major avenue by which house air can move into (or fan air can flow out of) the void network, overwhelming the wall ventilation fan(s). The effectiveness and the ease with which open top voids can be closed for wall ventilation will depend upon the construction details of the particular house. Several different situations might exist in different houses, or on different walls in the same house.

- The top void is readily accessible (that is, the sill plate is recessed sufficiently such that at least 4 in. of the open void is exposed inside the house). In these houses, there is sufficient space so that crumpled newspaper (or some other suitable support) can be forced down into each individual void, and the entire void then filled with mortar to a depth of 2 in. Such complete closure is illustrated in Figure 20a. It is crucial that the mortar be forced all the way to the far face of the void under the sill plate. This must be done for every void in the wall.
- The top void is reasonably accessible (that is, perhaps 1 to 3 in. of the void is exposed).



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.

Figure 20. Some options for closing major wall openings in conjunction with block wall ventilation.

There is sufficient room to force newspaper into the void, but not enough to permit mortar to be effectively spread across the void. In these houses, newspaper (or other support) is forced down into the void, and an expanding foam used to fill the void. This situation is also represented by Figure 20a. EPA used a single-component urethane foam that could be extruded through a hose and nozzle. Some foams are available in aerosol cans for household use, and some are available for commercial applications. The use of the hose and the expanding foam eliminates the need for a void opening large enough to accommodate part of a person's hand.

- The top void is inaccessible (that is, less than 1 in. of the void is exposed). To effectively fill the top void under these conditions, one would have to drill through the face of every block into each cavity (usually two cavities per block), and inject foam through the hole. The foam would have to have characteristics, or would have to be injected in a manner, such that — in the absence of crumpled newspaper support — the foam would expand and plug the top void before falling into the void network below. EPA has not been able to identify a commercially available foam that would satisfactorily plug the concealed top void when injected without support below. Various methods for making this approach work have been suggested, including: (1) inserting a deflated balloon into the hole in the face of the block, then injecting the foam into the balloon; and (2) drilling a second hole below each injection hole, then inserting some type of support through the lower hole.

In the EPA testing (He87a), where the top voids were inaccessible, an effort was made to use the sill plate to close the top voids. If none of the top void were exposed, the interior seam between the sill plate and the top blocks was caulked. When a fraction of an inch of void was exposed — too small to force crumpled newspaper and a foam nozzle through, but too large to close with caulk — EPA used one approach that involved a small strip of wood, illustrated in Figure 20b. Two sides of the strip were coated with caulk or some other suitable sealant, and this strip was nailed tightly in place over the void, pressed against the sill plate and the block. Use of the sill plate for void closure in this manner is less effective than would be successful injection of foam into the block cavity. For one thing, the inaccessible outside seam between the sill plate and the block is left uncaulked. However, use of the sill plate saves a lot of time and expense, and it appears to do an adequate job. Several of the successful wall ventilation houses tested in Pennsylvania (He87a), discussed in Section 5.4.3, had one or more walls where the top voids were closed in this manner.

Holes and cracks in walls. Visible holes or major cracks in the walls should be closed using grout, caulk, or other sealant. Such openings might include, for example, holes around utility penetrations, chinks in the block, and mortar joint cracks where pieces of mortar have crumbled and fallen out.

The pores present in blocks also permit air leakage. While the pores are small, they cover the entire face of the wall, and hence can add up to a lot of leakage area. It is not clear under what conditions it is cost effective from the standpoint of wall ventilation performance to try to close these pores (and other small wall openings, such as hairline cracks in the mortar joints). In the EPA testing, closure of the pores was considered only when the wall was constructed of cinder block, which is far more porous than regular concrete block. In one case where pores were closed, a waterproofing paint was used to coat the entire interior face of the block walls. Other options that can be considered for pore closure are discussed in Section 4. In some cases, concrete blocks might be encountered that are more porous than average, due to the nature of the concrete mix from which that batch of blocks was made. It might sometimes be desirable to try pore closure if wall ventilation is to be applied to a house having concrete blocks that appear to be unusually porous (based upon visual inspection or diagnostic tests). The results in Section 5.4.3 indicate that — where the concrete block is of typical porosity — good radon reductions can be achieved with wall ventilation without the effort and expense of closing the block pores.

Gap associated with brick veneer. In houses with exterior brick veneer, a gap occurs between the veneer and the sheathing and block behind the veneer. This gap is depicted in Figure 20c. Depending on how the bricks were laid and the size of the gap, this inaccessible gap could prevent effective suction from being drawn on the block voids. The fan intended to ventilate the walls could simply be drawing outside air (or house air) down through that gap into the voids (or forcing fan air up into the gap).

It is not clear from the available data under what conditions it will be cost effective, from the standpoint of wall ventilation performance, to try to close this veneer gap. In one house in the EPA test program, an attempt was made to close this gap by drilling through the band joist and using a hose and nozzle to extrude urethane foam into the gap (Figure 20c). There was no clear indication that this closure significantly improved performance. Some of the houses discussed in Section 5.4.3, where good performance was ultimately achieved, had exterior brick veneer without closure of this veneer gap. Thus, while closure of this gap could potentially be cost effective in some cases, it is apparent that good reductions can sometimes be achieved with wall ventilation without gap closure. In some cases, it appears that this gap is at least partially closed by excess mortar which falls into the gap when the bricks are laid during construction.

Fireplace structures. Fireplace structures incorporated into block walls offer the potential for large and inaccessible openings between the structure and the surrounding wall, between the structure and the outdoors, or between the structure and the upper levels of the house. Thus, attempts to ventilate the surrounding wall may be difficult — even when the top voids in the wall itself are well sealed — because air from outside or upstairs can leak into the wall through the fireplace structure. Such leakage points probably cannot be located, much less closed, except by tearing down the surrounding wall and/or the fireplace/chimney structure. As a result, it will generally be cheaper to handle the leakage around the fireplace by increased ventilation points and fan capability in the wall with the fireplace. A number of the houses in which EPA ultimately achieved good wall ventilation performance had fireplaces.

Openings in the slab should also be closed, to assist the wall ventilation system in extending a pressure field underneath the slab. Of particular importance would be the wall/floor joint, if it is anything more than a hairline crack, since its length and proximity to the wall could make it an important source of air leakage. Sump pits, major slab cracks, and other potential slab-related air leakage points should also be closed. Floor drains should be trapped or otherwise closed, as discussed in Sections 4 and 5.3.4. Even though they might not significantly affect the pressure field under the slab, they can be a significant slab-related soil gas source if they connect to the soil.

Post-mitigation diagnostics. Various post-mitigation diagnostics can aid in assessing the operation of the wall ventilation system, and in deciding on possible design improvements.

- Radon measurements in the house, as discussed in Sections 5.2 and 5.3.
- Gas flow and pressure measurements in the individual wall ventilation pipes, plus grab radon measurements, if the system is in suction. High flows and low pressures in the pipes to any one wall might suggest the need for more closure, more fan capacity, and/or more ventilation points in that wall. Alternatively, these results could be indicating that there is a leak in the piping. Low flows and low suctions could be suggesting excessive piping pressure losses between that point and the fan, or excessive flows entering the system from other walls. Any holes drilled in the piping to permit this testing must subsequently be plugged.
- Smoke tracer testing. If the wall ventilation system is operating in suction, a smoke source could be held near remaining openings around the walls. If the smoke is unambiguously drawn into the cracks, the block pores, etc., around the total perimeter, then suction is being maintained throughout the wall. If the smoke is blown outward at any point, soil gas might be entering the house at that point, and additional wall closure or ventilation capability in the vicinity of that point should be considered. If suitable cracks for this testing cannot be found, holes could be drilled through the face of the block to permit the testing. These holes would have to be effectively closed after the test is conducted. The smoke tracer can also be used, with the fan either in pressure or suction, to test the effectiveness of various seals (for example, at piping joints, or where the pipes penetrate the walls). If any seal is not tight, then the smoke should reveal a distinct flow through the insufficient seal.
- Measurement of pressure field. As a quantitative variation of the smoke tracer testing above, small test holes could be drilled around the walls, and quantitative pressure measurements made in the void network. This approach would confirm whether the desired pressure field was being maintained throughout the wall.
- Testing for back-drafting (suction systems). If the wall ventilation system is installed to operate in suction, post-mitigation testing should always include tests to ensure that the air being sucked out of the house by the system is not sufficient to create back-drafting of combustion appliances. If fireplaces or woodstoves are being back-drafted, this situation will generally be readily apparent, because the smoke and odors will usually be unmistakable. If cleaner-burning appliances are back-drafting (such as a gas-fired furnace), the problem can be less obvious. In those cases, it will sometimes be necessary to measure flow in the appliance flue. If back-drafting is a problem, the options are: a) to reverse the fans on the wall ventilation system, operating it in pressure; and b) to provide an external source of

combustion air to the appliance(s). Methods for providing an external source of combustion air are discussed in Section 6.1.4.2 and in Reference NCAT83.

Instrumentation to measure pressure/suction. A pressure gauge or manometer might be installed at one or more points in the piping, analogous to those discussed in Sections 5.2.4 and 5.3.4, to provide the homeowner with a continuous indication of whether the fan performance is remaining in the normal range for that house. However, with wall ventilation systems, normal pressures will likely be so low in many cases that the pressure measurement might not always confirm unambiguously that air leaks have not developed and system performance has not degraded.

5.4.4.2 Baseboard Duct Variation

Figure 19 illustrates ventilation of the wall void network by sealing a duct over the wall/floor joint, around the entire perimeter of the slab, and on any interior block walls which penetrate the slab. Holes are drilled into some of the voids within this duct to permit ventilation of the void network. The baseboard duct approach might be particularly applicable when the wall/floor joint consists of a French drain, since the drain facilitates ventilation of the sub-slab region by the system. However, this approach can be considered even if there is not a French drain.

Many of the design and installation considerations discussed in Section 5.4.4.1 for the individual-pipe variation also apply for the baseboard duct approach. These common design/installation considerations are not repeated here. Discussed below are only those considerations which differ for the baseboard duct approach.

Selection of location of baseboard ducts. In general, the baseboard duct should be placed over the joint between the slab and the perimeter foundation walls inside the house, around the entire perimeter. Interior block walls which penetrate the slab and rest on footings underneath the slab must also have a duct installed. For an interior wall on which both faces of the wall are accessible, installing the baseboard duct on just one face might be sufficient in some cases. If the interior wall separates a finished portion of the basement from an unfinished storeroom, the duct might conveniently be mounted on the unfinished side of the wall for the sake of appearance. In one house in Pennsylvania that EPA tested using a baseboard duct system, both sides of the interior block walls had to be fitted with a duct in order to treat the wall/floor joint adequately.

Ideally, the baseboard duct should be installed over the entire linear distance of the wall/floor joint, without interruption. If interruptions in the duct are necessary at particularly inaccessible locations (for example, behind a furnace, shower stall, or stairwell that is essentially against the wall), the wall/floor joint over the uncovered length should be closed, if it is anything more than a hairline crack. The concern is that the uncovered joint could serve as a site for air leakage into or out of the adjacent duct, reducing the effectiveness of the system in maintaining a pressure field inside the wall. The joint should *not* be closed wherever it is covered by the baseboard duct, since the joint will improve communication between the duct and the sub-slab region. Closure of the joint is also necessary on the untreated side of any interior walls where a duct is placed only on one side of the wall. If the uncovered length of joint is a French drain, it is particularly important that the exposed segment of the joint be closed, since a gap as wide as a French drain could serve as a major leakage source even if the uncovered length is fairly short. If the French drain is needed to collect water, so that the uncovered portion cannot be mortared closed, approaches can be considered for closing that portion *without* causing water problems (see Figure 6).

Since the baseboard duct is necessarily at the base of the walls, over the joint with the slab, the holes through the wall inside the duct will be near the bottom of the wall (usually within a few inches of the slab). This height for the wall suction points helps ensure treatment of the sub-slab and footing region, and ensures that the soil gas is not drawn up very far into the void network.

Installation of baseboard duct. Before the duct is mounted, holes must be drilled through the wall near the floor in the region that will be covered by the duct. These holes permit the ventilation system to draw the necessary suction on the void network uniformly around the perimeter of the basement. In the EPA testing, these holes were made with a 1/2-in. drill into each void in every block around the perimeter. This may have been more holes than necessary.

The baseboard ducts can be fabricated out of sheet metal, or they can be created with plastic channel drain which is sold commercially. This duct must be attached and sealed tightly to the wall and to the slab around the entire perimeter to form an airtight seal over the wall/floor joint and over the holes that have been drilled in the wall. In the EPA testing, sheet metal ducting was anchored to the wall and floor with masonry screws and sealed against the wall and the slab by a continuous bead of caulk. Others have suggested use of an epoxy bonding agent in conjunction with plastic channel drain (El87). It is crucial that the connection against the wall and the slab be permanently airtight. Otherwise, basement air will leak into the duct and reduce the system effectiveness. Masonry screws alone will not ensure an adequate seal. When the slab contains irregularities, special care and additional caulking are needed to ensure a good seal.

Whenever the duct turns a corner, the segments joining at the corner must be trimmed to fit well, and the seam between the segments must be carefully sealed. Wherever the duct must be interrupted, the open end of the duct at the interruption must be sealed — for example, with foam, or using a piece of sheet metal or plastic with adequate sealant applied over any resulting seams.

Figure 19 illustrates a sheet metal duct having a rectangular cross section. Triangular cross sections were also used in the EPA testing. Commercial channel drain is available with different cross-sectional shapes. The exact shape of the cross section is not important, and selection can be based on a homeowner's particular preferences or on any unique features of a specific basement. The cross-sectional area of the duct is important. Of course the duct must be large enough to cover the holes drilled in the wall and the French drain, if present. It must also be large enough to reduce the pressure drop created by the air and soil gas flowing through it. If the duct is too small, a large pressure drop will occur and much of the fan's suction capacity will be consumed in moving gas through the duct, which leaves less for maintaining suction on the walls. If a lot of air leakage is expected into the walls (for example, due to a brick veneer gap or to a fireplace structure), a larger duct will be required. In the EPA testing, the ducts ranged in cross section from 12 in.^{2} (a triangular duct attaching to the wall 8 in. above the floor and extending 3 in. away from the wall at the slab) to 36 in.^{2} (a rectangular duct 12 in. high and 3 in. wide). In general, the largest duct should be considered which can be accepted aesthetically, in view of the large air flows expected.

If a baseboard duct system is to be installed in a house that has a functioning French drain — that is, a drain which collects water entering the house through the face of the block or the block/footing joint, or from under the slab — then water handling features must be incorporated into the ventilation system. For example, if the French drain channel leads to a sump with a sump pump, the sump should be capped, and the French drain/sump connection enclosed in an airtight manner as an integral part of the baseboard duct enclosure over the wall/floor joint.

In some cases, drilling holes through the faces of the block as part of the baseboard installation might exacerbate an existing water problem in houses without French drains. If water collects inside the block cavities, the holes through the bottom blocks will allow the water to flow out onto the slab within the duct, whereas before the system was installed, more of this block water might ultimately have drained to the sub-slab. This water flowing in through the holes would then be trapped inside the baseboard duct. To the extent that such water problems occur, a sump and sump pump would have to be installed as part of the baseboard duct system, so that water entering through the wall holes would be directed to the sump. This sump would have to be enclosed as part of the ventilation system, as discussed above in connection with French drains. If a sump is installed in conjunction with the baseboard duct, the system would be a combination radon mitigation system/functioning channel drain.

If the room receiving the baseboard duct is finished, extra effort and expense will be required. Paneling and vertical furring strips will have to be cut off at the bottom of the wall to accommodate the duct, and carpeting trimmed around the perimeter. Where a stud wall extends perpendicular to the block wall, a penetration through the stud wall will have to be cut at the base of its joint with the block wall.

Design of piping to fan. The installed duct must be connected to one or more fans. There are a variety of ways to do this. The alternative shown in Figure 19 is to insert a vertical plastic pipe into the baseboard duct at the selected point(s), and to extend this pipe up to ceiling level where it would bend 90 degrees and penetrate through the band joist as shown. Alternatively, it could penetrate up through the house to a fan mounted in the attic or on the roof, if the system is in suction. The seam between the pipe and the duct (and between the pipe and the floor, outside the duct) would have to be well sealed. A 6-in. diameter plastic pipe is shown in the figure, in view of the large air flows expected. Four-inch pipe has also been used.

Other alternatives for connecting the fan(s) can be considered. For example, another alternative would be to extend a rectangular sheet metal duct vertically up the wall, connecting to the baseboard duct at the bottom. A plastic pipe would be inserted into the top end of this vertical duct, and would penetrate the band joist to a fan mounted on the pipe outdoors. An advantage of this approach is that the sheet metal duct can conveniently have a cross section larger than the plastic pipe, thus reducing pressure loss.

If more than one segment of baseboard duct has been used (that is, if the duct has had to be interrupted in two places and does not form a continuous loop), each segment must have a tap that connects to a fan. If two fans are used on a continuous loop, it would be reasonable to locate them at opposite ends of the house, to help ensure effective suction around the total perimeter.

Post-mitigation diagnostics. Post-mitigation diagnostic testing can be similar to that described for the individual-pipe variation, except adapted for the baseboard duct configuration. For example, flow and pressure measurements in the individual wall pipes would be replaced by measurements inside the duct around the perimeter. Smoke testing of seals would include the seals between the duct and the floor and wall around the perimeter, and the seals where the ventilation pipe penetrates the duct.

5.4.5 Operation and Maintenance

As with other active soil ventilation techniques, the operating requirements for a wall ventilation system consist of regular inspections by the homeowner to ensure that:

- the fan is operating properly.
- all system seals remain intact (for example, where the pipes penetrate the wall, where the baseboard duct attaches to the floor and wall, where sections of pipe are joined together, and where the pipe penetrates the baseboard duct). Smoke testing can be used if needed to ensure that no leakage is occurring through the seals.
- all wall and slab closures remain intact.
- combustion appliance back-drafting is not occurring (when system is in suction).
- if the system is in suction, smoke testing to ensure that all of the walls remain in adequate suction.

Maintenance would include any required routine maintenance to the fan motor (for example, oiling), replacement of the fan as needed, repair of any cracked or broken seals in the system, and re-closure of any wall or slab openings where the original closure has failed. The integrity of all seals and wall closures must be maintained to permit the system to provide proper wall ventilation. If smoke testing (for a system in suction) or if readings from system pressure gauges indicate that the system is no longer maintaining a pressure field throughout the wall, and if the above maintenance activities do not correct the situation, the homeowner should measure the radon level in the house and possibly contact a mitigation professional.

5.4.6 Estimate of Costs

The installed cost of a wall ventilation system can vary significantly, depending on the approach selected and the amount of effort required for effectively sealing the major wall openings.

If the individual pipe wall ventilation method is installed in a house that lends itself well to effective closure of major wall openings — that is, a house with reasonably accessible top voids, no exterior veneer, and no fireplace structure — EPA's experience suggests that a homeowner might have to pay about $1,500 to $2,500 to have such a system installed by a contractor (including materials and labor). This estimate assumes that the house does not have a finished basement, and that the fan is mounted on the side of the house (not in the attic or on the roof). The cost of an individual pipe wall ventilation system can be higher than that of a sub-slab suction system, even though the cost of taking piping up through the house is avoided when the wall system is in pressure. The higher cost results because of the increased number of ventilation points and increased wall closure effort potentially required.

In a house where effective wall closure is more difficult to achieve —possibly one requiring additional effort to close the top voids, built with porous cinder block, etc. — the costs could be significantly higher. Also, if the block walls are finished inside the house, additional cost could be encountered. Wall finish might have to be partially dismantled to expose the blocks so that wall openings could be closed; and, if the pipes are to be installed inside a finished basement, the paneling/wallboard, etc., might have to be modified to accommodate the pipes when the paneling is replaced. If the pipes are installed from outside, there will be some cost associated with excavating to expose the exterior block face and to bury the piping.

With the baseboard duct wall ventilation method, installation by a contractor might cost as little as $2,000 to $2,500 if the baseboard consists of plastic channel drain which is attached using epoxy adhesive, and if the house does not present unusual difficulties (El87). However, if the basement is finished, costs might be higher due to the costs of, for example: trimming the paneling and carpeting to expose the wall/floor joint and accommodate the baseboard duct (and refinishing afterwards); penetrating finished stud walls which run perpendicular to the block wall; and removing and replacing stairwells, shower stalls, etc., as needed to gain access to some segments of the wall/floor joint. In addition, if it becomes necessary to attach the baseboard duct using masonry screws (and sealant) in order to ensure a long-lasting airtight seal, labor costs would increase. If a sump and sump pump need to be installed due to water drainage considerations, costs could be higher. Thus, in some cases, baseboard duct systems might be expected to cost significantly more than $2,500.

Although installing wall ventilation would not be an easy do-it-yourself job, some homeowners might be willing to try it. In that case, the installation cost would be limited to the cost of materials — probably about $300 to $500 for the fans, piping, sheet metal or plastic channel drain, and incidentals, depending upon the number of fans required and the size of the basement.

Operating costs would include electricity to run the fan(s), and the heating and cooling penalty resulting from the increase in house ventilation caused by air leaking out of (or into) the walls. Occasional replacement of the fan(s) would also be a maintenance cost. The cost of electricity to run a 0.05 hp fan 365 days per year would be roughly $30 per year; thus, two fans would cost $60 to operate each year. Assuming that about half of the gas moved by the fans enters (or is exhausted from) the house through leaks in the walls — and considering the typical gas flows observed in EPA's systems in Pennsylvania (He87a) — the wall system might increase the house ventilation rate by roughly 80 cfm per fan, for the type of fan used in the EPA testing. This figure will vary from house to house. The cost of heating 80 cfm of outdoor air to house temperature throughout the cold season would be roughly $200 per year (depending upon outdoor temperatures and fuel prices). If the house is air conditioned, the cost of cooling 80 cfm through the summer would be very roughly $40 per year, depending upon temperature and humidity. Thus, the total operating cost for one fan would be roughly $270 per year, and, for two fans, $540 per year.

There is not sufficient experience to reliably estimate the lifetime of the fans. A new fan of the type commonly used in the EPA test program would cost about $100 (not installed).

5.5 Isolation and Active Ventilation of Area Sources

5.5.1 Principle of Operation

Where a large soil gas entry route (or a large collection of entry routes) exists, it may be economical to cover (or enclose) this large route, and to ventilate the enclosure with a fan. Thus, the source of the soil gas is isolated, and the soil gas cannot enter the living space. Examples of such an isolation/ventilation approach would be:

- covering an earth-floored crawl space or basement with an airtight plastic sheet ("liner"), and actively ventilating the space between the liner and the soil (for example, using a network of perforated piping under the liner).
- building an airtight false floor over a cracked concrete slab, and ventilating the space between the false floor and the slab.
- building an airtight false wall over an existing foundation wall which is a soil gas source, and ventilating the space between the false wall and the foundation wall.

Other specific variations of this approach can also be considered. These large entry routes (the earthen floor, the cracked slab, the foundation wall) are referred to here as "area sources."

In general, there are always alternatives to this isolation/ventilation approach which can often be more economical. For example, natural or forced ventilation of the crawl space will sometimes provide a less expensive or more easily maintained option for crawl space treatment. Or if a liner over the soil were installed as part of a sealing effort, it could be vented passively — with the sub-liner piping network simply opening to the outdoors at some point without a fan. Sub-slab suction will often prove an easier, cheaper, and perhaps even more effective approach than building a false floor. However, there will be individual cases where the isolation/ventilation approach should be considered.

Ventilation of an earth-floored crawl space, after isolation of the crawl space from the remainder of the house (e.g., by sealing the subflooring), can be pictured as a variation of this isolation/ventilation approach. In this document, such ventilation of the entire crawl space is considered in Section 3.1, as a variation of house ventilation.

5.5.2 Applicability

Lining an earth floored area and ventilating between the liner and the soil are most likely to be economical, relative to other options, when:

- the area is a crawl space not currently provided with vents to facilitate natural ventilation. Installation of vents in the perimeter foundation wall could be difficult for one reason or another (e.g., the crawl space is heated, and opens to the living area).
- the climate is sufficiently cold that natural or forced ventilation of the crawl space would be more expensive than the vented liner. That is, the cost of insulation for the crawl space, the residual heat loss from the house, and the installation of vents for crawl space ventilation, would be greater than the cost of installing and maintaining the liner and a fan.
- the earth floored area is beneath one wing of a larger house, and active soil ventilation is required in other wings of the house, so that a fan and piping network will have to be installed in any event.
- the area is rarely, if ever, occupied so that damage to the liner by persons walking over it is not a concern.

Construction of a false floor over an existing slab has the best chance of being economical when:

- the slab is badly cracked, and is a particularly significant source, *and*
- sub-slab permeability is poor, so that sub-slab suction to treat the cracks might not be sufficiently effective.

If there is reasonable sub-slab permeability, sub-slab suction will probably always be a lower-cost and more effective approach compared to the ventilated false floor. Installation costs for a sufficiently airtight false floor could be relatively high, especially if the slab area is partially finished or is relatively large. Moreover, the false floor will probably not treat wall-related entry routes as well as individual-point sub-slab suction systems can. The communication between the false floor enclosure and the sub-slab will probably be limited. Moreover, the suction (or pressure) that can be maintained inside the false floor enclosure will probably be limited, due to house air leakage into (or pressurization air leakage out of) the enclosure. Thus, the pressure field from the false floor enclosure might not effectively extend into the sub-slab region, into the void network of hollow-block foundation walls, or under the footings to the exterior face of the foundation.

Construction of a false wall will probably be economical only in limited cases. These cases would likely include those where:

- the foundation walls appear to be a major soil gas source;
- the entry routes in the walls are numerous and small, not suited to closure by simple methods, so that wall ventilation is not practical (for example, highly porous cinder block, extensive mortar joint cracks in a block wall, extensive cracking in a poured concrete wall, extensive chinks in a fieldstone wall);
- sub-slab suction is not an option for preventing soil gas entry into the walls (due to poor sub-slab permeability and other reasons); and
- the foundation wall openings inside the house can be totally enclosed by the false wall. This is most likely to be achievable with poured concrete walls; in hollow-block walls, coverage of difficult-to-access open top voids can present added complexity. Enclosure might be feasible with fieldstone walls.

Unless the wall openings could be totally enclosed by the false wall, a false wall would be of limited value. Thus, if there are inaccessible open top voids in a block wall — or if there is a block fireplace structure in the wall — the performance of a false wall system would be uncertain.

5.5.3 Confidence

Of the isolation/ventilation approaches, the one which has been used to the greatest extent has been the crawl space liner approach. The false floor and false wall approaches have been tested to a much lesser degree, usually under special circumstances.

The actively ventilated crawl space liner approach has been considered by a number of mitigators (Br87, Bro87b, Mi87, Sc87b, Si87). However, the available data are limited. None of the available data are for houses exclusively underlaid by a crawl space; the tested houses had adjoining basement or slab-on-grade wings. In one house, the actively ventilated crawl space liner approach was tested in conjunction with drain tile/sump suction in the adjoining basement (He87b, Sc87b). The area between the liner and the soil was ventilated using a loop of perforated plastic pipe, connected to the same fan that was drawing suction on the sump. The combined sump plus crawl space treatment effectively reduced the house from 30 to 2 pCi/L, indicating that the crawl space was being adequately treated. The crawl-space liner ventilation appeared to be contributing approximately 25 percent of the total reduction, based upon the rise in radon levels in the house when the liner vent was turned off. In another house (Os87a), the crawl-space liner approach was tested along with exterior sub-slab suction (Figure 15) plus exterior block wall ventilation on the adjoining slab on grade. A fiber matting, and a network of perforated piping connecting to a fan, were placed between the liner and the soil. This combined treatment provided a 97 percent radon reduction in the house, suggesting that the crawl space treatment was effective.

Intuitively, it would seem that the active liner ventilation approach should work reasonably well, if properly installed. However, in view of the lack of data with such systems, confidence cannot be considered any better than moderate at this time.

The data with false floors and false walls are very limited. Actively ventilated false (plenum) floors were tested in two unfinished basements in Canada, where soil gas was the source of the indoor radon (Ta87). This approach reduced levels from initial values of 0.1 to 0.2 WL (about 20 to 40 pCi/L) down to below 0.02 WL (4 pCi/L), reductions of 80 to 90 percent. These results are apparently based on grab sample working level measurements. Actively ventilated false (plenum) walls have been tested in one house, and passively ventilated false walls in about 20 houses, in poured concrete basements where the source of the radon was uranium mill tailings in the concrete aggregate used in the walls (Ta87). In all houses, each of the four basement walls was covered with a false wall. Initial indoor levels of 0.03 to 0.08 WL (about 6 to 16 pCi/L) were reportedly reduced to below 0.02 WL (4 pCi/L), again apparently based on grab sample measurements. Note that contaminated concrete walls as the radon source are particularly suited to the false wall approach, because the source is isolated to the walls, and because there are no block cavities which can serve as difficult-to-enclose channels for soil gas entry.

In view of the limited amount of data with false floors and false walls — and considering the potential difficulties in effectively installing an airtight enclosure over all floor or wall entry routes — confidence in these systems must be considered low at present.

5.5.4 Design and Installation

Given the limited experience to date with area source isolation/ ventilation, only a brief discussion of design and installation considerations is given here.

The intent with any of these systems is to construct an essentially airtight enclosure over the source, so that crawl space air or house air cannot leak through the enclosure and into the suction system. Sheets of suitable material which is impervious to convective gas flow — such as 6 mil polyethylene — must be incorporated into the enclosure structure, and sealed well at all seams.

In lining the crawl space, the polyethylene sheets must be laid over the entire crawl space. In an effort to make the liner airtight, any seams between overlaid sheets must be sealed well with a continuous strip of suitable tape, or with bonding agent. Any unavoidable penetrations through the polyethylene must likewise be well taped. Various approaches can be considered for sealing the sheet around the crawl space perimeter. One logical approach is to wrap the edge of the sheet around a strip of wood (such as a furring strip), and nailing or stapling the wood strip into the sill plate around the crawl space. The seam between the strip and the sill plate would then be caulked. Special provisions would be required around the crawl space access door, providing a basically airtight seal between the plastic sheeting and the door frame such that the sheeting is not easily torn when someone steps in through the access door. Care is required to ensure that the sheets are not punctured during installation. The network of perforated piping under the liner should form a logical pattern — such as a loop around the perimeter, or a large cross. This piping network would be connected to a fan by a length of solid (non-perforated) plastic pipe which would penetrate the foundation wall to connect to a fan outdoors. The penetration through the foundation wall should be sealed. Some investigators have tested methods for eliminating the perforated piping. In one house (Mi87), a fiber mat was laid under the plastic sheeting to provide an air space between the liner and the soil; the pipe from the outside fan penetrated the foundation between the liner and the soil, but terminated just inside the foundation wall, not connecting to perforated piping.

With a false floor or false wall, the structure is built using standard carpentry procedures, except that polyethylene sheeting must be placed directly under the flooring or behind the wallboard in an effort to make the enclosure airtight. All seams between sheets, and where the sheets contact the perimeter, must be sealed. The new flooring or wallboard would be installed on studs that create a basically airtight cavity (or plenum) between the new floor or wall and the original. A suction pipe would tap into this cavity at some convenient point, and would connect to a fan outdoors. One design for the installation of a false wall (but without a fan) is illustrated in Reference PDER85.

5.5.5 Operation and Maintenance

As with other active ventilation systems, operating requirements for isolation/ventilation systems include regular inspection of the fan and all system seals. Maintenance includes routine preventive maintenance, and repair and replacement of the fan and seals as required.

5.5.6 Estimate of Costs

The costs will be highly dependent upon the size of the house and, for the false floor and false wall cases, the nature of the interior finish. The crawl space might be lined and vented for $400 to $1,000, although costs could be higher with large crawl spaces and with fans mounted to exhaust above the eaves. The false floor or false wall approach would likely cost at least several thousand dollars. In current dollars, the false floor and false wall installations discussed in Section 5.5.3 would cost approximately $5,000 or more.

5.6 Passive Soil Ventilation

5.6.1 Principle of Operation

In concept, any of the fan-assisted ("active") soil ventilation approaches described in the previous sections could be attempted without the aid of a fan (that is, "passively"). With passive systems, natural phenomena are relied upon to develop the suction needed to draw the soil gas away from the entry routes into the house. A passive system involves a "stack," consisting of vertical plastic pipe, which ties into the piping network being ventilated (in the basement, for example), and which rises up through the house and penetrates the roof. A natural suction is created in the stack, by two phenomena: 1) the movement of wind over the roofline, which creates a low-pressure region near the roof;

and 2) the natural thermal effects inside the stack, when the outdoor air at the roof is lower in temperature than the gas inside the stack, causing the relatively warm stack gas to rise as the result of buoyant forces. This thermal effect in the stack is exactly analogous (and similar in magnitude) to the thermal stack effect which is sucking soil gas into the house; the difference is that the stack is providing the soil gas with a direct "thermal bypass" up to the roofline.

The suction which can be developed by these natural phenomena is quite limited, relative to that possible with a fan. The natural suction in passive stacks will depend upon the outdoor temperature and wind velocity (and hence will vary from day to day, and from hour to hour). Typically, it will be on the order of several hundredths of an inch of water at best. By comparison, as discussed in prior sections, the suction which can be developed in suction pipes by fans can be as much as 1 in. WC, or more — 10 to 100 times that in the passive stack. With such low suctions, passive systems will require careful design, with piping networks designed to minimize suction requirements, if they are to be successful.

For example, an active sub-slab suction system as described in Section 5.3 might require 0.5 in. WC suction in a single pipe entering the slab at a central location if it is to maintain a desired 0.015 in. WC suction under the slab at a location remote from the suction point. By comparison, a passive system might develop only, say, 0.04 in. WC in the pipe. Sub-slab suction will probably fall below 0.015 in. WC within a short distance of the passive suction pipe. Thus, a passive system could probably never maintain the desired sub-slab treatment using just a small number of individual sub-slab suction pipes, in the manner illustrated in Figure 14; the pressure loss through the sub-slab aggregate is just too high. A perforated piping network would have to be laid underneath the slab, or a large number of individual pipes would be needed, if the 0.04 in. WC passive system were to have any chance of maintaining 0.015 in. WC suction near all major entry routes.

One key advantage of a passive system, if it performs well, is that it avoids the need for homeowner maintenance of a fan. The risk is eliminated that the house occupants might be subjected to high radon exposures over a long period if the homeowner fails to notice or repair a malfunctioning fan. Such a no-maintenance concept is highly desirable for private residences. Passive systems have the further advantage of avoiding the noise associated with a fan, and the relatively low capital, operating, and maintenance costs of the fan. On the other hand, the key disadvantages of passive systems are variability in performance (perhaps changing as the wind and temperature change), and high initial installation cost (due to the piping network that must often be installed to accommodate the low suctions).

Definitive testing of passive systems is currently very limited. Thus, it is currently not possible to predict how often, and under what conditions, passive systems will prove to be effective.

5.6.2 Applicability

Passive systems might be most applicable under the following conditions.

- Soil ventilation systems where the limited amount of passive suction might have a chance of being sufficient. Such systems might include sub-slab suction where a network of perforated pipes is laid under the slab in a layer of clean, coarse aggregate several inches deep (such as in Figure 17), or where such a network of pipes already exists (such as sump ventilation where a complete loop of drain tiles drains into the sump, Figure 12). Such a perforated piping network, laid in the vicinity of major soil gas entry routes (e.g., near the wall/floor joint), might enable the passive system to maintain sufficient suction near the entry routes. A passive approach would probably not be practically applicable with the individual-pipe sub-slab system illustrated in Figure 14 because of the high suctions needed in the piping of such a system in order for adequate suction to be maintained remote from the suction pipe. Also, a passive approach would probably not be applicable with block-wall ventilation, because it is not apparent that the passive system could handle the relatively large air flows needed to maintain sufficient suction in such systems.
- Houses which have a complete interior drain tile loop in place, draining to an internal sump, and which also have good sub-slab aggregate. Such houses have a ready-made perforated piping network, and have the minimum practical sub-slab flow resistance, so that the low passive suction might be effectively extended.
- Houses with integral slabs (that is, minimum slab cracks) so the passive system does not have to address slab-related entry routes remote from the perforated piping, and does not have to handle increased air flow that might enter the sub-slab through these cracks.
- New houses, or existing houses where the existing slab must be torn out anyway (perhaps to remove contaminated material from under the house, or to replace a structurally deficient slab). In these houses, an extensive interior perforated piping network can be laid, embed-

ded in a good layer of aggregate, before the new slab is poured. The new slab can be reinforced to help reduce the size of subsequent slab cracks remote from the perforated pipe locations.

- Homeowners who strongly prefer a passive system, due to the advantages listed previously, and are willing to accept the potentially substantial expense of retrofitting a sub-slab piping network into their house to achieve those advantages. The homeowners must be willing to monitor the radon levels in their houses continually for a period of time after installation, in order to understand the conditions (such as warm temperatures and low winds) that overwhelm the passive system. The homeowner must also be prepared to install or activate fans on the system if necessary.
- Houses with poured concrete foundation walls, since passive systems might not have the suction or flow capability to treat major wall-related soil gas entry routes (as might be expected to exist with hollow-block or fieldstone foundation walls).

5.6.3 Confidence

Passive sub-slab ventilation in existing houses has been tested primarily in remediating houses in the U. S. and Canada that were contaminated with uranium mill tailings. Radon reductions of 70 to 90 percent are reported in many of these houses (Ar82). The interpretation of these reductions, in terms of the actual performance of the passive ventilation system, is complicated by the fact that the reported reductions often also include the effects of other mitigation measures that were implemented simultaneously — such as removal of mill tailing source material from under the slab, or trapping of floor drains. In addition, the performance measurements sometimes covered only a short period of time, and thus did not reflect the effects of changing weather conditions on performance.

In 18 installations in Canada, where particularly extensive sub-slab piping networks were installed under the slabs in new houses during construction, passive ventilation of the networks reportedly gave satisfactory reductions during the winter. However, their performance degraded during mild weather, with over half of the houses averaging above 0.02 WL. The systems had to be operated as active sub-slab systems to bring concentrations below 0.02 WL (Vi79). During warm weather, when the natural thermal stack effect was reduced, the passive stack apparently could not develop sufficient suction. Even with the very extensive piping networks used in these houses, passive operation could not ensure adequate radon reductions year round.

A passive sub-slab system has been retrofitted into one house in Pennsylvania where the source of the radon was naturally occurring radium in the surrounding soil and rock (Ta85a). The house had a basement with block foundation walls and an adjoining slab below grade. Both slabs were torn out, some of the underlying soil and rocks were removed, and a uniform layer of crushed rock several inches deep was put down. The ventilation system included essentially a complete loop of perforated pipe around the entire perimeter footing (and the footing for an interior block wall) in the basement, plus a second complete loop for the adjoining slab, embedded in the new layer of aggregate. Each loop had its own passive vent stack through the roof. A polymer liner was placed on top of the aggregate before the new reinforced slabs were poured. Efforts were also made to seal the exterior and interior faces of some of the block foundation walls. The radon levels in the house were reduced by greater than 99 percent, based upon periodic grab sample analyses (for working level) over a period of months, although one significant spike in working level was measured during one of the grab sampling campaigns. Fans in the vent stacks were activated for a period of time after the spike was observed; the fan in one of the stacks is still operated frequently by the homeowner. Grab samples do not reveal the variations in radon levels, or the average levels, that exist between sampling periods.

In summary, some high radon reductions have been reported with passive sub-slab ventilation systems. However, there are currently no rigorous, long-term data confirming that a passive system, by itself, can consistently maintain high reductions on a sustained basis, or defining the full range of circumstances under which the passive system might be overwhelmed. Most data on passive systems that cover more than one season, suggest that, as might be expected, these systems can be overwhelmed at least occasionally. The currently limited data do not permit a reliable assessment of how often or how severely the passive systems might be overwhelmed, or the design and operating conditions which might reduce or eliminate this occurrence. In view of this current limitation in knowledge, it is felt that, at present, EPA is not in a position to establish a confidence level for passive systems. Further testing of passive systems is intended, so that a more definitive statement on confidence can be made in the future.

5.6.4 Design and Installation

The following discussion focuses on passive sub-slab ventilation systems (or passive drain tile/sump ventilation systems), for the reasons discussed in Section 5.6.2.

5.6.4.1 Pre-mitigation Diagnostic Testing

While a variety of pre-mitigation diagnostics can be considered, those listed below would appear to be of particular value.

- Visual inspection—Among the factors to be noted during the visual inspection should be:
    - —the nature and location of slab cracks and other openings. Due to the low suction in passive systems, the system will probably not be able to effectively maintain suction at cracks remote from the perforated pipes. Also, if the cracks or other openings are too numerous or difficult to close, the house air flow down through these openings could be too great for the low-suction, low-flow passive system to handle.
    - —the extent of existing drain tiles under the slab. If the homeowner is not certain, blueprints might be inspected, or the builder contacted. If it is not known that the existing tiles form essentially a complete loop around the footings (or an otherwise reasonably comprehensive pattern), the existing tiles should probably not be relied upon for a passive system.
    - —the degree of finish over the slab, as an indicator of the difficulty and expense of tearing up part (or all) of the slab as necessary to lay a new perforated piping system.
- Measurement of sub-slab permeability—In view of the low suctions and flows achievable with sub-slab systems, it is particularly important that sub-slab permeability be very good. If the installation of the passive system will not involve tearing up part of the slab and putting down a layer of aggregate several inches deep before re-pouring, then measurements should be considered to determine whether the permeability of the existing sub-slab material is relatively high.

5.6.4.2 Design of the Sub-Slab Perforated Piping Network

Because of the suctions achievable with passive systems, it is important that the perforated piping be located as close to the slab-related soil gas entry routes as possible.

If the perforated piping consists of existing drain tiles which form a loop around the inside of the footings, and which drain to an internal sump, then the location of the piping is automatically determined. Fortunately, the drain tiles are probably ideally located, since the wall/floor joint which they are beside is often a major entry route. Moreover, the tiles are likely to be embedded in crushed rock, since they are intended to collect sub-slab water, so there is likely to be reasonable permeability, at least between the tiles and the neighboring wall/floor joint.

If there are no drain tiles in place, then they would have to be installed especially for the passive sub-slab system. One possible configuration is illustrated in Figure 21, which depicts a loop around the inside the footings. This configuration — which is a passive version of the active system shown in Figure 17 — is comparable to the pre-existing interior drain tile loop addressed in the previous paragraph. The advantages of this configuration are that it locates the pipe near a primary slab-related entry route (the wall/floor joint), and it might be installed by tearing up only a portion of the slab (that is, a channel around the periphery) rather than the entire slab.

Installation of a complete loop of perforated pipe, as illustrated in Figure 21, would intuitively be expected to provide the best passive treatment around the perimeter. However, it has been reported that better performance has sometimes been observed when the loop is severed midway around, opposite the riser, and the two severed ends capped (Ta83, Ta87).

More extensive piping networks might be proposed, in an effort to better ensure effective treatment of the entire sub-slab. The more extensive networks would likely require that the entire slab be torn out. (Alternatively, the system could be installed in a new house before the slab is poured.) The layout shown in Figure 22 is perhaps the most comprehensive that could be envisioned. This configuration was initially designed by the Atomic Energy Control Board of Canada, and was issued as guidelines by the Central Mortgage and Housing Corp. for new housing built near uranium mining and processing sites. This configuration was the one used for the 18 passive systems that were installed in Canada, discussed in Section 5.6.3 (Vi79). As indicated in that earlier section, passive operation could not ensure adequate reductions year-round in these installations, even with what could be considered the most extensive conceivable piping network. Even with the maximum network, the systems generally wound up being operated in an active mode, with a fan. It appears that few houses were actually built using such an extensive configuration; since a fan was required, such closely spaced perforated pipes were unnecessary. Thus, the network in Figure 22 should be viewed only as an example of the maximum that might be envisioned, and not as a network which has proven successful for passive applications.

5.6.4.3 Installation of Perforated Pipe Under Slab

If new perforated piping is to be installed under an existing slab, so that part or all of the original slab

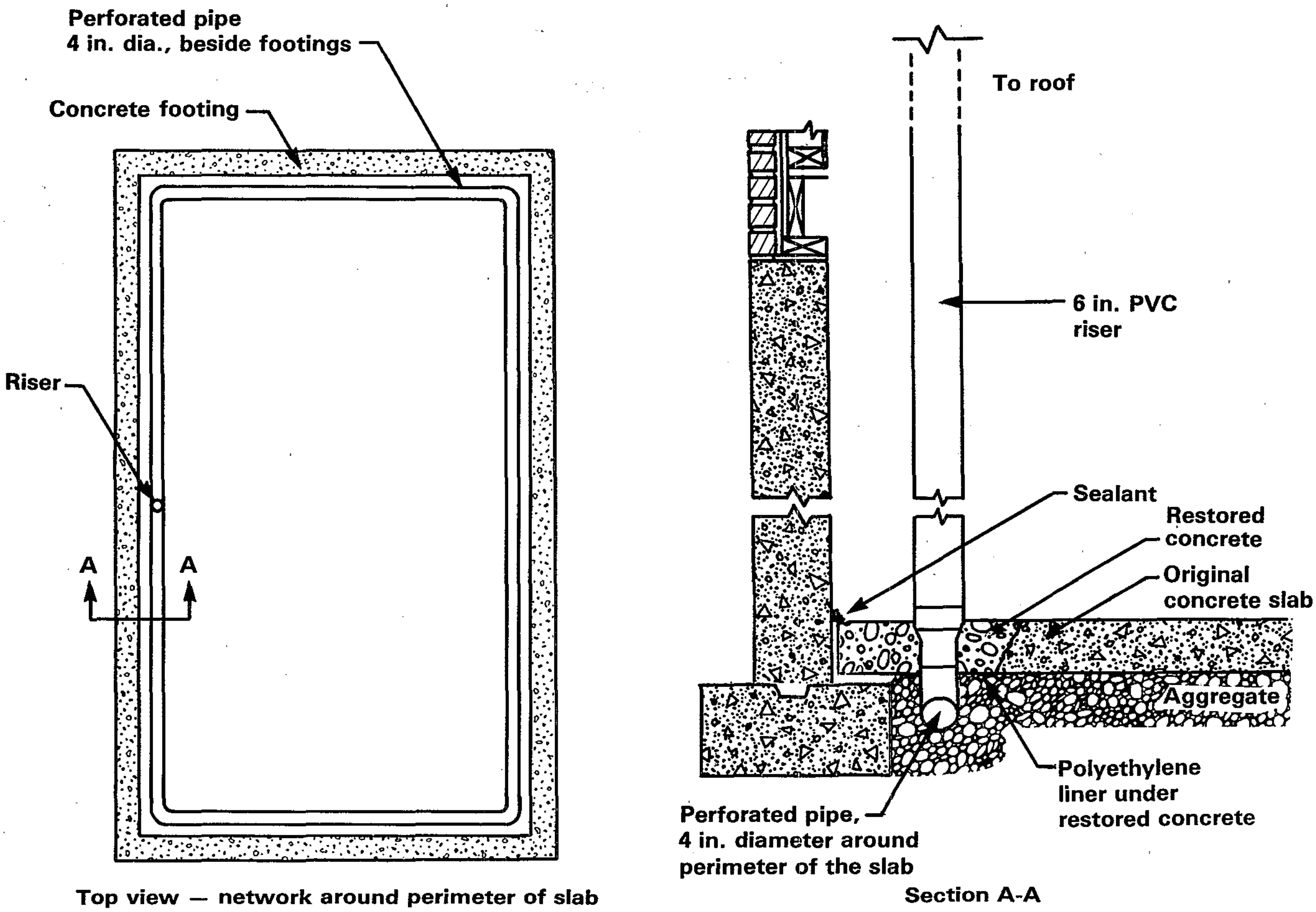
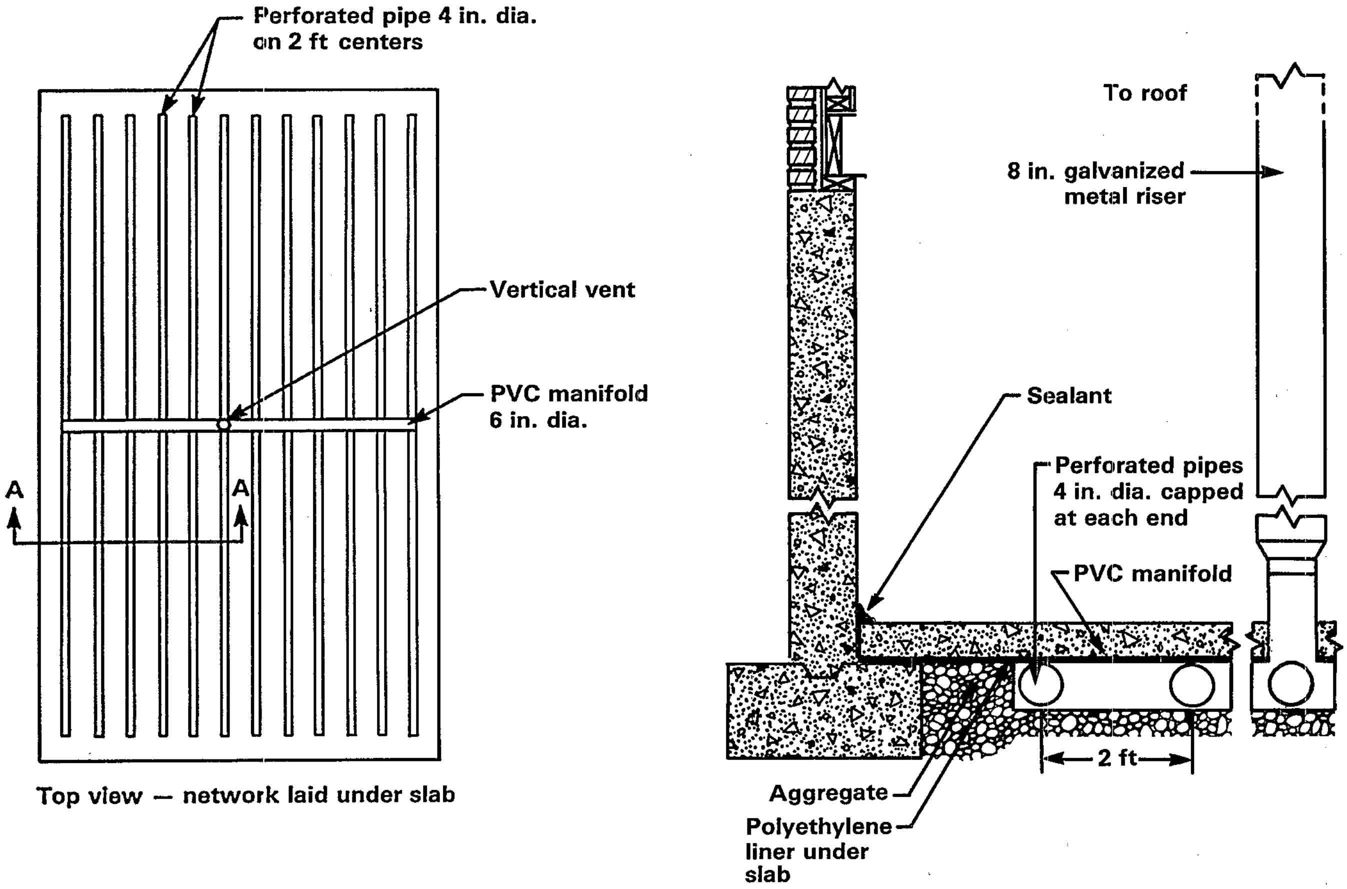


Figure 21. Passive sub-slab ventilation system involving loop of perforated piping around footings.

must be torn out, the installation of the piping should be accompanied by installing a good layer of clean, coarse aggregate several inches deep, if one does not already exist, to improve sub-slab permeability. In addition, sheets of polyethylene should be placed between the aggregate and the new concrete slab, to reduce blockage of the aggregate with concrete, and to help reduce air leakage into the sub-slab if cracks subsequently develop in the slab. If the entire slab is being replaced, it might also be worthwhile to include metal reinforcing in the concrete. Such reinforcing will not prevent the subsequent formation of slab cracks, but it should help reduce the size of the cracks that do develop.

If channels are being cut in the existing slab to install piping around the perimeter, the channels can initially be outlined with cuts about 2 in. deep into the slab using a concrete saw. The remainder of the concrete demolition could be completed with a jackhammer. The exposed channel would be excavated to a depth of at least 6 to 12 in., and filled to the underside of the slab with crushed rock. The deeper the crushed rock, the better. The crushed rock should be clean (eliminating dirt and fines) and coarse, in the size range of 1/2 to 1-1/4 inch. The 4-in.-diameter perforated pipe would be buried in the middle of this aggregate bed. If the piping forms a complete loop, a solid plastic tee would be inserted into the loop at a convenient point, with the leg of the tee pointing vertically upward for connection to the stack. The upward leg of the 4-in.-diameter tee would be fitted with a 4- to 6-in. adaptor, if the stack will be of 6-in. pipe. If the loop is fairly large, it could sometimes be beneficial to have more than one stack, so that a second tee might also be inserted elsewhere in the loop. (On the other hand, a second stack might not be helpful if the pressure field over the roofline is asymmetric in a manner that causes one of the two stacks to downdraft.) If the piping does not form a complete loop, the stack tee should be near the midpoint of the length of piping (Ta87). If there are multiple segments of piping, of course, each must have its own stack. In any case, the stack tees should be



Top view — network laid under slab

Section A-A

Figure 22. Passive sub-slab ventilation system involving comprehensive perforated piping network (from design by Atomic Energy Control Board of Canada).

positioned such that the stack can be raised from the point with minimum (if any) bends, penetrating the upper stories at convenient locations (for example, through a closet), and penetrating the roof preferably on the rear slope (to reduce visual impact from the front of the house).

The top of the aggregate in the entire trench should be covered with plastic liner (6 mil or thicker polyethylene). Seams between different sheets of plastic should be bonded, and seams between the liner and the sides of the trench (and between the liner and the penetrating riser for the stack) should be coated; e.g., with asphaltic sealant. Fresh cement is then poured to restore the slab. Some investigators propose that the broken concrete surface on the sides of the trench be cleaned and coated with an epoxy adhesive just before the new concrete is poured, to help ensure airtight adhesion.

If the entire slab is removed, it should be ensured that at least 6 in. of clean crushed rock underlies the entire slab area. If some sections have less, it is recommended that those areas be excavated and additional clean, coarse aggregate laid (1/2 to 1-1/4 in.). As long as the cost of removing the slab has been incurred, it is cost effective to do any further work needed to ensure a good aggregate layer. The aggregate will help improve the chances of the passive system to perform well, and, if the passive approach does not perform sufficiently, good aggregate almost guarantees that the system can be made to work very well by the addition of a fan. The perforated piping network is buried in the middle of the aggregate. Tees for one or more stacks are installed in the piping at logical locations, as before. The aggregate surface over the entire slab is then covered with overlapping sheets of plastic liner (which also overlap the top of the footings), and the seams between sheets bonded. In one installation (Ta85a), a layer of building felt was put over the crushed rock first, to help avoid puncturing of the plastic, and the plastic sheets were 24 mil thick. The new slab is then poured.

5.6.4.4 Installation of Stack

The stack must be solid (non-perforated) pipe.

The stack must rise up through the house. The gas in the stack must be warmed to house temperature if the thermal buoyancy effects, which contribute to passive suction, are to be effective. Therefore, taking the stack out through the basement band joist, and raising it to the roofline outside the house — discussed in the earlier sections for active soil ventilation — is not an option here.

The stack must extend up above the roofline.

Since the suctions which can be developed passively are so low, every effort is advisable to reduce the pressure loss in the stack. The stack should be as large in diameter as possible, in order to reduce gas velocities and hence pressure loss. Stack diameters of 6 in. are commonly considered. In such cases, the 4-in. tee tapping into the perforated piping would have to be equipped with an adaptor to accommodate a 6-in. stack. The Canadian design in Figure 22 envisions a stack of 8-in. galvanized metal ducting. It is not known whether passive flows will consistently be high enough to warrant the use of such large stack diameters. However, in view of the lack of data, it is considered advisable that large-diameter stacks be planned. Another consideration is that bends and elbows in the stack should be minimized (or eliminated, if at all possible) since each creates some pressure loss. The stack should ideally rise absolutely straight up through the house. A pair of 45-degree bends is sometimes used to direct the stack to a point where it can conveniently penetrate the floors above (Ta85a, Ta87). Elbows and horizontal pipe runs in the stack — considered in active systems as a means to simplify installation — would reduce any chance that a passive system might have for performing well. All joints in the stack piping must be well-sealed, since any air leakage through those joints could further reduce the suction developed.

The buoyancy effect inside the stack would be greatest if the stack gas is as warm as possible everywhere in the stack. Thus, it could be of help to insulate that segment of the stack which is in an unheated attic, or in any other unheated area.

The top of the stack should be protected to prevent leaves and other debris from plugging the stack. In some cases, a rain cap might also be required to meet codes. Cap designs that have been used include a passive wind turbine on top of the stack, and also a cap designed to create a venturi effect (Ta87). These designs have been reported to increase the suction in the stack, relative to an open-ended stack with no cap. Since the natural suction in the stack will be low, it is important that any protective cap at the top of the stack not create an obstruction which will significantly reduce this suction. In view of the limited data with passive systems, it would be advisable to make suction and flow measurements in the stack with and without any cap being considered, to ensure that the cap is not unduly inhibiting performance.

In the installation of the stack, consideration must be given to the possibility that a fan might have to be installed on the system in the future. Thus, the stack might be located near electrical outlets in the attic, and flexibility for subsequent addition of a fan provided wherever possible.

Where the vent pipe penetrates the roof, appropriate flashing and asphaltic sealant should be applied to prevent water leakage. Where the stack penetrates the floors and ceilings between stories of the house, any residual opening around the stack pipe should be closed to avoid a thermal bypass inside the house.

5.6.4.5 Closure of Major Slab and Wall Openings

Closure of major slab and wall openings is particularly important for passive systems, since they might easily be overwhelmed if there is much air leakage into the system through these openings. In addition, since the passive suction might not be adequate to extend very far (for example, to treat foundation walls), the closure effort might be an important supplement to the passive system simply in terms of reducing soil gas entry through these openings.

5.6.4.6 Post-Mitigation Diagnostics

The most important single post-mitigation diagnostic test would be numerous (preferably continuous) radon measurements under different wind and temperature conditions. These measurements would identify under what conditions that particular system seems able to keep radon levels down, and under what conditions it is overwhelmed.

A possible companion diagnostic test would be measurements of the suction being developed in the stack (near the slab) under these different conditions.

Other diagnostics could include smoke tracer and other testing to identify which entry routes are not being treated if the passive system does not reduce radon levels sufficiently.

5.6.4.7 Instrumentation to Measure Suction

If the suction that is maintained in the stack near the slab is adequate to be reliably measured — and if the post-mitigation diagnostics confirm that there is a reasonable correlation between stack suction and indoor radon levels — then a suitable pressure measurement device could be installed on the stack. The homeowner could use the stack suction as an indicator for when the passive system might (or might not) be performing well.

5.6.4.8 Installation of a Fan if Needed

As discussed previously, the currently limited data on passive systems do not permit a reliable assessment of how often or how severely these systems might be overwhelmed. Therefore, anyone installing a passive system should be prepared to supplement the system with a fan in suction if subsequent measurements show that the natural suction is insufficient during some periods.

As discussed in earlier sections, exhaust fans should always be mounted outdoors or in the attic. Thus, if a fan must be added to a passive system, it could logically be mounted in the existing stack, either on the roof or in the attic.

Because passive systems are designed to have a good sub-slab drain tile network and good sub-slab permeability, the addition of a sufficiently powerful fan to such a system could be expected to provide substantial radon reductions. The 0.05-hp, 270 cfm fans commonly used in the EPA testing would probably provide high reductions in most cases. If a uniform layer of clean, coarse aggregate several inches deep has been put in place under the slab, smaller fans could sometimes be sufficient. Some success has been reported using a small 6-W booster fan inserted into the side of the stack (Ta85a).

Any fan installed in the stack will create an obstruction which will hinder the natural suction effects. Thus, if the natural suction proves inadequate under some circumstances before the fan is installed, it will prove inadequate even more often afterwards. As a consequence, once the fan is installed, the system might have to be operated as an active system for much (if not all) of the time. The 6-W booster fan, mentioned previously, provides the least obstruction, but also provides the least suction.

More experience is required with passive systems to determine the best approach for supplementing the system with a fan if passive operation alone is sometimes insufficient. However, at the present time, it is recommended that the passive system be fitted with a sufficiently powerful fan under such circumstances, and be operated permanently as an active system. Such conversion to an active system will ensure continued high reductions, and will avoid the need for the homeowner to be continually alert to when the fan should be turned on.

5.6.5 Operation and Maintenance

Since there are no mechanical parts to a purely passive system, the operating requirements would consist only of regular inspections by the homeowner to ensure that all slab and wall closures remain intact, and that all piping joints remain sealed.

If stack pressure can be used as an indicator of system performance —and if a measurement device is installed on the stack — the homeowner would also have to check the gauge or manometer. If a fan does ultimately have to be installed in the system, the homeowner would have to activate the fan whenever natural suction is inadequate, if the fan is not operated continuously. If a fan is sometimes used, of course, checking fan operation would also be necessary.

Maintenance would include any required repair of broken seals, and re-closure of any major slab openings where the original closure has failed. If a fan is used, it must receive routine preventive maintenance.

5.6.6 Estimate of Costs

The installed costs of passive sub-slab ventilation systems will vary widely.

If the system involves passive ventilation of an existing sump/drain tile system, the installation will include capping the sump and taking a stack up through the house. The installed cost in this case might be roughly $2,000, depending upon the amount of finish that must be removed/replaced in taking the pipe up through the living area above the sump.

If the system involves cutting a channel around the perimeter of the slab, the cost would be several thousands of dollars, depending upon the amount of finish over the slab.

If the entire slab is removed and a piping network installed underneath (with new aggregate and a liner over the aggregate), the total system cost could be on the order of $10,000. Again, costs could be substantially affected by the degree of finish over the slab.

In any of these cases, if a fan must be added into the stack (in the attic or on the roof), installed costs would likely increase by a few hundred dollars.

If no fan is used, the operating costs of these systems would be essentially zero. There would be no cost for electricity if no fan is used, and the amount of increased house ventilation would probably be insufficient to cause a perceptible impact on heating costs.

Section 6

Pressure Adjustments Inside House

The primary mechanism causing the movement of radon into a house is convective movement: since pressures at the lower levels inside a house are commonly lower than the pressures in the surrounding soil, soil gas is drawn into the house. (Diffusive movement through cracks, a secondary mechanism, is not affected by this pressure differential.) If the degree of house depressurization is reduced, the driving force for convective movement is reduced, and thus the rate of soil gas influx might be reduced (reducing radon levels in the house). In the extreme, if the pressure difference could be reversed—so that the lower level of the house is *higher* in pressure than the surrounding soil—the convective influx of soil gas would be stopped altogether.

6.1 Active Reduction of House Depressurization

6.1.1 Principle of Operation

As discussed in Section 2.2.2, houses can become depressurized as a result of the weather and homeowner activity.

- Cold outdoor temperatures create a buoyant force on the warm indoor air, depressurizing the lower levels of the house. Winds can cause depressurization by increasing house air exfiltration on the low-pressure downwind side of the house.
- Exhaust fans and combustion appliances draw air out of the house, potentially contributing to depressurization.

In addition, certain house design and construction features can facilitate the flow of warm air up through and out of the house (the thermal stack effect) in response to the temperature-induced buoyant forces. These features include openings through the house shell above the neutral plane, and airflow bypasses between stories inside the house. Openings through the house shell can also contribute to wind-induced depressurization.

When the house is depressurized—or when stack-effect-induced flows of air out of the house occur—a driving force is created, sucking outdoor air and soil gas into the house to compensate for the exfiltrating house air. Usually, 95 to 99 percent of the gas that infiltrates in response to this driving force is outdoor air; only 1 to 5 percent is soil gas (Er84). If house depressurization and stack-induced exfiltration can be reduced, this driving force for infiltration is reduced. From a radon reduction standpoint, the objective of reducing this driving force is to reduce the percentage of the infiltrating gas which is soil gas. If the percentage which is soil gas can be reduced, the radon levels in the house will be reduced.

Whether the percentage of soil gas will in fact be reduced by a reduction in the driving force will vary from case to case. It will depend upon, for example, the leakage area above grade, the leakage area below grade, and the permeability of the soil. Results to date confirm that, at least in some cases, increases in the driving force do increase radon levels, thus apparently increasing the percentage of soil gas in the infiltrating gas. Therefore, to the extent that the driving force can be reduced by reducing depressurization and exfiltration, such steps should generally help reduce indoor radon levels.

Several approaches can be considered for reducing house depressurization:

- providing a route for outdoor air entry into the house to compensate for the house air exhausted by exhaust fans, or perhaps taking steps to avoid the use of exhaust fans.
- sealing cold air return registers in the basement for central forced-air heating and cooling systems, and sealing leaks in the low-pressure return ducting in the basement, to reduce basement depressurization.
- providing outdoor air in the vicinity of combustion appliances, to reduce any depressurization created by the movement of house air up the flue as a result of fuel combustion and flue draft.
- ensuring that windows are not opened solely on the low-pressure, downwind side of the house.

In addition, steps can be taken to reduce airflow out of the house during depressurization, including tightening the house shell at the upper levels, and closing airflow bypasses inside the house.

There are currently insufficient data to predict the radon reductions that will generally be achieved by implementing the approaches listed above. Moreover, since some of these sources of depressurization are only intermittent (such as fireplaces and exhaust fans), any radon reductions that are achieved will apply only over short time periods. However, it is known that these sources can sometimes be significant contributors to indoor radon, and that the benefits of addressing these sources can thus sometimes be significant, at least over short time periods. Therefore, to the extent that steps to reduce depressurization can easily be implemented by the homeowner, the homeowner is well advised to take these steps.

6.1.2 Applicability

Techniques for reducing house depressurization are applicable to any house which possesses the various individual sources of depressurization. Techniques for reducing the airflow up through and out of the house, via the thermal stack effect, also apply to any house. The techniques are most applicable where:

- the steps can be fairly easily implemented, since there is current uncertainty regarding their effectiveness. The steps can be easily implemented when: a window can conveniently be opened near an exhaust fan or combustion appliance; cold air return registers and return ducting for forced-air HVAC systems in the basement are reasonably accessible for sealing; and individual airflow bypasses, and openings through the house shell on the upper levels, are accessible for closing.
- the source of depressurization, or the airflow bypass, is large. For example, a kitchen range hood exhaust fan (commonly 150 to 400 cfm) or a whole-house exhaust fan (up to several thousand cfm) would be of greater concern than a bathroom exhaust fan (typically 50 to 100 cfm).
- the radon concentration in the soil gas is high. When soil gas radon levels are higher, the indoor reductions that would be achieved by reducing soil gas influx may be more dramatic.

6.1.3 Confidence

The radon reductions that can be achieved in a specific house by attempting to reduce depressurization and to reduce exfiltration are uncertain, although reductions have been shown to be significant in some houses. Reductions will vary from house to house, and can vary over time in a given house. The sources of the uncertainty include the following.

- It is not known what degree of depressurization will typically be created by some of the sources of depressurization. The degree of depressurization will depend upon the amount of house air that is exhausted (or which exfiltrates), and the tightness of the house (i.e., the ease with which outdoor air can naturally infiltrate to compensate for the exhausted house air).
- It is not known what increase in the soil gas influx rate, and in indoor radon concentrations, will result in a given house as a result of this depressurization. That is, it is not known to what extent (if any) the depressurization will increase the percentage of the infiltrating air that is soil gas. The increase will depend upon the relative ease with which outdoor air versus soil gas can infiltrate in response to the depressurization (or in response to the increase in stack effect exfiltration resulting from airflow bypasses and shell penetrations). The ease of outdoor air entry will depend on the tightness of the house shell above grade. The ease of soil gas entry will depend upon the nature of the entry routes and the permeability of the soil.
- It is not known what reductions in the depressurization (or in stack effect exfiltration) will in fact result from the proposed steps at a specific site. Nor is it known to what extent any reductions in depressurization will reduce the percentage of soil gas in the infiltrating air, and thus to what extent indoor radon levels will actually be reduced. Data to rigorously quantify these effects are very limited.

Testing is underway now, as part of EPA's radon reduction development and demonstration program, that should provide some rigorous information on the depressurization caused by various factors, and the effect of this depressurization on radon levels.

While the data are not currently available to verify that appliances always produce significant depressurization or significant radon increases, a number of individual cases illustrate that the impacts can be substantial, at least in some instances. In one house (initially a high-radon house, with a soil ventilation system in place to reduce radon), levels apparently jumped from a few pCi/L to about 200 pCi/L when an exhaust fan was activated in the basement (Ta87). In a second house (also a high-radon house with a soil ventilation system in place), levels spiked to about 3,000 pCi/L, apparently as the result of a high-volume kitchen range exhaust fan (perhaps in combination with an open downwind window). In a third house, with no radon mitigation system in place, operation of a coal stove in the basement caused basement levels to rise from a mean of 46 pCi/L to a mean of 104 pCi/L (Du87). In two other houses, each with a soil ventilation system in operation, use of a fireplace on the floor above caused levels in the basement to rise by roughly 20 to 30 pCi/L (Sc86d). However, in another study of the effects of fireplace operation (Na85b), fireplace operation upstairs was found to have no clear effect on the radon levels averaged throughout the house (basement and upstairs). In this latter study, the increase in soil gas influx and fresh outdoor air influx caused by the fireplace apparently offset each other, at least on a house-wide average.

In terms of the actual depressurization that is occurring, the natural thermal stack effect by itself is generally reported to be about 0.01 to 0.05 in. WC. By comparison, in one house, the exhaust fan associated with a clothes drier was found to create an additional depressurization in the basement of about 0.02 in. WC—that is, on the same order of magnitude as the natural stack effect. In another house (Hu87), pressure measurements were made in the basement as a gas-fired central forced-air furnace cycled on and off. With the gas burners on, but without the central fan in operation, the incremental basement depressurization caused by the burners alone was on the order of 0.001 in. WC, no more than 10 percent of that created by the natural stack effect. The central furnace fan by itself in that house, with the burners off, caused an incremental basement depressurization of roughly 0.01 in. WC. Evidently, leaks in the low-pressure cold air return ducting in the basement withdrew some air from the basement, so that the central furnace fan had the effect of an exhaust fan in the basement.

While it seems evident that exhaust fans and combustion appliances can create depressurization and increased radon levels in some cases, there are currently no definitive data regarding how well steps to reduce this depressurization will in fact decrease radon levels under various conditions. Also, it is expected that performance will vary from house to house. A window opened slightly during fireplace operation in one house might have a different effect from a differently positioned window opened in another house.

Another consideration in assessing the performance of these depressurization reduction techniques is that their performance will be time-dependent. For example, a technique aimed at reducing depressurization by an exhaust fan or a fireplace could have a significant impact when the exhaust fan or the fireplace is being operated. However, the average impact over the course of a year would be lower if the fan or fireplace is operated for only a relatively small percentage of the year.

In view of the data limitations, a confidence level cannot currently be determined for techniques to reduce depressurization. One cannot as yet reliably predict the amount of radon reduction that might be achieved under various circumstances for a given level of effort and resources expended in reducing depressurization. However, before better information becomes available, it is felt that—to the extent that steps can readily be taken to reduce depressurization—a homeowner is well advised to take these steps. The benefits can sometimes be dramatic, at least while the depressurizing appliance is in use.

6.1.4 Design and Installation

6.1.4.1 Exhaust Fans

In this discussion, an exhaust fan is defined as any fan which withdraws air from one part of the house and exhausts it outdoors (or sometimes to another part of the house). Examples of exhaust fans include:

- window fans or portable house ventilation fans, when operated to blow indoor air out.
- kitchen exhaust fans (including range hood fans).
- bathroom exhaust fans.
- attic exhaust fans.
- clothes driers.
- whole-house fans.

Exhaust fans of greatest concern are those with the highest exhaust volume, since these can potentially create the greatest depressurization. Whole-house fans are the largest, commonly exhausting as much as 3,000 to 7,000 cfm (HVI86). Window fans and attic fans typically exhaust between 500 and 2,000 cfm, range hood fans from 150 to over 400 cfm, and bathroom fans from 50 to 100 cfm.

Exhaust fans can potentially increase the soil gas influx, regardless of where in the house they are located. On the bottom story, below the neutral plane, they can contribute to depressurization in the vicinity of the soil gas entry routes. On upper stories, above the neutral plane, they can supplement the natural exfiltration which drives the thermal stack effect, thereby increasing the rate of air and soil gas infiltration below the neutral plane (and possibly increasing the flow of high-radon basement air up into the living area). Depending upon the flow dynamics in the house, an exhaust fan on an upper level might have a reduced effect on radon influx, compared to the same fan located on the bottom story. When the fan is upstairs, a greater fraction of the infiltrating gas (to compensate for the fan exhaust) might be outdoor air leaking in through the upper level, rather than soil gas.

Options that can be considered for reducing depressurization by exhaust fans are listed below.

Opening windows near the fan. The first option that can be considered is to open a window at some reasonable location in the house, whenever the fan is in use. Opening the window will help ensure that the makeup gas entering the house (to compensate for the air exhausted by the fan) will be outdoor air rather than soil gas. The window does not necessarily have to be opened all the way; depending on the fan flow, opening the window only an inch or two might be sufficient. The window should preferably be as close to the fan as possible. If the fan is intended to ventilate some particular area, such as a kitchen, a window on the opposite side of the kitchen should probably be opened, to provide cross-ventilation. If the fan is a whole-house fan, windows around the house below the neutral plane should be opened.

Opening a window during fan operation is a step which a homeowner can sometimes take fairly easily. To the extent that this can be done conveniently and without discomfort from drafts, it is suggested that this step be taken, even if extensive radon measurements have not been made to verify its effectiveness. This step is probably least important when the fan is relatively small, such as a typical bathroom exhaust fan.

Reversing the fan. In most cases, fans of the type being discussed here must be operated in the exhaust mode. The fans are designed for mounting in an exhaust configuration, to avoid the unacceptable draftiness that would exist near the fan if it blew inward, and to remove local contaminants (such as smoke and steam from a kitchen range) rather than blowing them throughout the house. Thus, reversing the fan to blow into the house is often not an option. However, it is possible in some cases, and should be considered when practical. Reversing the fan not only avoids the depressurization, but might also cause some slight pressurization, which could be helpful.

Exhausting into the house. In some special cases, it might be possible to consider a configuration where the fan exhausts back into the house instead of outdoors. For example, in one clothes drier configuration, the filtered drier exhaust is blown into the house during the winter. This arrangement will not be acceptable in some cases due to the heat, humidity, and lint in the drier exhaust.

6.1.4.2 Central Forced-Air HVAC Systems in Basement

A central forced-air furnace in a basement house can present a special variation of the exhaust fan problem. The furnace and much of the cold air return ducting are commonly located in the basement in such houses. The return ducting is under negative pressure; air from elsewhere in the house is being sucked through this ducting by the central fan, returning to the furnace. Such ducting is not airtight. Hence, basement air is drawn into this ducting through leaks in the ductwork. Air will often also be withdrawn from the basement by cold air return registers in the basement. The net effect is that more air can be drawn out of the basement by the HVAC system than is supplied via warm air supply registers, thus depressurizing the basement. The central furnace fan under these conditions would have the effect of an exhaust fan. As discussed in Section 6.1.3, limited data show that this effect can in fact occur, at least in some houses.

Where forced-air furnaces are present in a basement, all seams and openings in the cold air return ducting should be carefully taped, and possibly caulked if necessary, to reduce the amount of basement air leaking into the duct. In addition, all cold air return registers in the basement should be closed off.

6.1.4.3 Combustion Appliances

Combustion appliances that probably cause the most significant degree of depressurization are fireplaces and coal or woodstoves. Appliances which probably depressurize to a lesser degree would be central furnaces, water heaters, or any other vented combustion appliances.

Opening windows near the appliance. The easiest method for reducing depressurization by combustion appliances is to open a window somewhere near the appliance. Opening a window even an inch or two would help ensure that the makeup air leaking into the house (to compensate for that going up the flue) would be outdoor air rather than soil gas. Opening a window would generally be most easily applicable for those appliances which are operated only occasionally (such as a fireplace).

At first glance, it might appear that opening a window to let in cold air would defeat the purpose of the fireplace in heating the house. However, when a fireplace sends house air up the flue, a comparable amount of cold air will leak into the house one way or another (for example, around closed windows and doors, if not through an open window). By opening a window, the homeowner is simply controlling where that makeup air comes from, and ensuring that it is not soil gas. One difficulty is in being able to open a window situated such that the draft between the window and the fire is not uncomfortable for the occupants. Another difficulty is in determining the proper extent to which the windows should be opened.

Homeowners can easily implement the step of opening windows during the periods that certain intermittent combustion appliances are in operation, such as fireplaces. To the extent that this can be done conveniently and without discomfort from drafts, it is suggested that this step be taken, even if extensive radon measurements have not been made to verify its effectiveness.

Providing makeup outdoor air (other than open windows). For combustion appliances which operate routinely, such as a furnace, a continuously open window will not always be practical. Accordingly, approaches can be considered that bring outdoor air to the vicinity of the appliance in a permanent manner that minimizes the impact on the remainder of the house, and that avoid the security concerns associated with an open window. Some methods for doing this for gas furnaces are described in Reference NCAT83. One approach involves installing an opening through the house shell at some point (for example, a 4-in. diameter hole through the band joist, with a suitable vent cap on the outside). Insulated 4-in. metal ducting then leads from this point to the vicinity of the furnace. The duct might terminate with a draft diffuser somewhere near the burners. By various codes, this outside air duct could *not* be manifolded directly to the burners. Alternatively, a vent could be installed through the house shell without ducting, at a point near the appliance, so that outdoor air could flow into the region of the appliance. Either of these approaches is similar in concept to opening a window, except that an effort is made to direct the air toward the appliance in a permanent manner.

It is re-emphasized that current data do not enable a rigorous assessment of whether furnace or water heater burners in fact create sufficient depressurization such that this type of supplemental air system is in fact required or cost-effective for radon reduction. Supplemental air could provide certain additional benefits in addition to any radon reduction, including helping to ensure that a proper flame and draft is maintained, to further reduce the risk of combustion contaminants inside the house (ASHRAE81). This is especially important when an active soil ventilation system is being operated in suction for the house, due to the increased risk of back-drafting under some conditions with suction systems. Supplemental air might also help reduce heating costs, by providing cold outdoor air for combustion, rather than sending so much heated indoor air up the flue.

It can also be beneficial to provide a permanent source of outdoor combustion air to appliances which may operate only intermittently, such as fireplaces and woodstoves. Various designs are commercially used to provide outdoor air to these appliances.

Installing a permanent supply of outdoor air to a combustion appliance will involve some capital cost. Depending upon whether the area around the appliance is heated and cooled, it could also involve some operating cost, to heat and cool the outdoor air that will be infiltrating through the system's vents even when the appliance is not in operation. It is not recommended that a permanent supply of makeup air be installed until after radon measurements have been made with and without the appliance in operation. Such measurements would indicate whether the appliance is a sufficiently important contributor to indoor radon levels to make the investment worthwhile. Radon measurements over a few days using a continuous monitor would be best suited for making this assessment, identifying levels with the appliance on and off. If the appliance operates continuously for a day or more (such as a woodstove), charcoal canister measurements with the appliance on, and then with it off, would also be an option.

6.1.4.4 Reducing Depressurization Caused by Wind

The wind will create a low-pressure region on the downwind side of the house. Some depressurizing effect will result inside the house, because the house shell is not airtight. For example, house air will leak out around closed windows on the low-pressure, downwind side while outdoor air will leak in on the high-pressure, upwind side. The depressurizing effect could be significant if there is greater leakage area on the downwind side than on the upwind side. Such a situation could exist if windows or doors are open only on the low-pressure side of the house, improving the communication with the low-pressure region. Since it is not practical for the occupant of a house with open windows to be constantly noting wind direction, the best solution to this problem is to ensure that windows are always open on more than one side of the house at a time. In this manner, any air flowing out of the house on the low-pressure side will be matched by air flowing in on the high-pressure side (avoiding depressurization, and creating an effective cross-ventilation).

Another approach for reducing depressurization by wind is to close openings through the house shell, through which house air can exfiltrate under the influence of wind-induced, low-pressure regions. See the discussion of house tightening in Section 6.1.4.5. Of course, such closure will also close the openings through which outdoor air can infiltrate under the influence of wind-induced, high-pressure regions, or as a result of the thermal stack effect below the neutral plane. Therefore, to the extent that house shell penetrations are closed, they should be closed on *all* sides of the house, to avoid the risk that they may be closed preferentially on the high-pressure (upwind) side. Closure preferentially on the upwind side would reduce wind-induced infiltration to a greater extent than exfiltration, and could thus worsen wind-induced radon problems. Likewise, closure should be especially careful on the upper levels, above the neutral plane. Stack-effect-induced exfiltration (above the plane) should be reduced to an extent at least as great as stack-induced infiltration below the plane.

6.1.4.5 Reducing the Stack Effect

The previous sections have addressed methods for reducing depressurization in the house. This section discusses methods for reducing air flows up through the house, and air exfiltration from the upper levels, under the influence of temperature-induced depressurization. These steps will not reduce the depressurization, but they can reduce the soil gas infiltration that could result from the depressurization.

Two factors are of concern in reducing these air flows (i.e., in reducing the stack effect). One is the need to reduce the house air exfiltration from the upper levels. The second is the need to reduce the flow of basement (or lower-story) air upstairs where it will exfiltrate.

House tightening. If the upper levels of the house shell are tightened (above the neutral plane), less warm house air will be able to leak out under buoyant forces during cold weather. As a consequence, less makeup gas would have to leak in below the neutral plane. The reduction in exfiltration due to the tightening might cause the amount of infiltrating soil gas to decrease relative to the amount of infiltrating outdoor air, thus reducing indoor radon levels.

The effect on radon levels of tightening a particular house has not been demonstrated. The effect could vary from house to house. It will depend upon how the tightening influences the infiltration of outdoor air versus soil gas. This relationship will in turn depend on a number of factors, as discussed in Section 6.1.1. However, if the tightening is limited to parts of the house above the initially existing neutral plane, there is a reasonable likelihood that radon levels can be reduced.

House tightening must *not* be limited to parts of the house *below* the neutral plane. Tightening only below the neutral plane would not reduce the upper-level exfiltration, and hence would not reduce the amount of compensating infiltration. But it could reduce the percentage of the infiltrating air which is outdoor air, by closing off infiltration routes. Thus, the percentage that is soil gas could increase, increasing radon levels.

House tightening could have the additional advantage of reducing energy consumption in the house, but could have the disadvantage of increasing the levels of indoor air pollutants other than radon which are generated in the house.

Methods for tightening houses have been presented in a number of references (SCBR83, for example). Some tightening can be done fairly easily by the homeowner at a reasonable cost, including:

- — exterior caulking around upstairs window frames (and upstairs door frames, if present)
- — weatherstripping between frames and windows (and doors) upstairs
- — closing penetrations through the ceiling between the living space and the attic, including sealing around duct penetrations and weatherstripping around drop-down attic access doors.

Other steps are more difficult and expensive, such as placement of plastic sheeting as an air barrier under the insulation between the joists in the attic, and steps to tighten the upstairs walls (such as an air barrier between studs). Confidence that these steps will indeed produce any significant reduction in radon levels is too uncertain to justify the expense of these steps based upon radon reduction considerations alone.

Closure of airflow bypasses. Airflow bypasses are openings in the floors and ceilings which permit movement of air between stories of the house (and between the living space and the attic). Such bypasses serve as holes in the "damper" that the floor would otherwise create in the "chimney" formed by the house shell. They thus facilitate the flow of air from downstairs to upstairs, and hence its ultimate exfiltration, under the thermally induced stack effect. Such airflow bypasses should be closed to the extent possible in every floor/ceiling of the house.

Bypasses to consider include the following.

- Stairwells between stories of the house, especially between the basement and upstairs. If the stairwell includes a door, the door might be fitted with a spring-loaded device to ensure that it remains closed. It might also be helpful to weatherstrip around the door, to install a threshold, and to caulk around the door frame if warranted. Codes may require that basement doors be undercut; the gap under the door should not be closed with a threshold in such cases.

- Utility penetrations through the floors (such as those for plumbing and electricity). Any gaps around such penetrations should be caulked shut.
- Open dampers in chimneys and flues (airflow bypasses directly to the outdoors). Dampers should be kept closed when the fireplace or stove is not in use.
- Chases for flues and utilities. These chases should be blocked using sheet metal, plywood, foam, or other appropriate material, with caulk around all seams and gaps.
- Laundry chutes. Chutes should be fitted with covers or doors, which form as tight a fit as possible when the chute is not being used.
- Recessed ceiling lights, where these represent a penetration through the ceiling into the attic above. Any gaps between the light fixture and the ceiling should be caulked. For safety reasons, no effort should be made to cover or seal the top of the fixture itself unless it is designed to permit covering. Where the recessed fixture cannot be safely sealed, one option would be to replace the fixture with one that is not recessed, and closing the old opening through the ceiling.
- Drop-down attic access doors. Weatherstripping should be placed around these doors.
- The opening into the attic created by a ceiling-mounted whole-house fan. A cover should be placed over the fan when it is out of use for extended periods, especially during cold weather.
- Openings concealed inside block structures which penetrate floors between stories of the house. In many cases, there might be nothing that can be done about such concealed openings short of taking down the blocks. However, one should be alert to these openings, and should close them wherever they might be exposed. For example, if the structure is reduced in cross-sectional area or if it terminates in the attic, some of the openings might be exposed where the transition occurs.
- The cavity inside interior frame walls, and inside exterior frame walls with balloon-style framing. Little can be done easily to address these cavities, which can extend the entire height of the wall (from the bottom of the lower level up to the attic).
- Central heating/air conditioning ducts which connect upstairs and downstairs. Again, little can be done about these ducts, other than possibly closing the registers when the system is not in use.

If some large airflow bypass cannot be closed (such as an open stairwell), closure of other, small bypasses will probably not provide much benefit.

6.1.5 Operation and Maintenance

Some of these techniques have operating requirements in the form of opening windows at the appropriate times, or occasional inspection of seals (such as around sealed airflow bypasses). The only maintenance requirement would generally be repair of broken seals.

6.1.6 Estimate of Costs

In most cases, where any required work can be done by the homeowner, the installed costs for these techniques will be relatively low. The cost would be limited to the cost of materials, such as the cost of caulk, weatherstripping, or plywood. Operating costs will generally be close to zero in many cases. Even where windows are opened to reduce depressurization by exhaust fans or combustion appliances, the operating costs might not be large. The flow of cold air through the open windows might not be significantly greater than the infiltration that would have resulted anyway, so that the net heating penalty might not be large.

Where the house is tightened and where airflow bypasses are closed, there could be a savings in heating and cooling costs.

It is the fairly low cost and ease of implementation of most of these methods that led to the recommendation that they be considered despite the lack of data rigorously confirming their radon reduction effectiveness.

6.2 House Pressurization

6.2.1 Principle of Operation

If that part of the house which is in contact with the soil can be maintained at a pressure higher than the soil gas pressure, soil gas cannot enter the house by convection. All gas flow through floor and slab openings will be clean house air flowing out, rather than soil gas flowing in.

Pressurization of the house (or basement) as a means of reducing radon is a developmental procedure. Maintaining the basement at even a slightly elevated pressure (say, 0.01 to 0.02 in. WC) is difficult, because houses are not airtight. Air blown into the basement will leak through numerous small openings to the upstairs, to the outdoors, and to the soil. If there are combustion appliances in the basement, some of the air might be forced up the flue. Adding to the difficulty is that this pressurization must be accomplished in a manner which is comfortable for the occupants (e.g., which avoids unacceptable drafts).

To pressurize a basement, air must be blown into the basement from either outdoors or upstairs. To minimize the heating and cooling penalty, the testing of house pressurization to date (Tu86, Tu87b, Hu87) has involved blowing the air from upstairs. Even with this approach, there is still a heating and cooling penalty. There will be an increase in infiltration rate from outdoors caused by the depressurization upstairs, matching an increase in exfiltration of heated or air conditioned air to the outdoors from the pressurized basement.

In addition to the increase in heating and cooling costs, other potential disadvantages of house pressurization include: the noise of the fan inside the house; the discomfort due to drafts in areas where air is being blown; and moisture buildup in the walls during winter, with possible resulting damage to wooden members. If the house air is humidified during the winter, the moisture in the air will condense and freeze inside the house walls where the air exfiltrates as a result of the pressurization effects.

6.2.2 Applicability

As this developmental technique is further tested, house pressurization will probably be found to be most applicable under the following conditions.

- Houses with basements. In such houses, the portion of the house which is in contact with the soil can be more easily isolated and pressurized. Basements commonly contain fewer windows and doors than do living areas on grade, and hence might be more readily tightened against air leakage to the outdoors. Basements represent only a portion of the house area (no more than half), so that only a fraction of the house need be pressurized. Houses with basements provide a relatively convenient method for pressurizing the area in contact with the soil—that is, blowing upstairs air to the basement. House pressurization would be least applicable to a large slab-on-grade house.
- Houses with heated crawl spaces. Pressurization of the crawl space might prove to be an attractive option (relative to crawl space isolation, insulation, and venting), because the volume of the crawl space is relatively small.
- Houses where the basements are relatively tight. Unless the basement can be fairly well isolated from the outdoors and upstairs, maintaining pressure will be difficult. Pressurization will probably be possible only if the stairwell connecting the basement to upstairs can be closed with a door. If the stairwell is open with no framing for a separating wall and door, such closure must be added if basement pressurization is to be possible. Other openings through the basement shell must be reasonably accessible for closure.
- Houses without combustion appliances (such as fireplaces) upstairs. If upstairs air is blown downstairs, the upstairs will likely become slightly depressurized, increasing the risk of potential back-drafting. Back-drafting can be avoided by providing a supply of supplemental combustion air (see Section 6.1.4.2), although this will increase the ventilation rate and hence the heating penalty.
- Houses where the homeowner understands, and is prepared to live with, the pressurization system. The performance of the system could be completely negated if homeowners opened basement doors or windows.

In connection with the need to be able to isolate the basement, pressurization is generally most easily applicable in houses without central forced-air furnace and air conditioning systems (for example, with electric or hot-water heating). Central forced-air furnace ducts connect between stories of the house, and can thus complicate basement pressurization. However, with some additional effort, basement pressurization can be applied to houses with forced-air furnaces, as described later.

6.2.3 Confidence

Since house pressurization is a developmental technique, and since data on the system are thus limited and relatively short-term, EPA is not in a position to state a confidence level for this approach. Further testing of these systems is under way. If a viable method can be demonstrated for maintaining a consistent pressurization of the basement, this could turn out to be a potentially attractive approach where it can be applied.

The available results with this technique to date consist of initial data generated by Lawrence Berkeley Laboratory on four houses in eastern Washington State and northern Idaho (Tu86), and two houses in New Jersey (Tu87b, Se87). In three of the Washington/Idaho houses, reductions of about 90 percent and greater were obtained when the basement was pressurized by about 0.01 in. WC relative to the soil. In the fourth house, the reduction was about 70 percent. Increasing the pressurization to 0.02 in. WC generally improved performance, and reducing it below 0.005 in. WC reduced performance. In one of the New Jersey houses, a short-term reduction greater than 90 percent was achieved by pressurizing the basement by 0.02 in. WC. In the second of the houses, a major opening between the basement and upstairs could not be closed, and the basement could not be pressurized. A radon reduction of about 60 percent was achieved nevertheless, perhaps due in part to the resulting increase in ventilation rate.

Basement pressurization was also tested in a third block basement house in New Jersey (Hu87, Ma87). With the 270-cfm fan used, the maximum basement pressurization that could be maintained was less than 0.005 in. WC. At that limited pressurization, the radon reductions were only 40 to 50 percent, probably due in part to increased ventilation.

One key issue is how well the basement pressurization can be maintained as conditions change which could influence this pressure (such as outdoor temperature and wind velocity).

6.2.4 Design and Installation

The following discussion reviews design and installation considerations based upon experience to date. Improvements will no doubt be possible as further experience is gained.

6.2.4.1 Pre-Mitigation Diagnostic Testing

Key pre-mitigation diagnostics might be expected to include the following.

- Visual inspection—to identify the nature and accessibility of apparent or potential openings through the basement shell, which would have to be closed in order to maintain pressure effectively. These include openings to the upstairs, to the outdoors, and to the soil.
- Smoke stick or other testing, as part of the visual inspection, to help identify the presence and importance of specific shell openings.
- Blower door tests to identify the fan capacity required to pressurize the basement, and/or the extent of basement tightening needed.

6.2.4.2 Design of Ducting System

The objective of the fan and ducting system is to suck air from the upstairs and to blow it into the basement.

Experience suggests that the best location for the pressurizing fan is on the basement slab. If the fan is mounted in or on the upstairs floor, the fan noise and vibration effects can be unacceptable. Thus, one consideration in the design of the ducting is selection of an appropriate point on the basement slab where the fan can be located.

The ducting system for the fan intake must be configured so that the fan can suck air from the upstairs. If the house does not have a central forced-air furnace, the fan must be connected to grilles/registers installed through the floor upstairs. Suitable locations for these grilles upstairs must be selected. Preferably, they should be in a relatively open area upstairs, and not in a small area such as a closet. The openings through the floor should have a reasonable cross-sectional area (such as a typical register for a forced-air furnace), so that the fan does not suffer an undue pressure loss accelerating the upstairs air through this opening. A register in the floor would be the most logical method of supplying upstairs air to the fan. However, other configurations might be considered if necessary, so long as fan performance is adequate.

The register(s) in the upstairs floor must be connected to the suction side of the fan. Logically, sheet metal ducting might be used to narrow the rectangular register cross section down to an appropriate circular diameter. This circular duct can then be connected to the fan, using sheet metal ducting or perhaps flexible hose. All joints in the ducting should be sealed. Otherwise, some of the fan capacity will be consumed in sucking basement air into the leaky ducting. Under these conditions, the fan will simply be recycling basement air rather than sucking upstairs air into the basement.

Ideally the fan exhaust should blow the upstairs air generally toward the middle of the basement, not toward potential openings in the basement shell. The fan should avoid exhausting into living space in the basement in a manner which makes the space unacceptably drafty.

If the house has a central forced-air furnace, the suggested approach is as follows (Tu86, Tu87b):

- the cold air return registers upstairs (that withdraw upstairs air for return to the furnace) should be used as the upstairs air supply. This is accomplished by connecting the suction side of the basement pressurization fan to the cold air return duct, sucking returning cold air from upstairs out of the duct, and blowing it into the basement.
- if there are any cold air return registers in the basement, these should be closed and taped over. This is necessary so that the pressurization fan is not simply sucking basement air through these registers, into the return duct, and blowing it back out into the basement.
- a back-draft damper should be installed in the main warm air supply duct leaving the furnace, allowing air to move only in the direction away from the furnace (toward the supply registers in the house). Such a damper would prevent flow reversal, so that air will not get sucked through the basement supply registers back into the furnace, again giving the undesired basement recirculation effect through the pressurization fan.

The central furnace ducting should be modified only by a qualified HVAC contractor.

6.2.4.3 Fan Selection

In the testing to date (Tu86, Tu87b), fan flow rates between 250 and 500 cfm were needed to achieve 0.01 to 0.02 in. WC pressurization in the basement. From the results in Section 6.2.3, it appears that that a minimum level of pressurization is necessary if the system is to provide high radon reductions.

Preliminary results from several other houses suggest that smaller fans might be sufficient in some cases, if the basement is sufficiently tight. The required capacity of the fan is an important issue to be addressed in future testing.

6.2.4.4 Closure of Basement Openings

Openings in the basement shell must be closed if adequate basement pressurization is to be maintained. The shell must be tightened between the basement and upstairs, and between the basement and outdoors. Among the closure steps that should be conducted are the following.

- installation of a spring-loaded mechanism on the door between the basement and upstairs, to help ensure that it stays closed. A similar mechanism might be considered on any door which opens to the outdoors.
- weatherstripping around all doors to the basement, and addition of a threshold if a gap under the door is not required by code.
- weatherstripping around all window frames.
- caulking around all door frames and window frames, interior and exterior, as warranted.
- caulking utility penetrations between the basement and upstairs.
- caulking around HVAC registers which penetrate the floor, and around the register for the pressurization fan.
- ensuring that any fireplace and stove dampers are closed, and fit well.
- closing other airflow bypasses opening into the basement, such as flue and utility chases, and laundry chutes, as discussed in Section 6.1.4.3.
- caulking and otherwise closing the seam/gap between the sill plate and the foundation wall, and between the sill plate and the band joist, around the entire perimeter. Depending upon the nature of the joint between the basement foundation wall and the upstairs flooring, other closure efforts around this joint might also be warranted.

6.2.4.5 Post-mitigation Diagnostics

In addition to radon measurements, post-mitigation diagnostics must include measurements of the pressure difference between the basement and the soil or between the basement and outdoors, to confirm that the desired degree of pressurization is being maintained. These pressure measurements should be made under different conditions (and, in particular, under worst-case conditions of low outdoor temperature and high wind velocity). If adequate pressurization is not being maintained, diagnostics might also include tracer tests, attempting to locate the openings in the basement shell which are preventing the desired pressure level from being established.

6.2.5 Operation and Maintenance

Operating requirements include regular inspections by the homeowner to ensure that:

- the pressurizing fan is operating properly.
- all closures in the basement shell remain intact.
- all seals in the pressurization fan ducting remain intact.
- moisture is not depositing on wooden structural components in the basement during cold weather, due to the exfiltration of warm, moist indoor air. Such deposition could ultimately lead to moisture damage, and might suggest the need for an alternative radon reduction system.
- back-drafting is not occurring in upstairs combustion appliances.
- if the system is tied into a central forced-air furnace, the furnace is continuing to supply sufficient warm air upstairs.

At this stage, some type of periodic check on the basement pressure would also be in order, to confirm that the pressurization is being maintained. A device and wiring for measuring the basement vs. sub-slab pressure differential should probably be included in the permanent installation.

Maintenance would include any required routine preventive maintenance to the fan, replacement of the fan as needed, and repair of any cracked or broken seals. If upstairs combustion appliance back-drafting occurs, a supplemental air supply might have to be provided. If the system is found not to be maintaining basement pressure, and if the above steps do not correct the problem, the homeowner would be well advised to make a radon measurement in the house, and possibly to contact a knowledgeable professional.

6.2.6 Estimate of Costs

The installed cost of a basement pressurization system will vary depending upon the effort required to tighten the basement shell. Due to the limited experience with this approach to date, a reliable estimate of the installed cost is not possible. However, it would be expected that this cost would be no more than that for an individual pipe wall ventilation system—perhaps $1,500 to $2,500. Costs could be higher if more substantial basement tightening efforts were required.

Operating costs would include electricity to run the fan, plus the heating and cooling penalty resulting from the increase in infiltration caused by the fan. Occasional replacement of the fan would also be a maintenance cost. The cost of electricity to run a 0.065-hp 500-cfm fan 365 days per year would be roughly $40 per year. Assuming that about half of the gas sucked from upstairs by the fan is replaced upstairs by fresh air infiltration—and assuming the fan moves about 350 cfm total—the cost of increasing the house ventilation rate by 175 cfm throughout the cold season would be roughly $425 per year, depending upon outdoor temperatures and fuel prices. During the summer, the increased air conditioning costs could be roughly $85 per year. Thus, the total operating cost might be roughly $550 per year. This cost would be lower where smaller fans prove to be sufficient.

Section 7

Radon Reduction Techniques Involving Air Cleaning

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

The U. S. Environmental Protection Agency does not endorse the use of air cleaning devices as a recommended method of reducing radon concentrations in indoor air. Because unattached progeny might result in a greater health risk than attached progeny, air cleaning technology has not been demonstrated to be effective in reducing the health risks from radon progeny. However, as a result of the uncertainty in the health risks of unattached radon versus attached progeny, neither can the Agency advise against the use of air cleaners. More studies are needed to resolve this uncertainty. Anyone considering the use of an air cleaner to reduce radon progeny should be aware of these uncertainties. Some of the minimum requirements (such as minimum treatment rates) for an air cleaner to be successful in removing particles and radon progeny are pointed out in Section 7.2.

The discussion below is included since air cleaners are commonly used to condition indoor air for a variety of other health and comfort reasons, and because there have been attempts to market air cleaners for the purpose of radon reduction.

7.1 Relative Health Risks of Attached Versus Unattached Progeny

A significant scientific question that remains unresolved relates to the health effects associated with attached versus unattached radon decay products. Indoor air nearly always contains a significant concentration of aerosol particles from a variety of sources including cigarette smoke, unvented combustion devices, aerosol sprays, wear and deterioration of building materials, carpets, floors, furniture, and infiltration of outdoor air. The concentration of particles in indoor air typically varies from 3,000 to 30,000/cm^3 (Of84).

The radon progeny (see Section 1.5.2), which consist of metal atoms, readily agglomerate with clusters of other molecules and also readily attach to aerosol particles when they are present in sufficient concentrations [greater than 1,000/cm^3 (Of84)]. The newly created radon progeny along with their small molecular agglomerates (smaller than about 0.01 μm in diameter) are referred to as unattached progeny. When these agglomerates are adhering to aerosol particles (larger than about 0.05 μm in diameter), they are referred to as attached progeny. Concern has been raised over the health risk distinction between attached and unattached radon decay products. Several mathematical models (Ha81; Ja80; Ja81), developed to describe the dose of alpha radiation arising from the deposition of radon progeny in the lungs, predict that the radiation dose to the lungs from unattached radon progeny is much (9 to 35 times) greater than from attached progeny of the same total working level (see Section 1.5.2 for a description of working level).

However, these models may not adequately account for the fact that attached progeny do not necessarily deposit uniformly on the surfaces of the bronchial tubes, but may preferentially deposit at the branching points of the airways due to the inertial properties of the particles (Ma83). These resulting "hot spots" may significantly increase the calculated health risks from attached progeny. Until these effects are properly accounted for, the relative health risks associated with attached versus unattached progeny will remain somewhat uncertain.

This uncertainty may be further complicated by the fact that small hygroscopic particles will grow very rapidly in the humid environment of the lungs (Ma82, Ma83). These small particles absorb moisture to become condensation centers for the growth of water droplets. Therefore, unattached progeny in ultrafine hygroscopic agglomerates may grow rapidly once inhaled into the humid environment of the lungs, possibly growing to the point where they will behave like attached progeny when deposited in the lungs. Consequently, the deposition pattern of unattached radon progeny associated with hygroscopic agglomerates may be quite different from that of unattached progeny associated with nonhygroscopic agglomerates. The initial distribution of attached and unattached progeny prior to inhalation may not be indicative of the resulting deposition pattern in the lungs.

If it should occur that indeed the risk from unattached radon decay products is greater than the risk from attached radon decay products, there are some significant implications for air cleaners. An air filtration system can drastically reduce the concentration of indoor air particles and, consequently, the concentration of attached progeny, while at the same time resulting in a substantial increase in the unattached progeny. Under these circumstances, use of an air cleaner might increase health risks. On the other hand, if hygroscopic growth of the particles in the lungs controls the deposition pattern, the initially unattached progeny could behave like attached progeny in the lungs, so that the fact that they are initially unattached becomes less relevant. If this is the case, it would be more likely that air cleaners could provide a significant reduction in health risk.

7.2 Radon Progeny Removal by Air Cleaning

Much of the discussion in this manual has concentrated on methods of preventing radon gas from entering the house. It has been pointed out previously (see Section 1.5.2) that it is the radon progeny (not the radon itself) that give rise to the health risks associated with lung cancer. Consequently, it is appropriate to consider if it is feasible to remove the radon progeny without removing the radon itself.

While the removal of all the radon progeny without removing the radon gas would eliminate the health risk of lung cancer associated with indoor radon, the practicality of such an approach has not been demonstrated. The fundamental difficulty associated with this approach is that the source, the radon gas itself, remains undiminished. Consequently, the progeny must be removed at a rate comparable to the rate at which they are produced throughout the house. Such a removal rate presents a problem because no air cleaning device can practically treat all the air in the house at one time. Most devices require air to be circulated through them, and such circulation is possible at a rate which treats only a small fraction of the house air at once. Thus, very high circulation rates are required in order to adequately treat all the air within a house. It is also necessary that the air circulating through the device be drawn uniformly from everywhere throughout the house, so that all of the air within the house is treated at the same rate.

Typical natural air exchange periods for U. S. houses range from 1 to 2 hours (see Section 3.1.1). To be effective, the air cleaner must treat all of the house air in a period much shorter than the natural air exchange period. For the sake of discussion, suppose that the air cleaning device is nearly 100 percent efficient at removing both the attached and unattached radon progeny. In some respects, air cleaning is similar to the ventilation process. For the ventilation process to be effective, it is necessary to replace the indoor air with clean air several times during one natural air exchange period. Based on dilution considerations (see Section 3.2.2), the house air must be replaced about 10 times (by the ventilation process) during each natural exchange period in order to reduce the radon level throughout the house by about 90 percent. If the natural exchange period is 80 minutes, a 10-fold replacement during this period would correspond to one turnover every 8 minutes. If the radon progeny are to be removed by air cleaning devices, it will be necessary to circulate the house air through the device a comparable number of times during one natural air exchange period to achieve 90 percent reduction. For reference, this 10-fold circulation rate in a 2,000 ft^2 house with a natural air exchange rate of 0.75 air changes per hour (or 80-minute air exchange period) requires the cleaning device to treat air at the rate of 2,000 cfm. This treatment rate is comparable to the typical capacity of the HVAC system. This relatively high treatment rate requirement shows the futility of trying to implement some of the small air cleaners with a fan capacity rated at a few cfm to reduce radon progeny in houses. Many inexpensive air cleaners fall into this category. Some of these low capacity units may be useful in removing aerosol pollutants such as cigarette smoke when placed near the source, but they have little potential for reducing the radon level in a house.

Air cleaning consists of two important processes: one involves the removal of aerosol particles to which the progeny attach, while the other involves the removal of the unattached progeny. Low concentrations of unattached progeny are closely correlated with high concentrations of aerosol particles. For the lower concentration of particles (3,000 particles/cm^3), about 11 percent (5.5 percent of the equilibrium value) of the working level is associated with the unattached progeny, while for the higher concentrations (30,000 particles/cm^3) only about 1.6 percent (0.8 percent of the equilibrium value) is unattached (Of84; Ev69). Consequently, decreasing particle concentration and increasing unattached progeny concentration go hand-in-hand.

In the absence of reliable data on the health risks of attached versus unattached progeny, one way to ensure that an air cleaner has in fact reduced the health risk is to operate it in a manner such that the *total* working level with air cleaning does not exceed the working level of the unattached fraction alone in the absence of air cleaning. In that way, even if the progeny with air cleaning were entirely unattached, the absolute amount of unattached progeny could not be greater than it was without air cleaning. However, as shown below, such a demand on the air cleaner could necessitate impractically high air circulation rates through the device.

If one hypothetically began at time zero with a given radon gas concentration and zero progeny, the total progeny concentration would grow in 2 minutes to an average value of roughly 3 percent of its equilibrium value with the radon gas. After 6 minutes, the progeny would be about 5 percent of the way toward equilibrium with the radon (Ev69). As indicated above, when the concentration of particles in the room air is 3,000 particles/cm^3, the unattached progeny concentration represents about 5 percent of the equilibrium value. Therefore, if the room air contained 3,000 particles/cm^3 before air cleaning (which is lower than a typical house), all of the house air would have to circulate through the air cleaner about once every 6 minutes to ensure that the total working level with air cleaning did not exceed the level of unattached progeny prior to air cleaning. For a 2,000 ft^2 house, this circulation rate would require that the air cleaner handle about 2,700 cfm, a volume larger than the typical flows through a central forced-air HVAC system. If the room air had a more typical residential particle concentration of 10,000 particles/cm^3 before air cleaning, the house air would have to be circulated through the device about once every 2 minutes to keep the total working level with air cleaning below the low concentration of unattached progeny that would have existed before air cleaning. This corresponds to a flow rate through the device of about 8,000 cfm, which is impractical in most cases.

The above calculations overestimate the required flows somewhat. Not *all* of the progeny will be unattached when the air cleaner is operating, as this approach assumes. In addition, when the air cleaner is operating and particle concentrations are reduced, there will be increased plate-out of the progeny on walls and elsewhere, assisting in the removal of the progeny from the air. However, in view of the uncertainties involved in the health effects of unattached progeny, these calculations do serve as a conservative estimate of the needed treatment rate.

To this point, the discussion has related to treatment of the air in the whole house. It may be possible that someone would want to treat the air in only a single room. For treatment of the air in a single room to be practical, the room must be isolated from air exchange with the rest of the house. This applies especially to the HVAC system, but also for leaks around doors and electrical outlets. The considerations for removal of radon progeny by air cleaning in a single room are the same as for the whole house except that the volume is smaller. For a room of 240 ft^2, the concentration of 3000 particles/cm^3 would require a treatment rate of 320 cfm, while the typical particle concentration case (10,000 particles/cm^3) would require a treatment rate of approximately 1,000 cfm. This treatment rate is clearly possible, but may not be practical.

7.3 Types of Air Cleaners

A number of devices are available for removing aerosol particles from indoor air (Of84; Fi84). They can be categorized, according to their principles of operation, into mechanical filters and electrostatic filters. Mechanical filters collect particles from an air stream through mechanical forces exerted on the particles by the air flow and the filter media. Electrostatic filters collect particles primarily as a result of electrical forces exerted on the particles suspended in the air stream.

7.3.1 Mechanical Filters

The types of mechanical filtration most often applied to cleaning indoor air involve passing the air through fibrous media. The principles of operation of these filters involve three primary mechanisms (impaction, interception, and diffusion) by which particles are removed from the air. These mechanical filters fall broadly into three groups: panel filters, extended-surface filters, and HEPA filters.

7.3.1.1 Panel Filter

The most commonly used and least expensive filter is called a "panel filter." These filters have a low packing density of coarse fibers made of glass, animal hair, vegetable fibers, or synthetic fibers. They are often coated with viscous substances, such as oil, to increase their adhesive properties. These filters typically are inexpensive, have low pressure drops, and have high collection efficiencies for particles larger than 10 μm in diameter. These filters are often characterized as having low collection efficiencies for particles smaller than 5 μm in diameter; however, few data appear to be available relating to their collection efficiency in the particle size range dominated by the diffusion mechanism (smaller than 0.05 μm). This size range would include the unattached radon progeny. For low velocities, the collection efficiency for unattached progeny could be significant. The common residential furnace filter is an example of a panel filter. Portable units which use panel filters have typical fan capacities in the range 5 to 40 cfm.

7.3.1.2 Extended Surface Filter

The collection efficiency of a filter can be enhanced by reducing the diameter of the fibers, and by increasing the packing density of the fibers. This action would result in an increased resistance to flow by the filter, which would require an increased pressure drop across the filter in order to maintain the same flow rate. The most practical way to maintain the flow rate without the increased pressure drop is to extend the surface area of the filter media. One way to increase the surface area of the filter media is to fold or pleat the media so that a much larger filtering surface can be accommodated in a given volume. Air filters for automobiles are made in this manner. The resulting large ratio of filter surface area to flow face area gives rise to the name, extended surface filter. Such large ratios of filter surface area to face area allow filter media to be made of fibers with high packing densities resulting in highly efficient collection devices that can operate with reasonable pressure drops. The extended surface areas also provide high dust holding capacities. The capacities of these units typically range from 50 to 250 cfm.

7.3.1.3 High Efficiency Particulate Air (HEPA) Filter

HEPA filters are special types of extended surface filters characterized by their very high efficiency in removing submicrometer particles. Initially developed for use in nuclear material processing plants to control concentrations of fine airborne radioactive particles, a HEPA filter is defined as a disposable dry-type extended surface filter having a minimum particle removal efficiency of 99.97 percent for 0.3 μm particles and a maximum resistance, when clean, of 248 Pa (1.0 in. WC) when operated at the specified air flow rate. HEPA filters are constructed by hand to ensure that there are no paths for air bypassage. Much of their high costs arises from the labor involved in constructing and testing the filters. The filter core generally consists of a continuous web of filter media folded back and forth over corrugated separators that add strength to the core and form the air passages between the pleats. The media are composed of very fine submicrometer glass fibers in a matrix of larger diameter (1-4 μm) fibers. The capacities of these units typically range from 25 to 300 cfm.

7.3.2 Electrostatic Filters

A variety of electrostatic particle collection devices are available for air cleaning. In spite of the fact that mechanical processes such as diffusion and impaction may be simultaneously operative, the device is referred to as electrostatic if the dominant collection mechanism is controlled by electrostatic forces. These devices are usually described as having low pressure drop and high collection efficiency. Two types of electrostatic applications are commonly used. One is the application of a static electric field for the purpose of enhancing the collection of either charged or uncharged particles. The other application uses electrical discharges to place charges on the aerosol particles. The highest efficiency devices both charge the particles and collect them with strong fields. The most common types of electrostatic devices applied to indoor air cleaning are electrostatic precipitators, ion generators, and charged-media filters.

7.3.2.1 Electrostatic Precipitators

Most electrostatic precipitators used for cleaning indoor air are of the two-stage type. This means that the charging and collection are performed in separate steps. The corona process involves sufficient energy to produce ozone, an air pollutant, in the discharge. Since positive coronas have been observed to produce less ozone than negative coronas, the coronas are usually positive. After the particles become positively charged, they enter the collection stage, which usually consists of closely spaced parallel plates that are alternately grounded and highly charged. The collection efficiency depends on the applied voltage, the area of the collecting plates, and the velocity of the air through the device. Portable devices typically range in capacity from 20 to 300 cfm. Devices which fit in the HVAC system are also available.

7.3.2.2 Ion Generators

Ion generators are not really filters in the sense of precipitators and HEPA filters. In particular, ion generators make an entire room into a particle collector: they use a corona to produce ions which drift out into the room air to charge the aerosol particles present. Few data are available to characterize their effectiveness in charging particles. Unless sufficient concentrations of ions are present to develop space charge fields, the charging process would rely entirely on diffusion charging. The rate of diffusion charging depends sensitively on the local concentration of ions. It is doubtful that significant space charge fields could be developed from ions generated in this manner. In fact, it is questionable whether significant fields are desirable in living spaces. At any rate, the principle of operation seems to be that an ion space charge would charge the particles and cause the charged particles to migrate to the walls and floor where they would be deposited. Most data collected under controlled conditions with this method show only moderate particle removal rates. One serious question concerning this method is whether it is desirable to have all the particles depositing on the room surfaces.

7.3.2.3 Charged-Media Filters

The third type of electrostatic device uses a combination of electrostatic and mechanical processes. Charged-media filters augment the normal removal mechanisms of fibrous filters by charging the fibers. The electric field surrounding a charged fiber is quite nonuniform. Consequently, uncharged particles which approach the charged fibers will be polarized and attracted to the fiber by the nonuniform field. In one type of application, a gridwork of alternately charged and grounded members is placed in contact with the filtering medium, which is made of a dielectric material. An additional step that is taken in some instances is to charge the particles entering the device. In this case, the attractive forces are much stronger. Although such devices are relatively new, they show promise for both improving the efficiency of the filter and reducing the operating pressure drop. An alternative to applying an external field is to make the filter from a material (called an electret) embedded with a permanent charge. Although electret filters have shown some good performance results, there have also been some problems with their losing charge when they get dirty.

7.4 Radon Removal By Air Cleaning

It is apparent that, if the radon is removed, the progeny will not exist in the indoor air. Consequently, removing the radon is sufficient to remove the health risks associated with the radon progeny. Aside from reduction through ventilation, as discussed in Section 3, no effective means of removing radon gas directly from indoor air has yet been demonstrated as practical. Some removal techniques, such as adsorption on activated carbon and chemical scrubbing, have been studied, but their practicality has not yet been shown.

Activated carbon has been shown to remove radon gas from air; however, there are a number of complications. One problem is that the carbon bed becomes saturated, both with water and with a number of organics that occur in much higher concentrations than radon. In order to control the level of radon, it is necessary to treat the air at a rate at least as great as the radon entry rate. This corresponds to a treatment rate greater than the natural air exchange rate. Consequently, large carbon beds with significant air flows will be required. Since saturation and break-through will occur eventually, it will be necessary to rejuvenate the bed somehow. It has been proposed that two beds be designed to operate in parallel, so that one can be cleaned while the other is in operation (Bo87). Such systems are not currently commercially available.

Section 8

Radon In Water

Radon gas is fairly soluble in water at the temperatures which exist in underground aquifers. Thus, radon released by the surrounding soil and rock will dissolve in this ground water, building up to a steady-state concentration that is determined by the temperature and pressure of this water. If the ground water is brought directly into the house — from an individual private well, or perhaps via a small community well water system — some (perhaps most) of this dissolved radon will be released into the house air. The radon thus released will contribute to the airborne radon levels in the house (e.g., Pa79, Ge80, He82).

This release of dissolved radon into the house air is referred to here as "de-gassing" of the water. Degassing occurs primarily because the water is often aerated upon use in the house (i.e., brought into effective contact with air). Increased contact between the water and the air facilitates the escape of the radon from the water. Aeration occurs most effectively when the water is sprayed, as in showers, dishwashers, and clothes washers. Agitation of the water, as in clothes washers and faucet aerators, also increases aeration. In addition to aeration, another factor which contributes to de-gassing to a lesser extent is the increase in the temperature of the water when it enters the house, relative to its temperature underground. This is especially true if the water is heated. An increase in temperature decreases radon solubility and increases the rate of de-gassing, releasing dissolved radon. A third factor which can contribute to degassing is the reduction in the pressure of the well water when it enters the house, which decreases radon solubility. However, this effect is minor compared to the effects of aeration and temperature.

Thus, the most significant releases of waterborne radon into the house air would be expected from activities and appliances which spray or agitate large quantities of heated water, such as showers, dishwashers, and clothes washers.

As discussed in Section 1.5.2, the greatest concern about radon in water is this tendency of the dissolved radon to de-gas and hence contribute to the lung cancer risk associated with the airborne levels. Other risks associated with the radon that remains in the water (and is thus ingested) are being studied, but are currently thought to be much less significant than the lung cancer risks from the airborne radon. Accordingly, the discussion here focuses on the radon that is released from the water.

As stated in Section 1.5.1, a rule of thumb is that 10,000 pCi/L of radon in water will contribute about 1 pCi/L to the indoor air on the average throughout the house (assuming an average water use rate, house volume, ventilation rate, and that only half of the radon in the water is released). However, in the immediate vicinity of the water-use appliance during the period when it is operating — e.g., for the person standing in the hot shower — radon levels will be much higher than those space- and time-averaged values calculated using the rule of thumb. For example, in one house tested by EPA where radon levels in the well water varied between about 100,000 and 300,000 pCi/L, airborne radon concentrations in the basement rose from several pCi/L to as high as about 200 pCi/L over a several-hour period when the clothes washer in the basement was used (Sc86b). In a second house, with about 100,000 pCi/L in the well water, airborne levels averaging several pCi/L swelled to as high as 60 to 90 pCi/L in the basement over several hours when the clothes washer in the basement was used. Levels in one upstairs bedroom were not significantly affected by the clothes washer, but spiked to 20 to 50 pCi/L and higher when showers were being taken upstairs (Sc87c). In a third house, with 37,000 pCi/L in the well water, the airborne radon concentration in the upstairs bathroom spiked from roughly 2 to 222 pCi/L after the shower was run for 15 minutes (Os87b). In a fourth house, with 1.1×10^6 pCi/L in the water, airborne levels in the bathroom jumped from roughly 10 to as high as 2,000 pCi/L when the shower was operated (Lo86).

If measurements of airborne radon concentrations show that a particular house has elevated levels — and if that house uses a private well or a small community well water system — the homeowner would be advised to have measurements made of the radon in the water supply. This would be particularly advisable (but would not be limited to the case) where high radon levels have been found in other wells in the neighborhood. In some cases, appropriate State agencies may be able to conduct the water analysis, or to identify qualified laboratories that can. Alternatively, suitable testing laboratories might be identified by local water utilities, firms selling water treatment equipment, or radon mitigators.

If the radon levels in the water appear sufficiently high to be a significant contributor to the measured airborne levels, action to address the water source of radon could be warranted. Currently, no definitive guideline specifies what radon level in water is sufficiently high to require that the water be addressed. To some extent, this "action level" will be determined by the concerns of the individual homeowner. Using the 10,000:1 pCi/L rule of thumb mentioned previously, it would appear reasonable to consider some action regarding the water whenever water radon levels exceed about 40,000 pCi/L, although some homeowners might wish to consider action at lower or higher levels, depending upon circumstances. Some States recommend that action be considered at lower levels.

Note that the levels of radon in water from a given well have sometimes been observed to vary by a factor of 2 (or even greater) from season to season, or even from day to day. Thus, water radon measurements at different times of the year might be desirable to confirm the level in a given well.

This section provides only an overview of methods for addressing radon in water. This subject is also discussed in the EPA brochure, "Removal of Radon from Household Water" (EPA87e).

8.1 House Ventilation During Water Use

One approach for addressing the problem of elevated radon levels in well water is to remove the airborne radon from the house after it has been released from the water. The airborne radon can be removed by increasing the ventilation of the house in the regions where water is being used, during the periods water is being used.

If radon levels in the water are high, house ventilation should be looked upon as only an interim solution to the problem. It will often be inconvenient or impractical, especially during cold weather, to routinely increase house ventilation each time substantial quantities of water are used.

Methods for house ventilation have been discussed in Section 3. If windows are opened, they should be opened on more than one side of the house if at all possible, as discussed in Section 3.1 — preferably on opposite sides, or at least on adjacent sides. They should be opened at locations such that the room where water is being used is well ventilated, because the effects of water use on airborne radon can apparently be very localized. For example, in the second house referenced above, the basement clothes washer had a tremendous impact in the basement and essentially none upstairs. The upstairs shower had a significant effect upstairs but none in the basement, due to the circulation patterns in that particular house.

If a kitchen or bathroom exhaust fan is employed during water use in those rooms, then, as discussed in Section 6.1.4, a nearby window ideally should be opened to avoid depressurization which might increase radon influx via soil gas. If there is no window in the room where the exhaust fan is operating, it would generally be desirable to operate the exhaust fan anyway. This would especially be true where: a) radon levels in the water are particularly elevated; and b) the exhaust fan is relatively small, such as a bathroom exhaust fan. If the exhaust fan is larger than a bathroom fan, it would be desirable to leave open a window in a nearby room if possible.

Where windows are opened, their effectiveness will be determined by the extent to which they increase ventilation in the area where water is being used — that is, by the location of the windows, the extent to which they are opened, and weather conditions (especially wind velocity). The required effectiveness will depend, of course, upon the radon levels in the water. The operating costs associated with this radon reduction approach will depend upon the duration and extent to which ventilation is increased, the outdoor/ indoor temperatures, and fuel costs, as discussed in Section 3.1.6.

8.2 Radon Removal From Water

A more permanent approach for addressing the problem of elevated water radon levels is to remove the radon from the incoming well water before the water is used in the house.

8.2.1 Principle of Operation

Radon can be removed from water by any one of three approaches.

- Treatment of the water using granular activated carbon. All of the well water entering the house (or handled by the small community well water system) can be passed through a vessel containing activated carbon. The radon and radon progeny in the water, along with certain other constituents, are adsorbed on the carbon. The radon remains on the carbon, decaying into the subsequent elements in the decay chain. The low-radon water leaving the vessel is then used in the house.
- Aeration of the water, causing the radon in the water to de-gas. The de-gassing occurs inside

a vessel, and the released radon is exhausted outdoors. Low-radon water accumulated in the aeration vessel is then used in the house. Approaches that have been tested (and/or commercially offered) for aerating water for individual houses include:

  - — packed tower aerators, where the water cascades down through a column while up-flowing air strips out the radon and other dissolved gases. The column contains a bed of unusually shaped objects ("packing material") which is intended to ensure good air/water contacting.
  - — diffused aerators, where small bubbles of compressed air are blown through vessels full of water, stripping the radon from the water and sweeping it out the top of the vessel.
  - — spray aerators, where the water is sprayed into a chamber vented to the atmosphere. The spray heads break the water into small droplets, from which the radon can readily de-gas.

- Storage of the water above ground for a period of time sufficient to allow the radon to decay before use. The water would have to be stored for about 12 days before use in order for 90 percent of the radon to have decayed away. In view of the volume of water used in a typical household, and the storage volume that would thus be needed, this approach is considered impractical for residential use. Hence, water storage is not discussed any further in this document.

Both carbon adsorption and aeration are commonly used in water treatment plants for the removal of various water contaminants, such as organics and dissolved gases including hydrogen sulfide. Carbon adsorption units are also reasonably common in individual houses, often for the removal of organics from the house water supply. While aerators are being tested and offered for use in individual houses, their use in private residences is not yet widespread, as discussed later.

Granular activated carbon systems offer the advantages of being potentially low-maintenance devices that have no moving parts, that can be fitted into the existing house plumbing system with only minor modifications, and that can provide radon reductions as high as 99+ percent if properly designed. Carbon units currently appear to be the least expensive of the alternatives. Carbon units offer the further advantage of having a more extensive operating history in individual houses for the removal of various water contaminants, including some installations aimed specifically at removing radon (Lo85). Their primary disadvantages are:

- there are few definitive data demonstrating the performance of these units over multi-year periods.
- care must be taken to shield the tank containing the carbon, to prevent it from being a source of gamma radiation inside the house (see the discussion in Sections 8.2.3.1 and 8.2.4.1).
- when the carbon in the tank needs to be replaced, the spent carbon might have to be disposed of as a low-level radioactive waste, depending upon the accumulation of long-lived radionuclides, and depending on local regulations (see Sections 8.2.3.1 and 8.2.5).

There has also been some concern expressed that — if the organics content in the water is sufficient — the accumulation of organics on the carbon could sustain undesired biological growth inside the carbon unit. Such growth could increase the level of microorganisms in the water used in the house. There are not currently sufficient data to confirm the conditions under which such biological growth might become a problem.

Aeration systems avoid the creation of a potential gamma source inside the house, and of any need ever to address the issue of replacing the carbon or disposing of waste carbon. The threat of biological growth would also be reduced (although not eliminated) in aeration systems, since organics/nutrients would be less likely to accumulate in the units. Radon removals above 90 percent have been demonstrated in several developmental aeration units for residential use, although aerators have not generally provided the 99+ percent removal that has sometimes been reported for activated carbon systems. The primary limitations of aeration systems are:

- Aeration systems generally have higher installation and operating costs than do carbon units.
- Most aeration systems that are commercially available for residential use provide maximum radon removals of 90 to 95 percent, compared to over 99 percent for carbon units. Improvements can be made, at some cost, to increase aerator removals.
- The experience with aeration systems in individual houses is far more limited than that with carbon units.
- Aeration systems will necessarily be more complex than carbon systems. The packed tower and diffused aerator approaches will require a fan or compressor to provide stripping air; and, since the water must be reduced to atmospheric pressure for stripping in any aer-

ation system, an additional water pump will need to be incorporated into the system, to boost this low-radon water to the pressure needed to move it through the house plumbing. Thus, there will be maintenance requirements, noise, and an operating expense associated with the fan and auxiliary pump.

As an additional consideration, the aerator will have to be sized to treat water at a rate corresponding to the peak usage rate in the house, or else will have to store a sufficient amount of treated water. This equipment, which will have to be in heated space to avoid winter freezing, will likely have greater space requirements than will a carbon sorption tank. Also, aerators will produce a high-radon exhaust gas stream that will have to be properly vented. Current efforts by several developers to develop and market improved aerators for residential use could address some of the disadvantages listed above.

8.2.2 Applicability

Water treatment techniques can be considered whenever a house is served by a private well or a small community well, and whenever the radon levels in the well water are sufficiently high that the waterborne radon might be a significant contributor to the airborne radon concentrations. Water treatment might reasonably be considered whenever water radon levels exceed about 40,000 pCi/L, although some homeowners might wish to consider action at lower or higher levels. Radon removal from the water should be considered as a permanent approach for addressing high radon levels in water, since it will often be inconvenient or impractical to address elevated water radon levels by consistently increasing house ventilation whenever water is used. Water treatment is applicable even with high initial water radon levels, since radon reductions above 90 percent have been reported with both carbon and aeration units. If removals of 99 percent and above are required, it currently appears that a carbon unit would be the applicable approach.

Granular activated carbon units appear likely to be most applicable for residential use in the near term, for the reasons given in Section 8.2.1. Improvements in aeration systems might make these systems more competitive for residential use in the future. Either carbon or aeration systems might practically be considered for a small community well water facility, since there is more experience with aeration systems on the larger scale, and they might be more readily applicable and more cost competitive at this scale. Aeration systems might be particularly worthy of consideration where:

- trace levels of organic compounds (and possibly bacteria) are present in the well water. Under these conditions, there would be an increased risk of biological growth in the bed.
- State regulations are such that the used carbon removed from the tank could be considered as a low-level radioactive waste, complicating its disposal.

8.2.3 Confidence

Activated carbon sorption and aeration processes have been used in water treatment plants for many years. Carbon units are relatively common in residential use. However, these systems have most commonly been used to remove water contaminants other than radon. Thus, experience with their performance in removing radon is relatively limited.

8.2.3.1 Granular Activated Carbon Units

There is a moderate to high confidence that granular activated carbon systems will provide high radon removals from the water if properly designed. The primary uncertainty in carbon unit performance in removing radon results from the lack of definitive data demonstrating the long-term (multiyear) performance of the carbon under various conditions. Other concerns are that the source of the carbon must be properly selected, and the tank must be sized to provide suitable water residence time in the carbon bed, if high removals are to be obtained. Shielding of gamma radiation from the carbon bed, and possible requirements covering the disposal of waste carbon, are additional concerns which — although not affecting removal performance —must be considered in the evaluation and design of the carbon unit.

Granular activated carbon units have been installed specifically for radon removal in 100 houses by one vendor (Lo87d), and in a large number of additional houses by other suppliers. In addition, carbon units have been tested in two houses by EPA (Sc86c).

The 100 units installed by the one vendor are treating wells containing from as little as 1,500 pCi/L in one house to over 1 x 10^6 pCi/L in another house. Based upon single measurements made on 66 of these units after they had reached steady state, radon removals were almost always between 85 and 99+ percent, averaging 96 percent (Lo87d). Performance depends upon the specific brand of activated carbon in the carbon unit, with some individual carbons providing distinctly better radon removal performance than others. Of the 66 units mentioned above, 49 contain the carbon which has been found in laboratory tests to be the most effective for removing radon. These 49 units all provided reductions above 92 percent, based upon single measurements, and 36 gave removals above 99 percent; the average for all 49 was 99 percent, better than the average for the 66 units as a whole.

In addition to the brand of carbon, performance also depends upon the amount of carbon in the tank; i.e., the residence time of the water in the carbon bed. Between 2.5 and 3 ft^3 of carbon is needed for the very high reductions required with the highest radon concentration when the water use rate is high. As little as 1 ft^3 can be sufficient when the initial radon levels are lower (and required reductions are thus less), and when the water usage rate is low. The house having over 1×10^6 pCi/L in the water was reduced consistently below 1,000 pCi/L (over 99.9 percent removal) over a 3-month sampling period using a bed containing 3 ft^3 of the most reactive carbon (Lo86). One of the other houses, having 750,000 pCi/L in the water, achieved radon removals averaging about 99 percent over 10 months using a 2.5 ft^3 bed of carbon (Lo85). Some of these 100 installations have been in operation for a number of years (the oldest for 6 years) with no replacement of the carbon bed, without any reported degradation in radon removal performance.

In the two houses with carbon units tested by EPA, the one with a unit having 2.0 ft^3 of the more reactive carbon has experienced between 95 and 99 percent reductions over the 5 months that testing has been underway. The radon levels in the incoming well water, which range from about 100,000 to 300,000 pCi/L, are typically being reduced to 1,000-2,000 pCi/L. This carbon unit was purchased from a vendor who had designed it specifically for radon removal. The unit installed in the second house was not designed specifically for radon reduction, but was being marketed for organics removal. In this second house, the initial radon levels of 20,000 to 70,000 pCi/L were typically reduced by 75 to 80 percent over the 5-month period, with treated water levels in the range 3,000-6,000 pCi/L. These results support the observation that the type of carbon in the unit can be important in determining radon removal performance.

It is currently felt that — if a carbon unit is designed specifically for radon removal, with a suitable activated carbon and a sufficient water residence time in the tank — then even wells with the most severely elevated radon levels observed to date can be reduced to concentrations below 10,000 pCi/L. While experience is limited with carbon units for radon removal, some investigators estimate the lifetime of a single carbon bed to be on the order of decades (Lo85). The lifetime could be shortened by contaminants in the water other than radon that occupy radon sorption sites on the carbon particles. Unfortunately, no carbon unit for radon removal has been in service for longer than 6 years, and definitive year-to-year performance data are not available for these older units. Therefore, there is some uncertainty regarding how long a given carbon bed will continue to give the 99+ percent reductions suggested above, with different levels of other contaminants in the water.

One key issue concerning granular activated carbon units is that shielding is necessary around the tanks in order to protect house occupants from gamma radiation resulting from accumulated radon and radon progeny adsorbed on the carbon. As the accumulated radon and radon decay products proceed through the decay chain, they release three forms of radiation: alpha particles, discussed previously; beta particles; and photons of gamma radiation. The high-energy gamma radiation results primarily from decay of two of the progeny, lead-214 and bismuth-214. A limited amount also results from the decay of radon itself, and a small amount of low-energy gamma radiation can result from the decay of lead-210, the long-lived radionuclide to which the last of the short-lived progeny decays. The alpha and beta particles are effectively trapped within the tank, and pose no problems. But some of the high-energy gamma rays can penetrate through the carbon and water inside the tank, and through the tank shell, and can create high gamma exposures in the vicinity of the tank unless the tank is appropriately shielded. Even without shielding, gamma levels will drop dramatically with distance from the tank. However, levels will sometimes be undesirably high in the living areas near the tank. Gamma levels can be elevated not only on the story where the tank is located, but also on the floor immediately above (or below) the tank.

The gamma levels depend on the amount of radon and progeny that have accumulated in the tank. The amount of accumulation will in turn depend on the radon level in the well water, and on the rate of water use. Since radon has a 3.8-day half-life, the amount that can accumulate in the carbon can be significant when radon levels in the water are high. After the bed achieves steady state, about 3 weeks after being put into operation, the gamma levels will remain constant over time unless the radon concentration or water use rate changes.

In one of the houses tested by EPA (Sc86c), with between 100,000 and 300,000 pCi/L in the well water, the peak gamma dose rate equivalent flush against the outside of the tank was 10,000 microrems per hour (μrem/hr). Without shielding, levels fell to about 1,500 μrem/hr 3 ft away from the tank, 50 μrem/hr 6 ft from the tank, and 60 to 75 μrem/hr at the hottest point in the bedroom directly above the tank. By comparison, EPA's proposed standards for houses built over uranium mill tailings limit gamma exposure to 20 μrem/hr above the natural background levels. Since the background gamma levels in the absence of the carbon tank were 10 to 15 μrem/hr in this house, the proposed EPA standard would translate to a maximum allowable level of 30 to 35 μrem/hr. In this house, that level is not achieved until one is at least 10 ft away from the tank. In the second house tested by EPA, with 20,000 to 70,000 pCi/L in the water, the peak gamma dose rate equivalent flush against the tank was 4,000 μrem/hr, falling (without shielding) to 400 μrem/hr at 3 ft, 44 μrem/hr at 6 ft, and 26 μrem/hr at the hot spot in the bedroom above. The natural background level in this house was about 10 μrem/hr, so that the proposed EPA standard would translate to a maximum allowable level of 30 μrem/hr. Again, this level is not achieved until one is roughly 10 ft away from the tank. It is emphasized that the proposed standard for houses built over uranium mill tailings is used here only as a convenient measure for comparison; the proposed standard would not apply in these houses, since the radiation is not resulting from mill tailings.

Other investigators who have tested a larger number of carbon units report comparable results for the peak gamma levels flush against the side of the tank (Lo85). Their results suggest that, in general, the peak gamma level (in μrem/hr) will be 1/17.8 times the initial radon level in the well water (in pCi/L). However, these other investigators' results suggest a more rapid dropoff with distance than is indicated by the EPA data.

As discussed in Section 8.2.4, gamma radiation from the tanks can be shielded in various ways. The shielding material must have a high mass in order to stop the gamma rays, such as lead, concrete, or water. Materials such as wallboard, or such as the floor and carpeting in the room above the tank, will provide little resistance to gamma penetration. For the two EPA test houses, gamma levels were reduced to 40 to 50 μrem/hr at 3 ft through the use of a combination of concrete block, lead, and sand shielding.

Another key issue in the application of activated carbon systems is the need to dispose of the old, waste carbon whenever the bed needs to be replaced with fresh carbon. Such replacement will be necessary whenever the radon removal performance of the old carbon bed becomes insufficient, perhaps after many years. Over years of service, long-lived radionuclides will have accumulated on the carbon. Depending upon State regulations, the spent carbon might consequently be considered as a low-level radioactive waste, thus necessitating special considerations in disposal.

Long-lived radionuclides can accumulate on the bed as the result of the decay of the adsorbed radon. It is believed that, as the radon decays, its decay products remain adsorbed on the carbon. As discussed in Section 1.5.2, radon and its immediate four decay products have short half-lives. These elements would decay fairly quickly after the carbon bed is taken out of use (with 99 percent being gone after about 1 month). Thus, these elements are not of primary concern regarding disposal of the carbon. However, the fourth short-lived decay product (polonium-214) decays into a long-lived radionuclide, lead-210, which has a half-life of 22 years. The lead-210 thus does not decay away, but builds up slowly on the bed. Its own decay products, bismuth-210 (half-life of 5 days) and polonium-210 (half-life of 138 days), will also build up along with the lead. Lead-210 will have built up to only 3 percent of its radioactive equilibrium concentration (relative to the radon in the inlet water) after 1 year, and 27 percent after 10 years of bed service. Depending upon how much radon is present in the inlet water and the length of time that the bed has been in service, the lead-210 buildup can be sufficient to exceed certain regulations in some States governing the registration or disposal of low-level radioactive wastes.

The primary radioactive emissions from the lead-210 and its decay products are beta and alpha particles. If the waste carbon were disposed of in a suitable container, the container shell could trap essentially all of these particles. The practical concern is that — if this container were disposed of in an uncontrolled manner, such as in a municipal garbage dump —this container could rupture over many years. If it ruptured, the radioactive carbon dust could disperse over the dump site.

Long-lived radionuclides can also accumulate on the carbon bed when dissolved uranium is present in the well water. Available data suggest that uranium is effectively adsorbed on the carbon (Lo86, Ki87). Again depending on the uranium level in the water and the duration of bed use, uranium could accumulate sufficiently to exceed some State regulations.

Therefore, if an activated carbon system is being considered, the homeowner and the installer should contact the appropriate State agency to identify State regulations which could influence the disposal of waste carbon. State officials may also be able to suggest proper methods for disposing of the carbon. From the radon and uranium concentrations in the well water, equipment suppliers familiar with radon removal should be able to estimate how long the carbon bed can remain in service before the accumulation of long-lived radionuclides exceeds the regulations. Depending upon the disposal requirements that are imposed after these levels have been exceeded, it could sometimes be cost-effective to remove the bed from service before the levels are exceeded, even if radon removals remain satisfactory.

8.2.3.2 Aeration Units

Due to the lack of experience with aerators for radon removal, it is not possible to specify a confidence level for aerators at present. The limited results, together with the expectations based on scientific principles, suggest that aerators should be able to achieve significant radon reductions if properly designed. However, the commercial experience is too limited to have demonstrated practical, reliable, effective designs for residential units. On-going efforts by several developers to develop and market residential aerators could provide the needed commercial experience in the future. Among the issues needing to be demonstrated are: a) the required air and water contact times and flow rates needed to consistently ensure the desired radon removals; b) the conditions under which the deposition of iron and manganese oxidation products is and is not a problem, and the adequacy of proposed measures for avoiding plugging of the aerator and plumbing with these products; and c) the long-term reliability of aerators in residential applications.

Two developmental diffused aerator approaches for household use have been tested. One approach tested in the laboratory (Lo84, Lo87c) involves a single aeration stage (i.e., all air and water contact occurs in a single tank). Air flows are low, about 1 ft^3 of air per ft^3 of water entering the aerator. Radon removals up to 90 to 95 percent have been reported in a number of tests, depending upon test conditions, with inlet water concentrations in the range of 50,000 to 100,000 pCi/L. In the second diffused aeration approach (Lo87b), an aeration system involving between two and four stages is envisioned for removing radon (i.e., with the water leaving one tank entering the next tank for further treatment). Air flows would be much higher, on the order of 25 ft^3 of air per ft^3 of water. This multistage approach, designed specifically for radon removal from residential wells, is still undergoing laboratory tests. A variation of this multistaged approach has reportedly been installed in more than 20 houses for removing gasoline from the water from contaminated wells. In one of these houses, with a six-stage aeration system, the well water contained 250,000 pCi/L of radon; over 99.9 percent of the radon was reportedly removed after the first three stages (Lo87b, Lo87c). The developer of this multistage approach believes that a two- to four-stage system, with much less water residence time than is provided in the gasoline-stripping variation, could provide about 98 percent radon removal.

A diffused aerator installed for radon reduction in a municipal water treatment plant in England is reported to achieve radon removals of 97 percent (Lo85). Testing of a diffused aerator to remove radon from a small community well water system in New Hampshire is planned (Ki87).

A spray aerator for radon removal has been tested in one house in Maine, providing an average 93 percent reduction on water having initial radon levels between 44,000 and 63,000 pCi/L (Ro81). Spray aerators of this same design have reportedly been installed in five other houses, giving radon removals of 90 to 95 percent.

One vendor reports testing developmental packed-tower aerators for removing radon from well water in three individual houses having from 23,000 to 143,000 pCi/L in the water (La87). A 6-ft-high tower, aerating the well water on a once-through basis prior to use of the water in the house, gave radon reductions between 82 and 96 percent in these houses over a 2-month period. This unit is being marketed with an advertised radon removal efficiency of 90 percent. A packed-tower aerator of this design is scheduled for testing on a small community well water system in New Hampshire (Ki87). A second vendor is offering a somewhat different packed-tower approach for treating the wells for individual houses (PSC85). This second approach aerates the water standing in the well shaft casing by continuously pumping it through the packed column and returning it to the well casing. This aerator was designed to remove volatile organic compounds; no data are available on its performance in removing radon.

One issue in the application of water aerators is the steps that must be taken to avoid unacceptable degrees of plugging in the system when elevated levels of dissolved iron and manganese are present in the well water. These elements will become oxidized in the aerator, and can precipitate as deposits that can cause plugging of, for example, air diffusers, spray nozzles, and packing material in the aerators, and the house plumbing downstream of the aerator. In some cases, this deposition can be addressed through appropriate maintenance. For example, for the diffused aerator designs discussed above (Lo87b), the developer believes that, at iron levels below 0.2 ppm and manganese levels below 0.05 ppm in the water, deposition can be handled by adding a chemical cleaning agent to the tanks annually or semi-annually. Above these levels, it is recommended that an iron/manganese removal step be added prior to the aerator. Where an iron removal step is not included prior to the packed tower, a sediment filter may have to follow the aerator to remove the precipitated oxidation products, to prevent fouling of the house plumbing. For one of the packed tower aerators discussed above (La87), the vendor estimates that iron levels as high as 10 ppm can be addressed by replacing the tower packing annually. At higher levels, iron removal is required before aeration. Where an iron removal step is not included prior to the packed tower, a sediment filter may have to follow the aerator to remove the precipitated oxidation products, to prevent fouling of the house plumbing. In some cases, even activated carbon units might need a preceding iron removal step to avoid blinding of the carbon bed with precipitated iron products.

8.2.4 Design and Installation

Water treatment devices must be designed and installed by qualified vendors and plumbing contractors. The firm selected to design, supply, and install the activated carbon or aeration system should be one which has previous experience with these systems specifically for radon reduction. As mentioned in the prior section, units which have proved satisfactory for removing other water contaminants might not always be optimum for removing radon. The appropriate State agency will sometimes be able to suggest qualified contractors with experience in radon removal.

The knowledge required in the design and installation of water treatment systems necessarily extends beyond what can be presented in this manual. The discussion which follows is intended to aid the homeowner in dealing with the installer.

8.2.4.1 Granular Activated Carbon Units

An activated carbon unit for household use is typically a fiberglass tank approximately 4 ft tall similar in appearance to a water softener. The tank stands on the floor and usually contains between 1 and 3 ft^3 of activated carbon. The carbon tank is installed in the house plumbing so that all incoming well water, after passing through the pressure tank, enters the carbon unit at pressure before being piped elsewhere in the house. The carbon tank is usually most conveniently placed inside the house (or crawl space), where the piping from the well enters the structure. However, in view of the concerns regarding gamma radiation from the tank, it might be desired with exceptionally high-radon wells to place the tank in a separate structure outside the dwelling. Units not installed inside the house must be protected against freezing during cold weather.

A sediment filter must precede the carbon tank to remove solid particles from the incoming water. This filter, if not already present, should be installed in the water line between the pressure tank and the carbon tank when the carbon tank is installed. The sediment filter will significantly reduce the rate at which the carbon bed will become blocked by the buildup of waterborne solids in the bed. Carbon filters must be backwashed to remove the accumulated solids whenever the buildup becomes too great. Results have shown that backwashing temporarily reduces the radon removal performance of a carbon unit, apparently due to desorption of radon from the bottom of the bed (Lo85). Thus, it is desirable to reduce the frequency of backwashing. Field experience demonstrates that, with the sediment filter, the frequency of backwashing can be reduced to perhaps annually.

The cheapest and most convenient type of sediment filter to use will often be the replaceable cartridge. The filter cartridge is replaced whenever the sediment buildup on the filter becomes sufficiently great. Another type of filter, which could be applicable in some cases, is a media filter. With this type, the media that effect the filtration remain permanently in place, and are backwashed whenever the sediment buildup is sufficiently great.

Because of the need to reduce the frequency of backwashing of the carbon tank, the activated carbon unit should not include automatic backwash controls. Such controls might trigger backwashing (and cause temporary reductions in radon removal) more frequently than is necessary. As long as there is a sediment filter upstream, the homeowner would generally be best served simply by manually implementing the backwash cycle once each year. If it turns out that backwashing is needed more frequently in a given house, due to greater-than-normal solids buildup in the bed, the homeowner will be made aware of this need through a loss of water pressure in the house.

The selection of the specific brand of activated carbon that is used in the tank is important in determining radon removal performance, as discussed previously (Lo85, Sc86c). The carbon in units commercially offered for organics removal will not always be optimum for radon removal. The firm which is designing and installing the system should be aware of suitable sources of carbon for optimum radon removal.

The amount of carbon that is needed will depend upon the concentration of radon in the inlet water, the desired level in the outlet, and the rate of water usage in the house. Where greater removals and/or a lower outlet concentration are desired, and where the water usage rate is higher, the amount of carbon must be increased in order to provide increased residence time for the water in the carbon bed. It is currently believed that 3 ft^3 of a suitably reactive carbon should generally be sufficient, at typical household water use rates, to effectively treat even the highest-radon wells discovered to date (over 1×10^6 pCi/L). At lower radon levels, as little as 1 ft^3 of carbon can be sufficient. It is noted that the carbon requirements are determined by the necessary water residence time, and not by any threat of the bed's becoming saturated with radon and its decay products. Even at 1×10^6 pCi/L, the actual mass of radon in the water is so small that it would theoretically take decades for the carbon to become saturated with radon decay products.

Protection of house occupants from gamma radiation from the tank must be a consideration with any carbon unit installation, as shown by the data presented in the previous section. Without any shielding around the tank, EPA's data suggest that a person would have to stay at least 10 ft away from the tank when the inlet water is in the range of 50,000 to 300,000 pCi/L for the gamma levels to have dropped to a dose rate equivalent to or no greater than 20 μrem/hr above background. Thus, if no shielding were provided, the tank would have to be placed in an unoccupied room, and there could not be living area directly above the tank, if one wished to remain within 20 μrem/hr above background relying solely on the dropoff of gamma dose rate with distance. The necessary distance could be less than 10 ft if the radon level in the inlet water were lower than 50,000 to 200,000 pCi/L, so that the amount of radon and progeny built up in the bed were less. Conversely, the necessary distance would be greater if the inlet radon levels were higher. To avoid shielding where the water radon concentrations are exceptionally high, it would be desirable to place the tank in a separate heated building away from the house.

In most cases, it will be more convenient and economical to install shielding around the carbon tank. The shielding material must have a high mass in order to effectively block the high-energy gamma rays. The shielding structure must also be designed to enable access to the tank for any servicing that might be needed. One convenient shielding approach that is being used is to immerse the carbon tank in a larger vessel full of water, using water as the shielding material. One vendor places the carbon tank inside a 2- to 2.5-ft diameter polyethylene outer tank filled with water, which provides between 7 and 15 in. of water shielding on all sides, and on top, of the carbon unit (Lo87b). In EPA's two test houses, a wall of hollow concrete block was built around the tanks, and the top of the block structure was covered with solid concrete patio blocks. In the house having about 200,000 pCi/L in the water, it was further necessary to line the inside of the block structure with sheet lead, and to fill the structure with sand. This approach of building a block structure with a removable top permits reasonably easy access to the top of the tank, where the plumbing connections are located, but could require partial dismantling of the structure if the tank ever had to be removed. Another approach that can be considered in lower-level cases is to wrap the tank with sheet lead. With the 200,000 pCi/L house in the EPA program, it was neither practical nor economical to wrap sufficient sheet lead around the tank to get the needed reductions.

Where there are high iron and manganese levels in the well water, it might be necessary to include an iron/manganese removal step prior to the carbon unit, to prevent deposited oxidation products from blinding the carbon. Current data are not sufficient to identify under what conditions the inclusion of such a step will be warranted. It currently appears that iron/manganese removal to protect the carbon is not necessary in most cases. An increase in the frequency of backwashing might be sufficient to remove deposited oxidation products.

8.2.4.2 Aeration Units

All household aeration units involve a depressurization of the water being pumped out of the well, an exposure of the depressurized water to air at atmospheric pressure, and a re-pressurization of the water for use in the house. Aeration systems can be designed in various ways to accomplish these steps. The discussion below describes some demonstrated or proposed designs.

A diffused aeration system would generally involve either one aeration tank, or multiple tanks in series, located inside the house upstream of the pressure tank. That is, water from the well is pumped directly into the aeration tank (or into the first tank in the series) using the existing well pump. An auxiliary water pump moves the low-radon water out of the tank (or out of the last tank in the series) into the pressure tank, for use in the house.

The radon removal effectiveness of a diffused aerator will depend primarily on the residence time of the water in the tank, the flow rate of air through the tank, and the effectiveness with which the air is distributed. With the single-stage diffused aerator that has been tested in the laboratory, the tank capacity was varied from 50 to 120 gal. (Lo84, Lo87c). An air blower forced air into the bottom of the tank at rates up to 50 scfh of air. If a water flow rate of 5 gpm is assumed, these conditions would correspond to a water residence time of 10 to 24 min., and a maximum air-to-water ratio of roughly 1 ft^3 of air per ft^3 of water. The air must be forced into the bottom of the tank through a diffuser which causes it to rise up through the water in the form of many small bubbles. In the particular single-stage design being described here, the bubbles were created by forcing the air through a porous ceramic diffuser arranged to distribute the air bubbles over the entire bottom of the tank. The porous ceramic is a reasonable diffuser at the low air flows involved here. With such low air flows, the depth of the water in the tank can influence performance. For best results, the water should be as shallow as practical (i.e., the tank as wide in diameter as practical), to achieve good aeration of the water near the top.

The multistage diffused aerator design (Lo87b, Lo87c) is intended to ensure that all of the water has a minimum residence time in the system. Much higher total air flows are now being considered, relative to those used previously in the single-stage testing, in order to achieve higher radon removals with less water residence time (i.e., smaller tanks). In the developmental multistage system now envisioned, two to four tanks of roughly equal capacity are anticipated, with a total combined capacity of 15 to 30 gal. At an assumed water flow of 5 gpm, this would provide 3 to 6 min. of water residence time. Total air flow rates into the several tanks would be on the order of 25 ft^3 of air per ft^3 of water. At these high air flows, the porous ceramic diffuser is no longer practical; the diffuser could be a perforated plastic pipe around the bottom of each tank. By comparison, the six-stage aerator mentioned in Section 8.2.3.2 for gasoline removal — where 99.9 percent radon reduction was reported after three stages — was much larger than the radon-specific system described above (125 gal.), and provided longer water residence times. By the third stage of the gasoline stripper, the water would have had a minimum residence time of 12 min., assuming a flow of 5 gpm.

With either diffused aerator design, air and stripped radon collect in the head space above the water in each tank, and must be vented outdoors. The vent should release the stripped radon away from windows and doors, preferably above the eaves, to keep the radon from flowing back into the house.

In one design for a spray aeration system (Ro81), the incoming water from the well is pumped directly into a 50-gal. tank, using the existing well pump. This water is sprayed into the tank through an atomizing spray nozzle. Water accumulated in the tank is continuously recirculated, being pumped back into the tank through a second spray nozzle. Dissolved radon should be effectively released from the fine droplets that these spray nozzles create. The released radon collects in the head space of the spray tank, and must be vented outdoors, as described previously for the diffused aerators. The low-radon water collected in the tank is pumped to the pressure tank, using a new auxiliary pump, for use in the house as necessary. A sediment filter would be needed to treat the incoming well water, so that the spray nozzles would not become plugged.

With one of the designs for a packed-tower aerator (La87), water from the well is pumped directly to the top of the 6-ft-high packed column using the existing well pump. The water then cascades down through the column packing material while a fan forces stripping air up from the bottom of the column. The stripped water at the bottom of the column flows by gravity to a 30-gal. storage tank inside the house. A new auxiliary water pump then pumps the water from this tank to the existing pressure tank, for use in the house. This unit is being marketed with an advertised radon removal efficiency of 90 percent. In this design, no attempt is made to improve radon removals by recycling water from the storage tank back to the top of the column, for another pass through the packed tower; the water makes one pass only. In this design, a sediment filter follows the aerator whenever there are elevated levels of iron in the water, to remove oxidized iron compounds that precipitated in the aerator.

Another packed-tower approach (PSC85) avoids the need for an indoor storage tank by using the existing well shaft casing as the "storage tank." In this configuration, the existing well pump would continuously pump water to the top of a 5.5-ft tall packed column inside the house. Stripped water collected at the bottom of the column would continuously flow by gravity back into the well casing. Thus, the water standing in the well casing is being continuously recycled through the column. The water to the top of the column flows from a tee in the line which connects the well pump directly to the pressure tank. Thus, unlike the other aerators discussed previously, this particular packed tower configuration does not place the column in series between the well and the pressure tank. When water is used in the house, the water flows directly from the well to the pressure tank and into the house. One uncertainty associated with this approach is that the capacity of the "storage tank" might be unknown and variable. This capacity will depend upon: a) the diameter of the well casing; and b) the height of the water column in the casing, which in turn is determined by the pressure in the underground aquifer. The capacity of this treated water storage might not be sufficient to handle peak water use rates in the house. If high water usage in the house consumes the water stored in the casing — or if the well pump draws water directly from the aquifer rather than from that accumulated in the casing — then the water used in the house would be largely untreated.

Where iron and manganese levels in the well water are high, a treatment step to remove these elements will sometimes be necessary prior to aeration, for any of the aeration system designs. Otherwise, precipitated oxidation products can deposit in, and plug, certain components of the aeration system, as well as the downstream plumbing. The need for such a treatment step will depend upon the iron/manganese levels in the water, the nature of the aerator, and the maintenance that one can practically perform to remove deposits. For example, as discussed in Section 8.2.3.2, annual or semiannual cleaning of diffused aerator tanks, or replacement of the packing material in packed towers, has been proposed as maintenance which can handle iron and manganese deposition up to certain concentrations.

8.2.5 Operation and Maintenance

8.2.5.1 Granular Activated Carbon Units

With granular activated carbon treatment systems, operating requirements will include the following.

Radon measurements in the water. The radon concentrations in the water leaving the carbon unit, and preferably also in the water entering the unit, should be measured at least once each year. Such measurements will alert the homeowner if performance is degrading. Ideally, it would be useful if radon could be measured more often than once per year, since radon levels in the inlet water, along with water usage rates, will vary over time, possibly influencing performance.

In some cases, appropriate State agencies may be willing to analyze the water, or to identify qualified laboratories that can. Local water utilities, vendors of water treatment equipment, and radon mitigators might also be able to suggest suitable testing laboratories.

If the measurement results suggest that radon removal performance is degrading, the homeowner should contact a water treatment professional. If the bed has been in place for a number of years, it might be time to replace it.

Servicing sediment filter. The cartridge in the sediment filter which precedes the carbon unit should be replaced as necessary. The required frequency of replacement will depend upon the amount of sediment present in the incoming well water. A drop in water pressure could be indicating that the filter cartridge needs to be replaced.

If a permanent filter is used as the sediment filter, the media bed must be backwashed at suitable intervals.

Backwashing carbon unit. The carbon unit should be manually backwashed once each year, to remove any sediment which has accumulated in the bed. Since it is recommended that any automatic backwash provided with commercial carbon units be disconnected when the unit is used solely for radon removal, the homeowner must be alert to the need to backwash manually. With the sediment filter upstream of the carbon unit, annual backwashing has been generally found to be sufficient in most cases. If backwashing once per year were not sufficient in a specific case, the homeowner would be alerted by a reduction in water pressure in the house. If water pressure appears to be dropping over time and if the sediment filter is clean, it could be time to backwash the carbon bed. If there are elevated iron levels in the water, the deposition of oxidized iron products on the bed could necessitate an increased frequency of backwashing.

Since radon removal performance can degrade somewhat for a period of 24 hours or more after backwashing, backwashing should not be done more often than necessary.

Measurement of bacterial levels. There is concern that bacterial growth in the carbon unit can occur under some circumstances, and can increase the level of microorganisms in the house water. Thus, it is advisable to have periodic measurements made of the total bacteria levels in the water leaving the carbon unit. These measurements would preferably also be made in the water entering the unit, to confirm that the carbon unit is indeed the source of any observed bacteria in the house water.

Appropriate State agencies should be able to identify qualified laboratories that can make such analyses, and to indicate the total bacteria levels at which the homeowner should become concerned.

If bacterial levels do appear to be rising toward undesirable levels, the homeowner might take steps to disinfect the carbon unit. Use of the carbon unit might have to be discontinued.

No health problems have been reported in connection with the carbon units installed to date for radon removal.

Gamma measurements. Even with a shield around the carbon unit, gamma levels may still be elevated near the unit. These levels can increase if the radon level in the well water increases, or if the water usage rate increases. Thus, periodic measurements of gamma levels in the vicinity of the tank could be advisable, especially if the area near the tank is frequently occupied. Perhaps additional shielding might become warranted. Or, if the shielding must be dismantled for maintenance on the tank, gamma measurements should be made several weeks after the carbon unit is reactivated to confirm that the shielding was effectively restored.

Replacement of the carbon bed. After the carbon unit has been in place for some time, it will become necessary to replace the carbon bed in order to maintain high radon removals. The frequency with which this will have to be done is uncertain. As discussed previously, bed lifetime could theoretically be as long as decades, but will likely be shorter, especially where other water contaminants are present which could deactivate the carbon.

As discussed earlier, the levels of gamma radiation resulting from accumulated short-lived radon progeny on the carbon will be very high. There will also be high alpha and beta radiation, but this radiation will be trapped inside the container holding the carbon. All of the radiation associated with the short-lived radon and radon progeny will decay away relatively quickly. About 90 percent will be gone after the bed has been out of service for 2 weeks, and 99 percent after 4 weeks. Accordingly, when the carbon is taken out of service, it should be stored in a shielded or remote area for about a month before extensive handling or disposal. One option would be to bypass the carbon unit for that period, leaving the spent bed in the unused tank. The radon and progeny would then decay inside the shielded tank. If the spent bed is to be removed immediately, so that the carbon unit can be promptly put back into use with a fresh bed, the spent carbon should be rapidly placed in an isolated area outside the house with minimum handling. Persons handling the spent carbon should minimize the time spent close to the bed.

As discussed in Section 8.2.3.1, after the short-lived radionuclides have decayed away, there will be some continuing radiation (largely alpha and beta) from long-lived radionuclides. These long-lived elements include lead-210 and its decay products, which result from the radon sorbed on the carbon. The long-lived radiation can also result from sorbed uranium, if dissolved uranium is present in the water. The amount of long-lived radionuclides in the carbon will depend upon the concentration of radon (and uranium) in the water, and the length of time the bed was in service. If this amount is sufficiently high, the waste carbon could be covered by regulations in some States which address the registration or disposal of low-level radioactive wastes. In some cases, the waste carbon may have to be ultimately disposed of in a controlled manner, consistent with applicable State regulations. The appropriate State agency should be contacted for information regarding applicable regulations, and for information on proper methods for ultimately disposing of the carbon.

Depending upon the disposal requirements that are imposed after the minimum accumulation of long-lived radionuclides is exceeded, it could sometimes be cost-effective to replace the carbon bed before these levels are exceeded, even if the old carbon is still highly effective in adsorbing radon.

8.2.5.2 Aeration Units

With aeration systems for water treatment, operating requirements also include periodic radon measurements to verify continuing satisfactory performance. These measurements might be made immediately after periods of peak water use (such as when a dishwasher or clothes washer is operating), in order to determine performance under the conditions that aerators will find most challenging. The requirements will also include regular inspection by the homeowner of the auxiliary pump(s) and air blower associated with the aeration system, to ensure that these are operating properly. The general functioning of the aeration units themselves should be observed: do the water and air flows seem to be occurring as they should? Some commercial units are equipped with indicator lights and buzzers to signal inadequate water or air flows, due to, for example, plugged air intake passages, plugged sediment filters, or spray nozzles. The inspection should also include the vent which directs the released radon outdoors, to ensure that leaks in the indoor segments of the vent pipe have not developed which would enable the radon from the aerator to escape into the house.

As with activated carbon units, operation of aerators should include periodic measurements of total bacteria levels in the effluent, to ensure that unacceptable bacterial growth is not occurring inside the unit.

Routine maintenance would include any needed maintenance on the fan/air compressor and auxiliary pump, and replacement of the cartridge in the sediment filter upstream or downstream of the aerator where necessary. Any problems with the air or water flows should be addressed in accordance with the instructions which accompany the aeration unit (including contacting the vendor of the unit where required). Any maintenance should be conducted in connection with possible deposition of oxidized iron compounds or sediment buildup, such as addition of a chemical cleaning agent to the diffused aeration tanks, or annual replacement of the packing material in the one packed tower design. Any apparent leaks in the piping which vents the released radon gas outdoors should be caulked or otherwise sealed.

If the performance of the aerator degrades significantly, and if the steps above do not correct the problem, the homeowner should contact the vendor.

8.2.6 Estimate of Costs

The total installed capital cost of a residential granular activated carbon unit specially designed for radon removal — including a sediment filter, if one does not already exist, but excluding any gamma shielding —is estimated at $750 to $1,200 (Lo87a, Lo87c). If gamma shielding is included, the additional cost might be about $200, if the shielding consists of immersing the carbon tank in a vessel full of water (Lo87c). Other shielding approaches, such as construction of a concrete block wall around the tank, could add a similar amount to the installation cost if done by a contractor. Operating costs will include the nominal cost of periodic replacement of the sediment filter cartridges, and, at some interval, replacement of the carbon bed. Replacement beds are estimated to cost perhaps $200 to $300 installed (Lo87c).

Estimates are available for typical installed capital costs for some residential aeration systems offered by specific vendors. These costs, excluding the cost of any iron removal step, are approximately $2,500 for the envisioned two- to four-stage diffused aerator system designed specifically for radon removal (Lo87b), over $4,000 for one spray aerator design, and $3,000 for one of the packed tower approaches (La87). Inclusion of iron removal upstream of the aerator, if required, could increase costs by $600 to $1,000.

Operating costs for aerators will include the electricity costs to operate the new auxiliary water pump in each case (about 1/3-hp), and, for the diffused and packed tower aerators, to operate the blower that provides the stripping air. This blower could be about 1/3-hp for the diffused aerator, and about 1/40-hp for the packed tower. The annual cost for electricity for any of these aerators would depend upon the water usage in the house (i.e., how long the pump and blower were running), among other factors. The cost of electricity would probably range between $20 and $75 per year. Other operating and maintenance costs include: the minor cost of replacing the cartridge of a sediment filter; maintenance costs for the fan, pump, and other equipment; and maintenance costs associated with the buildup of iron deposits. To replace the packing material each year in the one packed tower design, the cost would be roughly $25 for the new packing, plus labor if the homeowner has a contractor do the work.

Section 9

New Construction

9.1 Background Research

Until recently, EPA research in radon reduction techniques has focused on techniques applicable to existing houses with measured elevated radon concentrations. Justification for emphasizing the reduction of radon levels in existing houses with radon problems over the design of radon prevention for new houses has been based on the perception that a significant radon health risk is already present in the current U.S. housing stock. Moreover, new house construction would add only marginally to that risk during the time required to conceive, evaluate, and apply radon reduction methods to existing houses.

With the knowledge that has been obtained in the existing house radon reduction program, it is now easier to project the house design concepts that are likely to prevent radon entry. Three separate research projects testing radon prevention in new houses have begun in 1987, and results from these projects should be available for the next update of this document.

9.2 Interim Guidance

To assist homebuilders and others interested in potential radon prevention alternatives in new construction, a recent EPA document, "Radon Reduction in New Construction: An Interim Guide," (EPA87d) has been included as Appendix B of this document. The information available in Appendix B is a logical extension of the EPA's current understanding of radon entry and of the experience obtained in sub-slab suction in existing houses. The recommendations included in Appendix B are possible because many of the likely radon prevention alternatives for new houses are also demonstrated effective radon mitigation techniques for existing houses. Unfortunately, until some of these techniques have actually been applied during construction and evaluated for applicability, cost effectiveness, radon prevention, and durability after construction, the value of these techniques cannot be fairly assessed.

If it is assumed that many of the radon-reducing concepts appropriate for existing houses are equally appropriate for new houses, at least portions of the radon mitigation methods for existing houses should be applicable to new houses. It is expected that applying many of these techniques during construction can prevent radon entry at a significant savings over the same techniques applied after construction. Furthermore, some radon-reducing techniques may be applicable only during construction prior to the completion of sub-floor surfaces, floors, and walls. For specific information related to these potential radon prevention techniques in new houses, see Appendix B.

Section 10

Sources of Information

The first point of contact for information concerning indoor radon and radon reduction measures should be the appropriate State agency. Table 17 lists the appropriate agency to contact for each of the States.

If further information is desired, additional assistance and contacts can be provided by the EPA Regional Office for the region that includes your State. Table 18 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 17. 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-06F
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

Table 17 (continued)

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

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

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 Mall
Boise, ID 83720
(208) 334-5879

Illinois
Illinois Department of Nuclear Safety
Office of Environmental Safety
1035 Outer Park Drive
Springfield, IL 62704
(217) 546-8100 or (800) 225-1245 (in State)

Table 17 (continued)

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

Kansas
Kansas Department of Health and Environment
Forbes Field, Building 321
Topeka, KS 66620-0110
(913) 862-9360, Ext. 288

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) 333-3120 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

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
(402) 471-2168

Nevada
Radiological Health Section
Health Division
Nevada Department of Human Resources
505 East King Street, Room 202
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)

New Mexico
Surveillance Monitoring Section
New Mexico Radiation Protection 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
Empire State Plaza, Corning Tower
Albany, NY 12237
(518) 473-3613 or (800) 458-1158 (in State) or
(800) 342-3722 (NY Energy Research & Development Authority)

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

Table 17 (continued)

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

Ohio
Radiological Health Program
Ohio Department of Health
1224 Kinnear Road
Columbus, OH 43212
(614) 481-5800 or (800) 523-4439 (in Ohio only)

Oklahoma
Radiation and Special Hazards Service
Oklahoma State Department of Health
P. O. Box 53551
Oklahoma City, OK 73512
(405) 271-5221

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

Pennsylvania
Bureau of Radiation Protection
Pennsylvania Department of Environmental Resources
P. O. Box 2063
Harrisburg, PA 17120
(717) 782-2480 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 Radiological Control
Rhode Island Department of Health
206 Cannon Building
75 Davis Street
Providence, RI 02908
(401) 277-2438

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 217
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

Utah
Bureau of Radiation Control
Utah State Department of Health
State Health Department Building
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

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 18. Radiation Contacts for EPA Regional Offices

Address and Telephone	States in EPA Region
Region 1 U. S. Environmental Protection Agency 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 3AM11 U. S. Environmental Protection Agency 841 Chestnut Street Philadelphia, PA 19107 (215) 597-4084	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, Texas 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-092 U. S. Environmental Protection Agency 1200 Sixth Avenue Seattle, WA 98101 (206) 442-7660	Alaska, Idaho, Oregon, Washington

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

Table 18 (continued)

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

Section 11

References

A186 — Alter, H. W. and R. A. Oswald, Nationwide Distribution of Indoor Radon Measurements: A Preliminary Data Base, *JAPCA* 37(3): 227-231, 1987.

Ar82 — Arix Corporation, Planning and Design for a Radiation Reduction Demonstration Project, Butte, MT, Report to the Montana Department of Health and Environmental Sciences, Appendix C, January 1982.

ASHRAE81 — American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Ventilation for Acceptable Indoor Air Quality, ASHRAE Standard 62-1981, Atlanta, GA, 1981.

ASHRAE83 — American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., ASHRAE Handbook: 1983 Equipment Volume.

ASHRAE85 — American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., ASHRAE Handbook 1985 Fundamentals, Atlanta, GA, 1985.

ATCON86 — American ATCON, Inc., Low Cost Reduction of Indoor Radon: Industrial Foam Study, April 1986.

Bo87 — Bocanegra, R. and P. K. Hopke, The Feasibility of Using Activated Charcoal for Indoor Radon Control, In P. K. Hopke (ed), Radon and Its Decay Products: Occurrence, Properties, and Health Effects, ACS Symposium Series 331, pp. 560-569, 1987.

Br83 — Bruno, R. C., Sources of Indoor Radon in Houses: A Review, *JAPCA* 33(2):105-109, 1983.

Br86 — Brennan, T., Camroden Associates, Inc., Rome, N.Y., personal communication, February 1986.

Br87 — Brennan, T., Camroden Associates, Inc., Rome, N.Y., personal communication, July 1987.

Bro86 — Brodhead, W., Buffalo Homes, Riegelsville, PA, Sub-slab Ventilation Results, February 1986.

Bro87a — Brodhead, W., Mitigation Quality Control Checklist, in Reducing Radon in Structures: Student Manual, prepared for EPA radon reduction training course, January 1987.

Bro87b — Brodhead, W., Buffalo Homes, Riegelsville, PA, personal communication, July 1987.

Ch79 — Chakravatti, J. L., Control of 222Rn-WL in New Construction at Elliot Lake, presented at a Workshop on Radon and Radon Daughters in Urban Communication Associated with Uranium Mining and Processing. Bancroft, Ontario, March 1979.

Co86 — Cothern, C. R., W. L. Lappenbusch and J. Michel, Drinking Water Contribution to Natural Background Radiation, *Health Phys.*, 50(1): 33-47 (1986).

CR85 — *Consumer Reports*, 1986 Buying Guide Issue, Mount Vernon, NY, December 1985.

DOC82 — U. S. Department of Commerce. Statistical Abstract of the United States 1982-83. Bureau of the Census, Washington, DC, 1982.

DSMA79 — DSMA ATCON Ltd., Investigation and Implementation of Remedial Measures for the Radiation Reduction and Radiation Decontamination of Elliot Lake, Ontario, Atomic Energy Control Board, Canada, 1979.

DSMA80 — DSMA ATCON Ltd., Investigation and Implementation of Remedial Measures for the Radiation Reduction and Radioactive Decontamination of Elliot Lake, Ontario, Atomic Energy Control Board, Canada, February 1980.

Du85 — Dumont, R., The Effect of Mechanical Ventilation on Rn, NO2, and CH2O Concentrations in Low-Leakage Houses and a Simple Remedial Measure for Reducing Rn Concentrations, Proceedings of the APCA Conference on Indoor Air Quality in Cold Climates, Ottawa, Ontario, 1985.

Du87 — Dunn, J. E. and D. B. Henschel, Statistical Aspects of Autoregressive Models in the Assessment of Radon Mitigation, presented at The Fourth International Conference on Indoor Air Quality and Climate, Berlin, West Germany, August 1987.

EI87 — Ellison, H., Safe-Aire, Inc., Canton, IL, personal communication, January 1987.

EMR85 — Department of Energy, Mines and Resources (Canada), How to Operate a Heat Recovery Ventilator, Ottawa, Ontario, 1985.

EMR87 — Department of Energy, Mines and Resources (Canada), R-2000 Super Energy Efficient Home Program: R-2000 Heat Recovery Ventilator Rating Guide, Ottawa, Ontario, May 26, 1987.

EPA78 — Windham, S.T., F.D. Savage and C.R. Phillips, The Effects of Home Ventilation Systems on Indoor Radon/Radon Daughter Levels, U.S. Environmental Protection Agency, EPA-520/5-77-011 (NTIS PB291925), Montgomery, AL, October 1978.

EPA85 — U. S. Environmental Protection Agency, unpublished data involving simultaneous continuous radon monitor and continuous working level monitor results in a house with an HRV, December 1985.

EPA86a — Sanchez, D. C. and D. B. Henschel, Radon Reduction Techniques for Detached Houses: Technical Guidance, U. S. Environmental Protection Agency, EPA-625/5-86/019, Research Triangle Park, NC, June 1986.

EPA86b — U. S. Environmental Protection Agency, A Citizen's Guide to Radon, OPA-86-004, Washington, DC, August 1986.

EPA86c — 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.

EPA86d — 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.

EPA86e — U. S. Environmental Protection Agency, unpublished data with an HRV in House 2A under EPA Contract 68-02-4203, January 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, 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, Radon Reduction Methods: A Homeowner's Guide, Second Edition, OPA-87-010, September 1987.

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

EPA87e — U. S. Environmental Protection Agency, Removal of Radon from Household Water, OPA-87-011, September 1987.

EPA87f — U. S. Environmental Protection Agency, Radon Reference Manual, EPA-520/1-87-020, (in preparation).

Er84 — Ericson, S. O., H. Schmied and B. Clavensjo, Modified Technology in New Construction, and Cost Effective Remedial Action in Existing Structures, to Prevent Infiltration of Soil Gas Carrying Radon, in *Proceedings of the 3rd International Conference on Indoor Air Quality and Climate*, Stockholm, Sweden, Vol. 5, pp. 153-158, August 20-24, 1984.

Er87 — Ericson, S. O. and H. Schmied, Modified Design in New Construction Prevents Infiltration of Soil Gas that Carries Radon, in *Radon and Its Decay Products: Occurrence, Properties, and Health Effects* edited by P. K. Hopke, pp. 526-535, American Chemical Society, Washington, DC, 1987.

Ev69 — Evans, R. D., Engineers' Guide to the Elementary Behavior of Radon Daughters, *Health Phys.*, 17:229-252, 1969.

Fi80 — Fisk, W. J., G. D. Roseme and C. D. Hollowell, Performance of Residential Air-to-Air Heat Exchangers: Test Methods and Results, Lawrence Berkeley Laboratory, Report LBL-11793, September 1980.

Fi83a — Fisk, W. J. and I. Turiel, Residential Air-to-Air Heat Exchangers: Performance, Energy Savings and Economics, *Energy and Buildings*, 5: 197-211, 1983.

Fi83b — Fisk, W. J., K. M. Archer, R. E. Chant, D. Hekmat, F. J. Offermann and B. S. Pedersen, Freezing in Residential Air-to-Air Heat Exchangers: An Experimental Study, Lawrence Berkeley Laboratory, Report LBL-16783, September 1983.

Fi84 — Fisk, W. J., R. K. Spencer, D. T. Grimsrud, F. J. Offermann, B. Pedersen and R. G. Sextro, Indoor Air Quality Control Techniques: A Critical Review, Lawrence Berkeley Laboratory, Report LBL-16493, March 1984.

Fi87 — Fisher, G., Radon Detection Services, Inc., Ringoes, NJ, personal communication, April 13, 1987.

Fr75 — Frank, J. C. and L. T. Nazur, Polymeric Materials for Sealing Radon Gas into the Walls of Uranium Mines, Spokane Mining Resource Center, Spokane, WA, 1975.

Ge80 — Gesell, T. F. and H. M. Prichard, The Contribution of Radon in Tap Water to Indoor Radon Concentrations, in *Proc. Symp. Natural Radiation Environment III*, Vol. 2, U. S. Department of Energy report CONF-780422:1347-1363, 1980.

Go83 — Goldsmith, W. A., J. W. Poston, P. T. Perdue and M. O. Gibson, Radon-222 and Progeny Measurements in "Typical" East Tennessee Residences, *Health Phys.*, 45(1):81-88, 1983.

Gr83 — Grimsrud, D. T., M. H. Sherman and R. C. Sonderegger, Calculating Infiltration: Implications for a Construction Quality Standard, Lawrence Berkeley Laboratory, Report LBL-9416, 1983.

Ha81 — Harley, N. H. and B. D. Pasternak, A Model for Predicting Lung Cancer Risks Induced by Environmental Levels of Radon Daughters, *Health Phys.*, 40, pp. 307-316, 1981.

Ha86 — Hackwood, H. J., The Application of Sealant Materials for Radon Gas Diffusion Restriction, Master's thesis, Queens University, 1986.

Ha87 — Harris, D. B., U. S. Environmental Protection Agency, Research Triangle Park, NC, personal communication, May 1987.

He82 — Hess, C. T., C. V. Weiffenbach and S. A. Norton, Variations of Airborne and Waterborne RN-222 in Houses in Maine, *Environ. Int.* 8: 59-66, 1982.

He85 — Hess, C. T., J. Michel, T. R. Horton, H. M. Prichard and W. A. Coniglio, The Occurrence of Radioactivity in Public Water Supplies in the United States, *Health Phys.*, 48: 553-586 (1985).

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.

Ho85 — Holub, R. F., R. F. Droullard, T. B. Borak, W. C. Inkret, J. G. Morse and J. F. Baxter, Radon-222 and 222 Rn Progeny Concentrations Measured in an Energy-Efficient House Equipped with a Heat Exchanger, *Health Phys.*, 49(2): 267-277, August 1985.

Hu87 — Hubbard, L. M., Princeton University, Princeton, NJ, personal communication, July 1987.

HVI86 — Home Ventilating Institute, Home Ventilating Guide: Air Handling Equipment (Fans and Blowers), Publication No. 12, Arlington Heights, IL, 1986.

HVI87 — Home Ventilating Institute, Certified Home Ventilating Products Directory: Air Delivery and Sound Levels, Publication No. 11d, Arlington Heights, IL, 1987.

Ja80 — Jacobi, W. and K. Eisfeld, Dose to Tissues and Effective Dose Equivalent by Inhalation of 222-Rn, 220-Rn, and Their Short-lived Daughters, GSF Report s-626, 1980.

Ja81 — James, A. C., W. Jacobi and F. Steinhausler, Respiratory Tract Dosimetry of Radon and Thoron Daughters: The State-of-the-Art and Implications for Epidemiology and Radiology, in M. Gomez (ed.), *Radiation Hazards in Mining: Control, Measurement, and Medical Aspects*, New York: Society of Mining Engineers, pp. 42-54, 1981.

Ki87 — Kinner, N. H., C. E. Lessard, G. S. Schell, H. Stewart, R. Thayer, J. D. Lowry and K. R. Fox, Radon Removal from Small Community Public Water Supplies Using Granular Activated Carbon and Low Technology/Low Cost Techniques, presented at the American Water Works Association Annual Conference, Kansas City, MO, June 1987.

La87 — Lamarre, B. L., North East Environmental Products, Inc., Lebanon, NH, personal communication, September 1987.

Lo84 — Lowry, J. D., W. F. Brutsaert, T. McEnerney and C. Molk, GAC Adsorption and Diffused Aeration for the Removal of Radon from Water Supplies, presented at the American Water Works Association Annual Conference and Exposition, Dallas, TX, June 1984.

Lo85 — Lowry, J. D. and J. E. Brandow, Removal of Radon from Water Supplies, *J. Environ. Eng.*, 111(4), 511-527, August 1985.

Lo86 — Lowry, J. D. and E. Moreau, Removal of Radon and Uranium from a Water Supply, in *Environmental Engineering: Proceedings of the 1986 Speciality Conference* (Cincinnati, OH), pp. 264-270, American Society of Civil Engineers, New York, July 1986.

Lo87a — Lowry, J. D., Domestic Water: Radon Measurement and Control, in Reducing Radon in Structures: Student Manual, prepared for EPA Radon Reduction Training Course, January 1987.

Lo87b — Lowry, J. D., Lowry Engineering, Inc., Thorndike, ME, personal communication, June 1987.

Lo87c — Lowry, J. D., W. F. Brutsaert, T. McEnerney and C. Molk, Point of Entry Removal of Radon from Drinking Water, *J. Am. Water Works Assoc.* 79(4): 162-169, 1987.

Lo87d — Lowry, J. D. and S. D. Lowry, Modeling Point-of-Entry Radon Removal by GAC, *J. Am. Water Works Assoc.* 79(10): 85-88, 1987.

Ma82 — Martonen, T. B., K. A. Bell, R. F. Phalen, A. J. Wilson and A. Ho, Growth Rate Measurements and Deposition Modeling of Hygroscopic Aerosols in Human Tracheobronchial Models, *Ann. Occup. Hyg.*, 26:93-108, 1982.

Ma83 — Martonen, T. B., Measurement of Particle Dose Distribution in a Model of a Human Larynx and Tracheobronchial Tree, *J. Aerosol Sci.*, 14:11-22, 1983.

Ma87 — Matthews, T. G., Oak Ridge National Laboratory, Oak Ridge, TN, personal communication regarding radon mitigation testing in seven New Jersey houses under Interagency Agreement No. DW89932018-01-0 between EPA and the U. S. Department of Energy, July 21, 1987.

Mi87 — Michaels, L.D., T. Brennan, A. Viner, A. Mattes and W. Turner, Development and Demonstration of Indoor Radon Reduction Measures for 10 Homes in Clinton, New Jersey, prepared for U.S. Environmental Protection Agency by Research Triangle Institute, EPA-600/8-87-027 (NTIS PB87-215356), Research Triangle Park, NC, July 1987.

Na81 — Nazaroff, W. W., M. L. Boegel, C. D. Hollowell and G. D. Roseme, The Use of Mechanical Ventilation with Heat Recovery for Controlling Radon and Radon-Daughter Concentrations in Houses, *Atmos. Environ.* 15: 263-270, 1981.

Na83 — Nazaroff, W. W. and S. M. Doyle, Radon Entry into Houses Having a Crawl Space, Lawrence Berkeley Laboratory, LBL-16637, 1983.

Na85a — 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.

Na85b — Nazaroff, W. W., H. Feustal, A. V. Nero, K. L. Revzan and D. T. Grimsrud, Radon Transport into a Detached One-Story House with a Basement, *Atmos. Environ.*, 19(1) 31-46, 1985.

Nag85 — Nagda, N. L., M. D. Koontz and H. E. Rector, Energy Use, Infiltration, and Indoor Air Quality in Tight, Well-Insulated Residences, prepared for Electric Power Research Institute by Geomet Technologies, Inc., EPRI EA/EM-4117, June 1985.

NAS81 — National Academy of Sciences, *Indoor Pollutants*, National Academy Press, Washington, DC, 1981.

NCAT83 — National Center for Appropriate Technology, Introducing Supplemental Combustion Air to Gas-Fired Home Appliances, prepared for U. S. Department of Energy, DOE/CE/15095-7, December 1983.

NCAT84 — National Center for Appropriate Technology, Heat Recovery Ventilation for Housing, prepared for U. S. Department of Energy, DOE/CE/15095-9, March 1984.

Ne85 — Nero, A. V., M. B. Schwehr, W. W. Nazaroff and K. L. Revzan, Distribution of Airborne Radon-222 Concentrations in U. S. Homes, Lawrence Berkeley Laboratory, Report LBL-18274, July 1985.

Ni85 — Nitschke, I. A., G. W. Traynor, J. B. Wadach, M. E. Clarkin and W. A. Clarke, Indoor Air Quality, Infiltration and Ventilation in Residential Buildings, prepared for New York State Energy Research and Development Authority and Niagara Mohawk Power Corporation, NYSERDA Report 85-10, March 1985.

Of82 — Offermann, F. J., J. B. Dickinson, W. J. Fisk, D. T. Grimsrud, C. D. Hollowell, D. L. Krinkel, G. D. Roseme, R. M. Desmond, J. A. Defrees and M. C. Lints, Residential Air Leakage and Indoor Air Quality in Rochester, NY, Lawrence Berkeley Laboratory, Report LBL-13100 (and Report NY-SERDA-82-21), 1982.

Of84 — Offermann, F. J., R. G. Sextro, W. J. Fisk, W. W. Nazaroff, A. V. Nero, K. L. Revzan and J. Yater, Control of Respirable Particles and Radon Progeny with Portable Air Cleaners, Lawrence Berkeley Laboratory, Report LBL-16659, 1984.

Os87a — 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.

Os87b — Osborne, M. C., Four Common Diagnostic Problems that Inhibit Radon Mitigation, *JAPCA*, 37(5): 604-606, May 1987.

Pa79 — Partridge, J. E., T. R. Horton and E. L. Sensintaffer, A Study of Radon-222 Released from

Water During Typical Household Activities, U. S. Environmental Protection Agency, Technical Note ORP/EERF-79-1, Montgomery, AL, 1979.

PDER85 — Pennsylvania Department of Environmental Resources, General Remedial Action Details for Radon Gas Mitigation, May 1985.

PSC85 — PSC Water Products, Inc., VOC-OUT Well Water Aeration System Owners Manual, King of Prussia, PA, February 1985.

Pu87 — Puskin, J. S. and N. S. Nelson, Office of Radiation Programs, U. S. Environmental Protection Agency, Washington, D.C., personal communication, September 1987.

Re87 — Reid, B., Retrotec USA, Inc., Indianapolis, IN, personal communication, April 1987.

Ro81 — Rost, K. L., Report on Spray Aeration, prepared for Maine Department of Human Services, November 1981.

Sa84 — Sachs, H. M. and T. L. Hernandez, Residential Radon Control by Subslab Ventilation, presented at 77th Annual Meeting of the Air Pollution Control Association, San Francisco, CA, June 24-29, 1984.

Sa87a — Saum, D. and M. Messing, Guaranteed Radon Remediation through Simplified Diagnostics, presented by INFILTEC Radon Control Services at the Radon Diagnostics Workshop sponsored by EPA at Princeton University, Princeton, NJ, April 13-14, 1987.

Sa87b — Saum, D., INFILTEC Radon Control Services, Falls Church, VA, personal communication, June 1987.

Sc83 — Scott, A. G. and W. O. Findlay, Demonstration of Remedial Techniques Against Radon in Houses on Florida Phosphate Lands, EPA 520/5-83-009 (NTIS PB84-156157), U. S. Environmental Protection Agency, July 1983.

Sc86a — Scott, A. G., American ATCON, Wilmington, DE, personal communication, February 26, 1986.

Sc86b — Scott, A. G., unpublished data from House 30 under EPA Contract 68-02-4203, May 1986.

Sc86c — Scott, A. G., unpublished data from Houses 2A and 30 under EPA Contract 68-02-4203, November-December 1986.

Sc86d — Scott, A. G., American ATCON, unpublished data from Houses 9A and 12 under EPA Contract 68-02-4203, February 1986.

Sc87a — Scott, A. G., unpublished data from House 31 under EPA Contract 68-02-4203, January 1987.

Sc87b — Scott, A. G., American ATCON, unpublished data from House 29 under EPA Contract 68-02-4203, February 1987.

Sc87c — Scott, A. G., American ATCON, unpublished data from House 20 under EPA Contract 68-02-4203, March-April 1987.

Sc87d — Scott, A. G., American ATCON, unpublished data from Houses 39 and 40 under EPA Contract 68-02-4203, June 1987.

Sc87e — Scott, A. G., American ATCON, Inc., Wilmington, DE, personal communication, July 1987.

SCBR83 — Swedish Council of Building Research, Air Infiltration Control in Housing: A Guide to International Practice, prepared for the International Energy Agency, Stockholm, Sweden, 1983.

Se87 — Sextro, R. G., Lawrence Berkeley Laboratory, Berkeley, CA, personal communication regarding radon mitigation testing in seven New Jersey houses under Interagency Agreement DW89930801-01-0 between EPA and the U. S. Department of Energy, June 1987.

Sh86 — Sherman, M. H., Infiltration Degree-Days: A Statistic for Quantifying Infiltration-Related Climate, presented at the ASHRAE Semi-Annual Meeting, Portland, OR, June 1986.

Si87 — Simon, R., Barto, PA, personal communication, April 13, 1987.

Ta83 — Tappan, J. T., Mitigation Methods for Natural Radioactivity Associated with Energy Efficient Structures, presented at National Conference on Environmental Engineering, Boulder, CO, July 1983.

Ta85a — Tappan, J. T., Radon Mitigation Remedial Action Demonstration at the Watras Residence, Report to Philadelphia Electric Co. by Arix Corp., June 1985.

Ta85b — Tappan, J. T., Indoor Radon and Engineering Assessment of Residential Structures Located in the Reading Prong Area, prepared for the Pennsylvania Department of Environmental Resources by Arix Corp., March 1985.

Ta86 — Tappan, J. T., Radon Mitigation Seminar, NJ Department of Community Affairs, March 1986.

Ta87 — Tappan, J. T., Arix Corporation, Grand Junction, CO, personal communication, June 1987.

Tat87 — Tatsch, C. E., Research Triangle Institute, Research Triangle Park, NC, personal communication, April 1987.

Tu83 — Turiel, I., W. J. Fisk and M. Seedall, Energy Savings and Cost-Effectiveness of Heat Exchanger Use as an Indoor Air Quality Mitigation Measure in the BPA Weatherization Program, *Energy* 8(5): 323-335, 1983.

Tu86 — Turk, B. H., R. J. Prill, W. J. Fisk, D. T. Grimsrud, B. A. Moed and R. G. Sextro, Radon and Remedial Action in Spokane River Valley Residences: An Interim Report, presented at the 79th Annual Meeting of the Air Pollution Control Association, Minneapolis, MN, June 1986.

Tu87a — Turk, B. H., J. Harrison, R. J. Prill and R. G. Sextro, Interim Report on Diagnostic Procedures for Radon Control, prepared for U. S. Environmental Protection Agency by Lawrence Berkeley Laboratory, in preparation.

Tu87b — Turk, B. H., Lawrence Berkeley Laboratory, Berkeley, CA, personal communication, May 1987.

Vi79 — Vivyurka, A., Assessment of Subfloor Ventilation Systems, presented at the Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, Brancroft, Ontario, March 12-14, 1979.

We86 — Wellford, B. W., unpublished data from House 8 of the NuTone/ Airxchange HRV radon reduction demonstration project, June 1986.

We87 — Wellford, B. W., Airxchange, Inc., Rockland, MA, personal communication, July 1987.

Appendix A

Summary of Sealing Results for Houses in Elliot Lake, Ontario

Table A-1. Key to Remedial Actions Performed at Elliot Lake, Ontario, During 1978

Fix Number	Description	Number of Times Performed
1	Replace floor drain	60
1.1	Replace drained collection pit	9
2	Replace sump	12
2.1	Replace soaking pit	4
3	Close wall-floor joint	27
4	Close cracks and openings through poured concrete surfaces	31
5	Seal exterior walls	0
6	Cover exposed earth in crawl spaces	3
7	Cover exposed rock in basement	6
8	Coat masonry walls (interior)	1
9	Fill concrete block walls	1

This key applies for Tables A-2 and A-3.
Reference: DSMA79

Table A-2. 1978 Results From Remedial Actions at Elliot Lake: Houses Which Complied* After Stage I Work

House Number	Contract Number	Fix Number†											Estimated Annual Average (mWL)	
		1	1.1	2	2.1	3	4	5	6	7	8	9	Before	After
1	0	x				x	x						29	7
7	0	x				x	x						29	11
10	2					x	x						61	11
12	0	x											62	7
17	2	x											24	7
18	0	x											78	10
19	0	x				x							54	2
20	2	x											31	7
22	0	x				x	x						25	13
23	1	x											50	8
25	1			x									33	12
27	1		x				x			x			44	8
31	0	x											D	7
32	0	x				x							35	7
34	0	x											D	7
39	0	x				x							28	7
40	1	x											D	3
44	1			x									31	9
45	3	x											24	13
52	2	x	x			x	x						39	12
53	0			x									D	3
55	1	x											21	6
57	1	x											33	6
65	1					x	x						38	14
66	2	x											21	9
70	0			x									32	5
72	1	x											37	4
73	3	x					x						21	15
80	1			x									29	8
83	0	x											D	4
87	2	x											D	9
89	2	x				x	x						24	8
91	0	x											D	4
92	2	x											34	9
94	0	x											26	5
96	0	x			x	x							22	16
97	0	x					x						D	6
99	3	x					x						25	8
104	0			x									36	8
109	1	x											21	7
110	1	x											D	4
115	0	x											35	13
123	3	x											28	9
128	0				x								23	9
129	1	x											47	9
136	2	x											44	13
137	2	x					x						32	6
138	2	x											28	4
207	3	x											26	9
218	2	x											30	11
226	3	x											40	14
266	3	x			x		x						22	14
384	3	x					x						43	7
390	3	x											27	15
426	3			x			x						32	9
586	3	x											30	9
597	3						x						31	11

*Compliance for this project is defined as achieving an estimated annual average radon concentration less than 20 mWL.

†The key to the remedial actions is given in Table A-1.

NOTE: D indicates that the house was fixed as part of the remedial demonstration program. The annual average was believed to be greater than 20 mWL before the remedial work was carried out, but measurements were made over too short a period to properly estimate the annual average.

Reference: DSMA79

Table A-3. **1978 Results From Remedial Actions at Elliot Lake: Houses Which Complied* After Stage II Work**

House Number	Contract Number	Fix Number†											Estimated Annual Average (mWL)	
		1	1.1	2	2.1	3	4	5	6	7	8	9	Before	After
4	1/0					x	x			x	x		112	14
11	1/0	x	x			x			x	x			30	18
30	2/0	x				x	x						60	17
121	1/0	x					x						21	2
415	3/0	x				x							27	18
429	3/0			x		x	x			x			86	13
596	2/3/0	x				x	x						32	3

Total number of houses: 7
*Compliance for this project is defined as achieving an estimated annual average radon concentration less than 20 mWL.
†The key to the remedial actions is given in Table A-1.
Reference: DSMA79

Table A-4. **Key to Remedial Actions Performed at Elliot Lake, Ontario, During 1979**

Fix Number	Description	Number of Times Performed
1	Water-trap weeping tile connected to floor drain	22
2	Water-trap weeping tile connected to sump	8
3	Close wall-floor joint	15
4	Close cracks and openings through poured concrete surfaces	18
5	Seal exterior surface of basement walls	3
6	Cover exposed earth in basements	0
7	Cover exposed rock in basements	3
8	Seal interior surface of basement walls	0
9	Fill concrete block walls with cement grout	4
10	Remove radioactive concrete or fill	3
11	Place shielding over active concrete	0
12	Install fan for improved ventilation	1

This key applies for Tables A-5 and A-6.
Reference: DSMA80

Table A-5. **1979 Results From Remedial Actions at Elliot Lake: Houses Which Complied* After Stage I Work**

House Number	Contract Number	Remedial Work† (Fix Number)	Estimated Annual Average (mWL)	
			Before	After
13	4	1,3	21	5
28	4	1	26	7
54	4	1,4	54	15
60	4	1,4	20	4
114	0	1	23	5
116	0	1	28	7
122	3	1,3,4	32	17
139	5	1,2,3,4,10	44	4
206	4	1	21	5
222	0	1	20	10
268	0	1,3,4	29	12
420	3	3,4	31	15
436	5	5	56	7
437	5	5	48	9
488	6	1,3,4,10	49	7
580	4	3,4,12	38	5
600	4	2,4	27	10
830	4	1	43	5
833	4	1	26	6
860	4	1	36	5
878	5	1	35	18
885	0	5	23	2

Total number of houses: 22
*Compliance for this project is defined as achieving an estimated annual average radon concentration less than 20 mWL.
†The key to the remedial actions is given in Table A-4.
Reference: DSMA80

Table A-6. **1979 Results From Remedial Actions at Elliot Lake: Houses Which Complied* After Stage II Work**

House Number	Contract Number	Remedial Work† (Fix Number)	Estimated Annual Average (mWL)	
			Before	After
14	1/4/5	1,2,3,4,7	53	13
29	0/5	3	94	5
35	2/0	3,10	24	13
38	0/0	2,4,9	41	7
43	4/4	2,4,9	21	13
50	0/1	1,3,4,7	43	15
64	1/2/3	1,3,7	32	4
67	0/3	1,2	23	11
81	0/0	1,3,4	35	11
88	1/2/3	1,3,4	36	3
120	0/2	2,4,9	41	8
413	0/0	2,4,9	45	8
427	3/0	3,4	29	16

Total number of houses: 13
Total number of houses complying in 1979: 35
Total number of houses complying to December 31, 1979: 98
*Compliance for this project is defined as achieving an estimated annual average radon concentration less than 20 mWL.
†The key to the remedial actions is given in Table A-4.
Reference: DSMA80

Appendix B

Interim Guide to Radon Reduction in New Construction

The following EPA document has been reproduced in its entirety for the convenience of the reader. The document was prepared by the EPA's Office of Radiation Programs (ORP) in coordination with the National Association of Home Builders Research Foundation and with the assistance of the EPA's Office of Research and Development (ORD). More detailed information on radon prevention in new construction will be published as soon as results from current new construction radon projects become available.

United States
Environmental Protection
Agency

Offices of
Air and Radiation and
Research and Development
Washington DC 20460

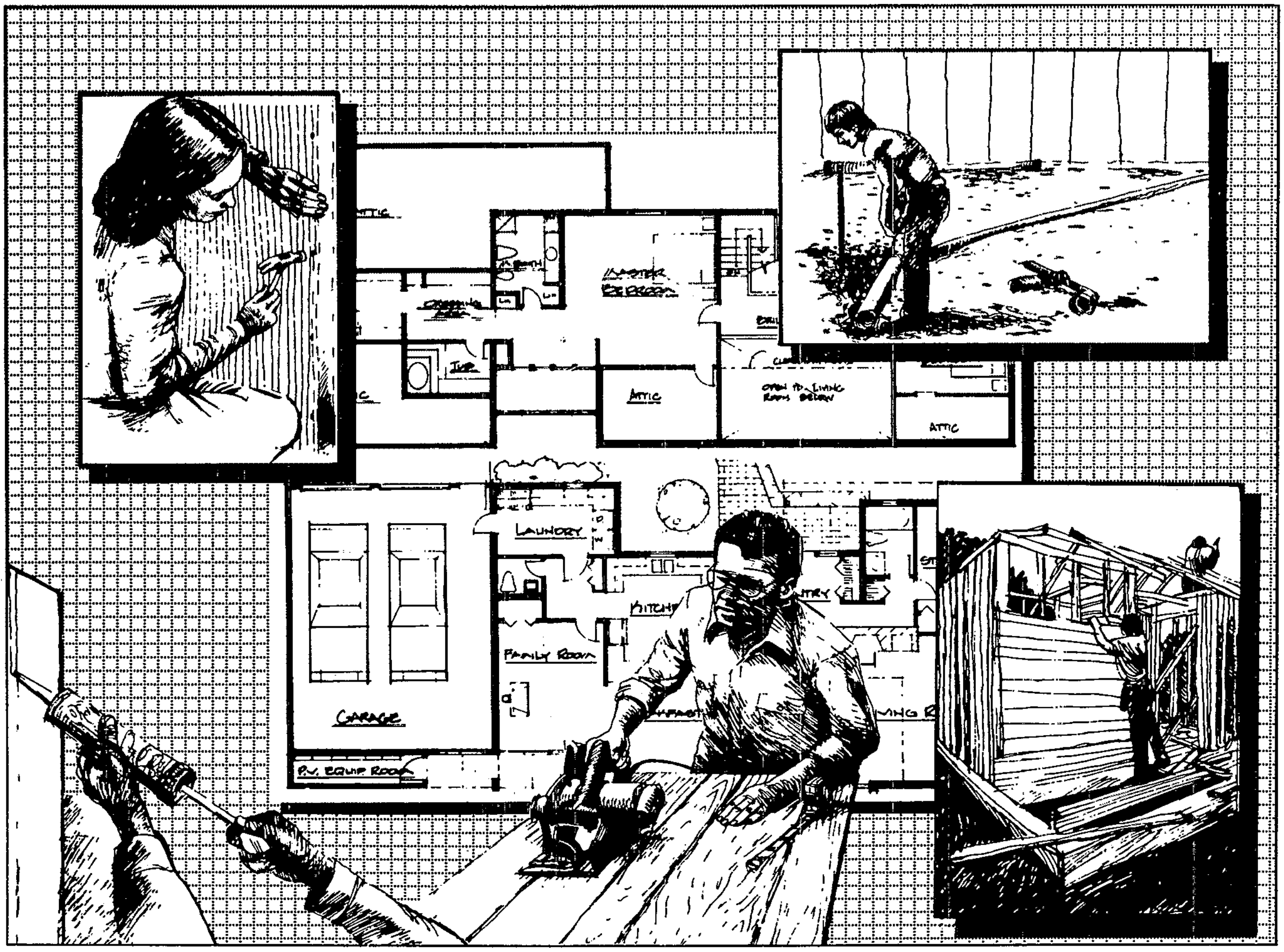
August 1987
OPA-87-009

EPA

NAHB
RESEARCH
FOUNDATION, INC.

Radon Reduction in New Construction

An Interim Guide



Comments on the information in this booklet should be addressed to:
Radon Division (ANR-464)
Office of Radiation Programs
U.S. Environmental Protection Agency
Washington, D.C. 20460

Introduction

The U.S. Environmental Protection Agency (EPA) is concerned about the increased risk of developing lung cancer faced by persons exposed to radon in their homes. Because many families already face the problem, early emphasis was placed on identifying the danger in existing homes and developing cost-effective methods to make such housing safer. Based on this early research, EPA published three documents in 1986: *A Citizen's Guide to Radon: What It Is and What To Do About It*, *Radon Reduction Methods: A Homeowner's Guide*, and a more detailed manual, *Radon Reduction Techniques for Detached Houses: Technical Guidance*. These documents were designed to help homeowners determine if they have a radon problem and to present information on how to reduce elevated radon levels in their homes.

This pamphlet is the next step in attempting to reduce the radon hazard in homes. It is designed to provide radon information for those involved in new construction and to introduce methods that can be used during construction to minimize radon entry and facilitate its removal after construction is complete. If there is concern about the potential for elevated indoor radon levels, it may be prudent to use these construction techniques in new homes. The "Techniques for Site Evaluation" section of this pamphlet outlines several methods for assessing the potential for elevated indoor radon levels. The decision to incorporate these construction techniques rests solely with the builder or homeowner.

In addition to extensive internal EPA review, this pamphlet has been developed in coordination with the National Association of Home Builders Research Foundation, Inc. (NAHB-RF) a not for profit organization, and other federal agencies including the Department of Energy (DOE), Housing and Urban Development (HUD), United States Geological Survey (USGS), and the National Bureau of Standards (NBS). It also reflects comments solicited from a broad spectrum of individual experts in home construction and related industries.

It is potentially more cost-effective to build a home that resists radon entry than to remedy a radon problem after construction. The construction methods suggested in this pamphlet represent current knowledge and experience gained primarily from radon reduction tests and demonstrations on existing homes. Field tests are underway to develop and refine the most cost-effective new-home construction techniques. After completion of these field tests, a more detailed "Technical Guidance" manual will be published to expand and revise, as necessary, the interim guidance presented in this pamphlet. Accordingly, *this Interim Guide should not be referenced in codes and standards documents.*

Radon Facts

Radon is a colorless, odorless, tasteless, radioactive gas that occurs naturally in soil gas, underground water, and outdoor air. It exists at various levels throughout the United States. Prolonged exposure to elevated concentrations of radon decay products has been associated with increases in the risk of lung cancer. An elevated concentration is defined as being at or above the EPA suggested guidelines of 4 pCi/l or 0.02 WL average annual exposure.* Although exposures below this level do present some risk of lung cancer, reductions to lower levels may be difficult, and sometimes impossible to achieve.

Soil gas entering homes through exposed soil in crawl spaces, through cracks and openings in slab-on-grade floors, and through below-grade walls and floors is the primary source of elevated radon levels (Figure 1). Radon in outside air is diluted to such low concentrations that it does not present a health hazard. In some small public and private well-water supplies, radon is a hazard primarily to the extent that it contributes to indoor radon gas concentrations. When water is heated and agitated (aerated), as in a shower or washing machine, it will give off small** quantities of radon.

Radon moves through the small spaces that exist in all soils. The speed of movement depends on the permeability of the soil and the presence of a driving force caused when the pressure inside a home is lower than the pressure outside or in the surrounding and underlying soil. A lower pressure inside a home may result from:

- Heated air rising, which causes a stack effect.
- Wind blowing past a home, which causes a down-wind draft or Venturi effect.
- Air being used by fireplaces and wood stoves, which causes a vacuum effect.
- Air being vented to the outside by clothes dryers and exhaust fans in bathrooms, kitchens, or attics, which also causes a vacuum effect.

In homes, where a partial vacuum exists, outdoor air and soil gas are driven into the home.

New Construction Principles

The facts just discussed form the basis for the following new-construction principles:

- Homes should be designed and constructed to minimize pathways for soil gas to enter.
- Homes should be designed and built to maintain a neutral pressure differential between indoors and outdoors.
- Features can also be incorporated during construction that will facilitate radon removal after completion of the home if prevention techniques prove to be inadequate.

The following techniques for site evaluation and construction are based on these principles.

Techniques for Site Evaluation

The first step in building new radon-resistant homes is to determine, to the degree possible, the potential for radon problems at the building site. At this time, there are no standard soil tests or specific

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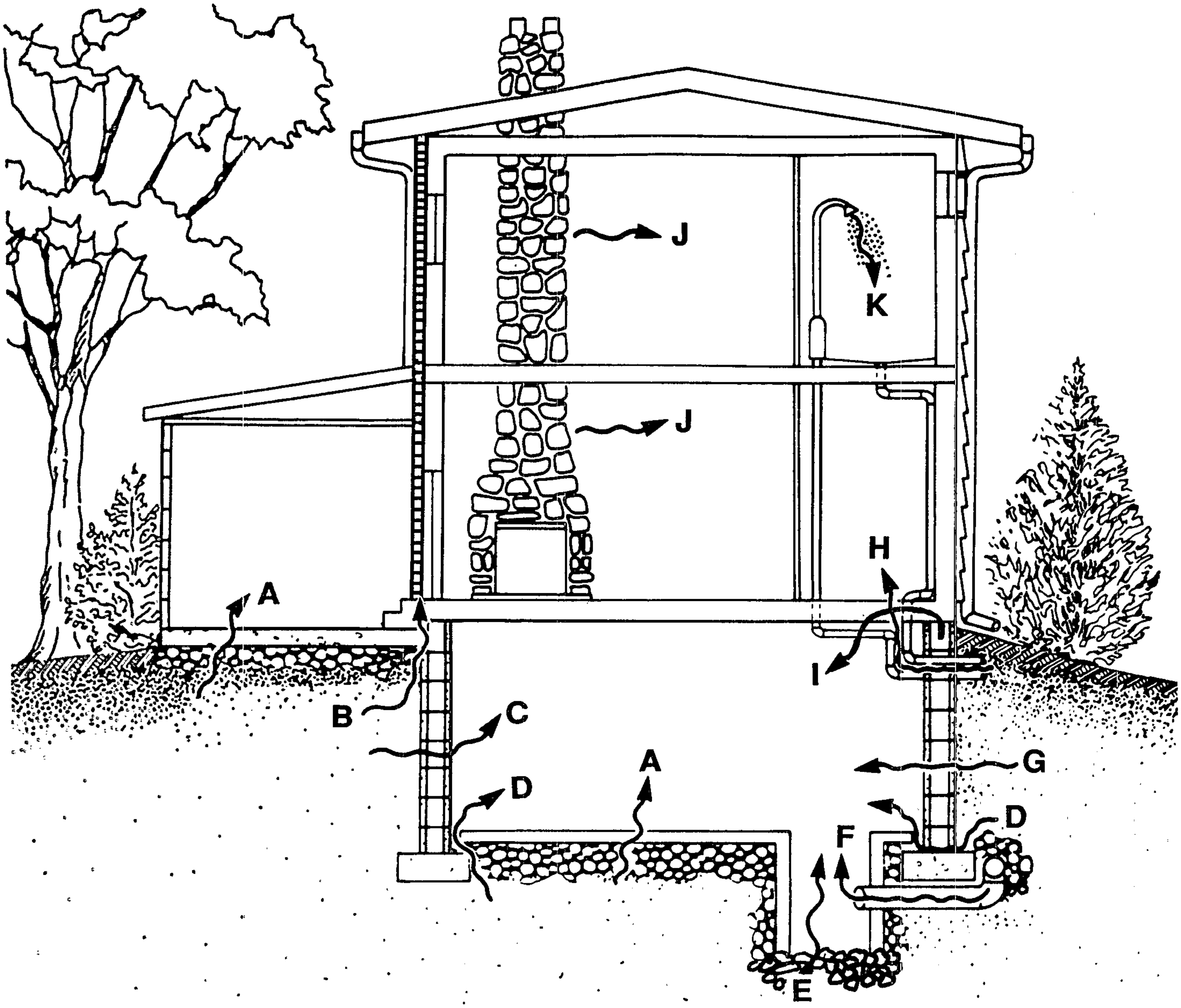
* *pCi/l, the abbreviation for pico Curies per liter, is used as a radiation unit of measure for radon. The prefix "pico" means a multiplication factor of 1 trillionth. A Curie is a commonly used measurement of radioactivity. WL, the abbreviation for Working Level, is used as a radiation unit of measure for the decay products of radon. The relationship between the two terms is generally 200 pCi/l = 1 WL.*

** *The generally accepted rule of thumb for emanation of radon gas from water is: 10,000 pCi/l of radon in water will normally produce a concentration of about 1 pCi/l of radon in indoor air.*



MAJOR RADON ENTRY ROUTES

A. Cracks in concrete slabs
B. Spaces behind brick veneer walls
   that rest on uncapped hollow-block foundation
C. Pores and cracks in concrete blocks
D. Floor-wall joints
E. Exposed soil, as in a sump
F. Weeping (drain) tile, if drained to open sump
G. Mortar joints
H. Loose fitting pipe penetrations
I. Open tops of block walls
J. Building materials such as some rock
K. Water (from some wells)

Figure 1

standards for correlating the results of soil tests at a building site with subsequent indoor radon levels. The variety of geological conditions in the United States will probably continue to preclude establishment of any all-inclusive, nationwide standards for such correlation. We can, however, estimate the radon potential at a building site based on factors other than soil tests. If the answer to any of the following questions is yes, radon problems might be anticipated and radon reduction features should be considered for inclusion in construction plans.

- Have existing homes in the same geologic area experienced elevated radon levels? ("Same geologic area" is defined as an area having similar rock and soil composition characteristics.) State or regional EPA offices may be able to assist in obtaining this information.
- What are the general characteristics of the soil? State and local geological or agricultural offices can normally help in providing answers to the following questions on soil:
  —Is the soil derived from underlying rock that normally contains above-average concentrations of uranium or radium, e.g., some granites, black shales, phosphates or phosphate limestones?
  —Is the permeability of the soil and underlying rock conducive to the flow of radon gas? Note that soil permeability (influenced by grain size, porosity, and moisture content) and the degree to which underlying and adjacent rock structures are stable or fractured can significantly affect the amount of radon that can flow toward and into a home.
- If the source of water to the site is going to be a local or onsite well, have excessive levels of radon been detected in other wells within the same geologic area? (Levels measured above 40,000 pCi/l of water could alone produce indoor radon concentrations of about 4 pCi/l or above. Such levels are considered excessive.) State or local health agencies, departments of natural resources, or environmental protection offices may be able to assist in providing this information. Testing well water for radon before the home is built could provide an additional indication of a potential radon problem. If excessive radon levels are confirmed, a granular activated-carbon filtration system or an aeration system might be designed into the plumbing plan.

Construction Techniques

Some of the radon prevention techniques discussed below are common building practices in many areas and, in any case, are less costly if accomplished during construction. Costs to retrofit existing homes with the same features would be significantly higher. Although these construction techniques do not require any fundamental changes in building design, there is a continuing need for quality control, supervision, and more careful attention to certain construction details. Construction techniques for minimizing radon entry can be grouped into two basic categories:

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

Typically, the techniques in both categories are used in conjunction with each other.

Methods to Reduce Pathways for Radon Entry (Figure 2)

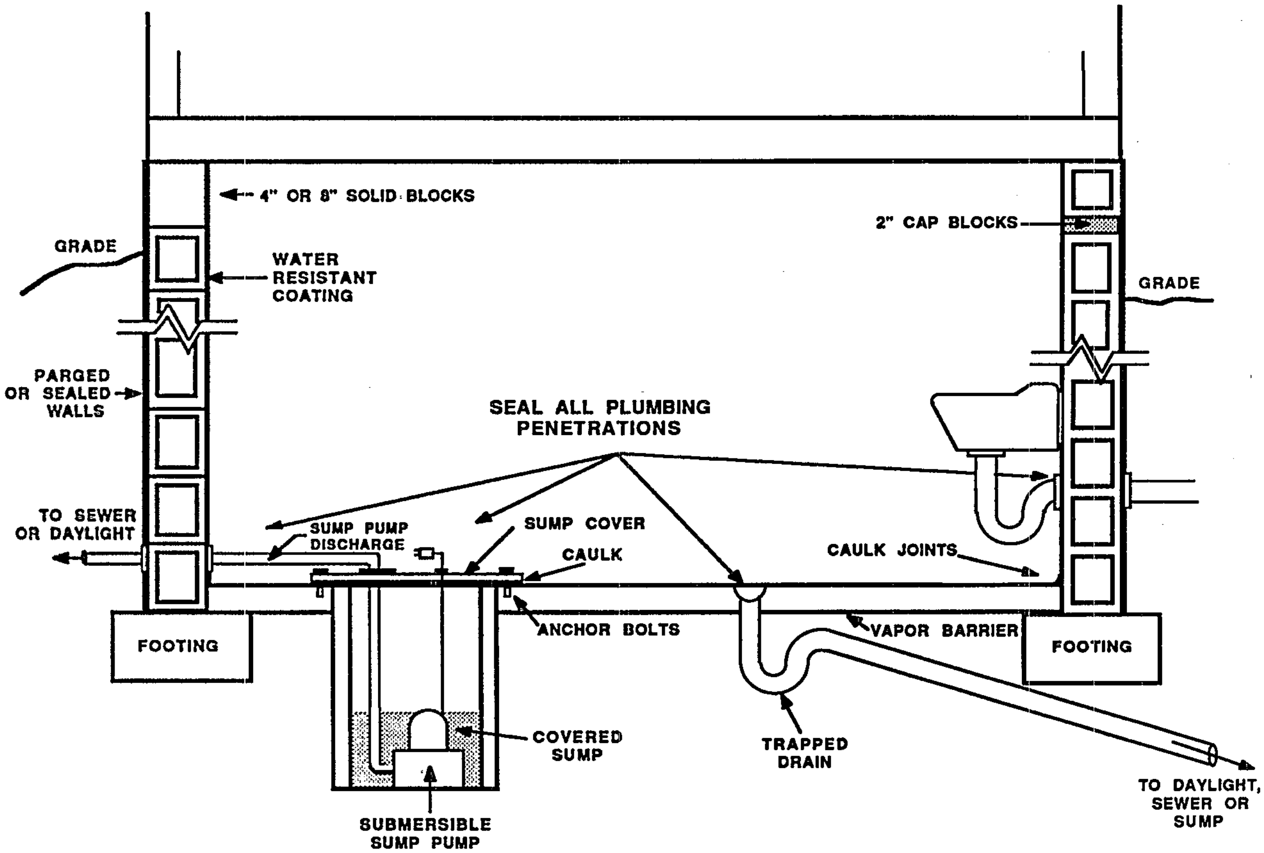
In Basement and Slab-on-Grade Construction:

- Place a 6-mil polyethylene vapor barrier under the slab. Overlap joints in the barrier 12 inches. Penetrations of the barrier by plumbing should be sealed or taped, and care should be taken to avoid puncturing the barrier when pouring the slab.
- To minimize shrinkage and cracks in slabs, use recommended water content in concrete mix and keep the slab covered and damp for several days after the pour.
- To help reduce major floor cracks, ensure that steel reinforcing mesh, if used, is imbedded in (and not under) the slab. Reducing major cracks in footings, block foundation, and poured-concrete walls will reduce the rate of radon entry. Radon can, however, enter homes through even the smallest of cracks in concrete slabs and walls if a driving pressure is applied to those surfaces.
- The most common radon-entry pathways are inside perimeter floor/wall joints and any control joints between separately poured slab sections. To reduce radon entry through these joints, install a common flexible expansion joint material around the perimeter of the slab and between any slab sections. After the slab has cured for several days, remove or depress the top 1/2 inch or so of this material and fill the gap with a good quality, non-cracking polyurethane or similar caulk. Similar techniques for sealing these joints may also be used.
- In some areas, basement slabs are poured with a French Drain channel around the slab perimeter. To be effective, this moisture control technique requires that the floor/wall joint be open to permit water to seep out into the sub-slab area. To reduce radon entry through such open joints, it may be necessary to install a perforated drain pipe loop under the slab, adjacent to the footing and imbedded in aggregate, and to tie this pipe into a sub-slab ventilation system to draw radon gas away from the French Drain joint (Figure 4). For additional information on water control techniques, refer to National Association of Home Builders (NAHB) publication *Basement Water Leakage: Causes, Prevention, and Correction.*
- When building slab-on-grade homes in warm climates, pour the foundation and slab as a single (monolithic) unit. If properly insulated below grade-level, shallow foundations and slabs can also be poured as a single unit in cold climates.
- Remove all grade stakes and screed boards and fill the holes as the slab is being finished. This will prevent future radon pathways through the slab, which might otherwise be created as imbedded wood eventually deteriorates.
- Carefully seal around all pipes and wires penetrating the slab, paying particular attention to bathtub, shower, and toilet openings around traps.
- Floor drains, if installed, should drain to daylight, a sewer, or to a sump with pump discharge. Floor drains should not be drained into a sump if such a pit will be used as part of a sub-slab ventilation system. Suction on the sump could be defeated by an open line to the floor drain.
- Sumps should be sealed at the top. In closed sumps used for sub-slab

ventilation systems, the continuous flow of moist air through the sump can cause rapid corrosion of exposed sump pump motors. For this reason, submersible-type sump pumps are recommended for closed-sump applications.

In Basement and Crawl space Construction:

- Seal or cap the tops of hollow-block foundation walls using one of the techniques shown in Figure 2.
- Carefully seal around any pipe or wire penetrations of below-grade walls.
- Exterior block walls should be parged and coated with high-quality vapor/water sealants or polyethelene films. For additional information on wall sealing, refer to NAHB publication *Basement Water Leakage: Causes, Prevention, and Correction.* Several new products for use on exterior walls are designed to provide an airway for soil gas to reach the surface outside the wall rather than being drawn through the wall. Similar materials may also be used in sub-slab ventilation applications.
- Interior surfaces of masonry foundations may be covered with a high-quality, water-resistant coating.
- Heating or air-conditioning ductwork that must be routed through a crawl space or beneath a slab should be properly taped or sealed. This is particularly important for return air ducting, which is under negative pressure. Due to difficulty in achieving permanent sealing of such ductwork, it may be advisable to redesign heating and ventilating systems to avoid ducting through sub-slab or crawl space areas, particularly in areas where elevated soil radon levels have been confirmed.
- Install air-tight seals on any doors or other openings between basements and adjoining crawl spaces.
- Seal around any ducting, pipe, or wire penetrations of walls between basements and adjoining crawl spaces, and close any openings between floor joists over the dividing wall.
- Place a 6-mil polyethelene vapor barrier on the soil in the crawl space. Use a 12-inch overlap and seal the seams between barrier sections. Seal edges to foundation walls.



METHODS TO REDUCE PATHWAYS FOR RADON ENTRY

Figure 2

Methods to Reduce the Vacuum Effect (Figure 3)

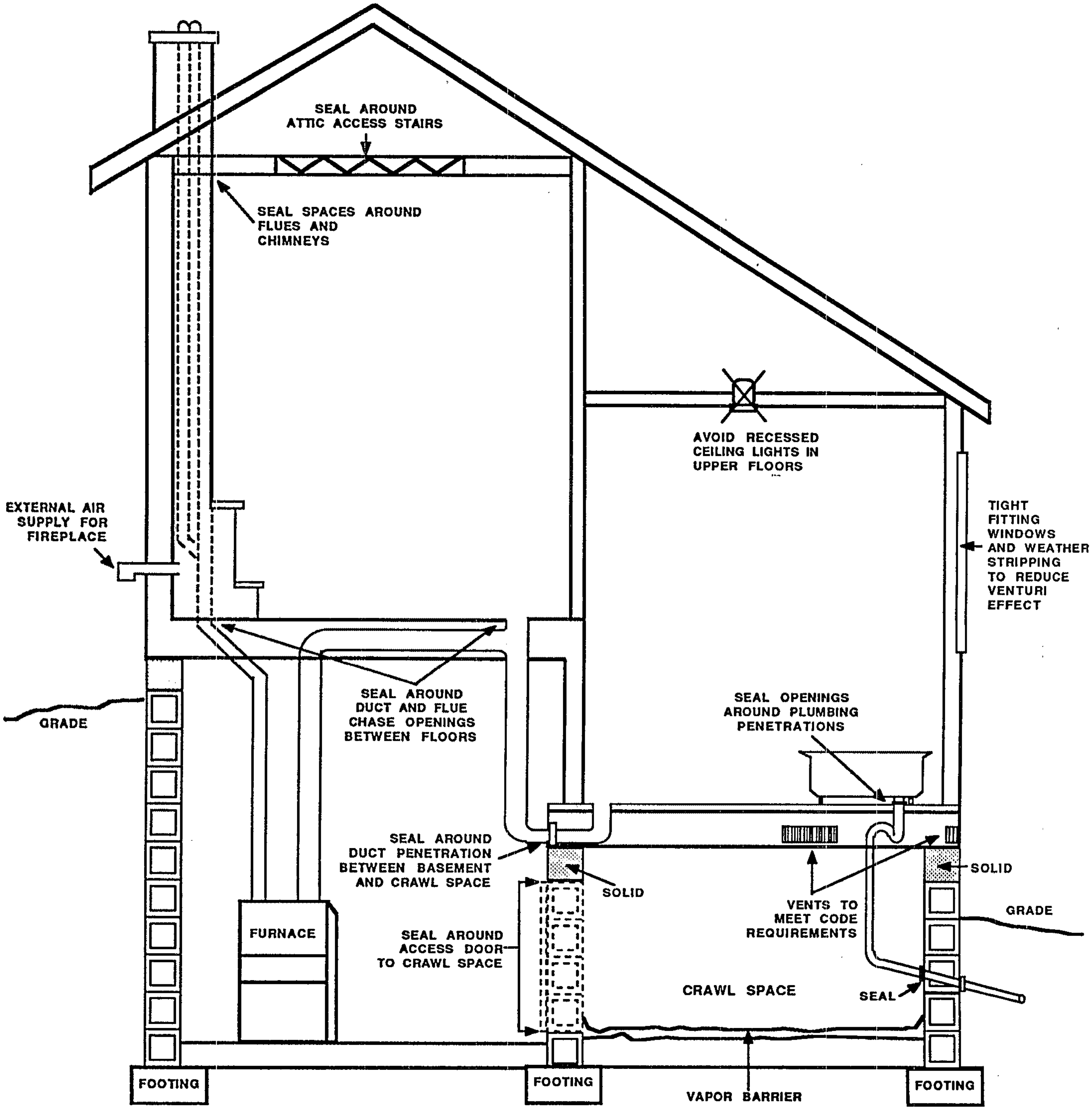
- Ensure that vents are installed in crawl space walls and are sized and located in accordance with local building practices. Adequate ventilation of crawl spaces is the best defense against radon entry in crawl space-type homes.
- Reduce air flow from the crawl space into living areas by closing and sealing any openings and penetrations of the floor over the crawlspace.
- To reduce the stack effect, close thermal bypasses such as spaces around chimney flues and plumbing chases. Attic access stairs should also be closed and sealed. (Note: Because of potential heat buildup, most codes prohibit insulating around recessed ceiling lights. Such lights should therefore be avoided in top-floor ceilings. As an alternative, use recessed ceiling lights designed to permit insulation or "hi-hat" covers and seal to minimize air leakage.)
- Install ducting to provide an external air supply for fireplace combustion.
- In areas frequently exposed to above-average winds, install extra weather sealing above the soil line to reduce depressurization caused by the Venturi effect. Such sealing will also save energy and reduce the stack effect.
- Air-to-air heat exchange systems are designed to increase ventilation and improve indoor air quality. They may also be adjusted to help neutralize any imbalance between indoor and outdoor air pressure and thus reduce the stack effect of the home. They should not, however, be relied upon as a stand-alone solution to radon reduction in new construction. (A slightly positive pressure, in the basement, may contribute to reducing radon flow into a home.)

Construction Methods That Will Facilitate Post-Construction Radon Removal (Figure 4)

Recognizing that radon prevention techniques may not always result in radon levels below the suggested guideline of 4 pCi/l average annual exposure, there are several additional construction techniques that can be used to facilitate any post-construction radon removal that may be required.

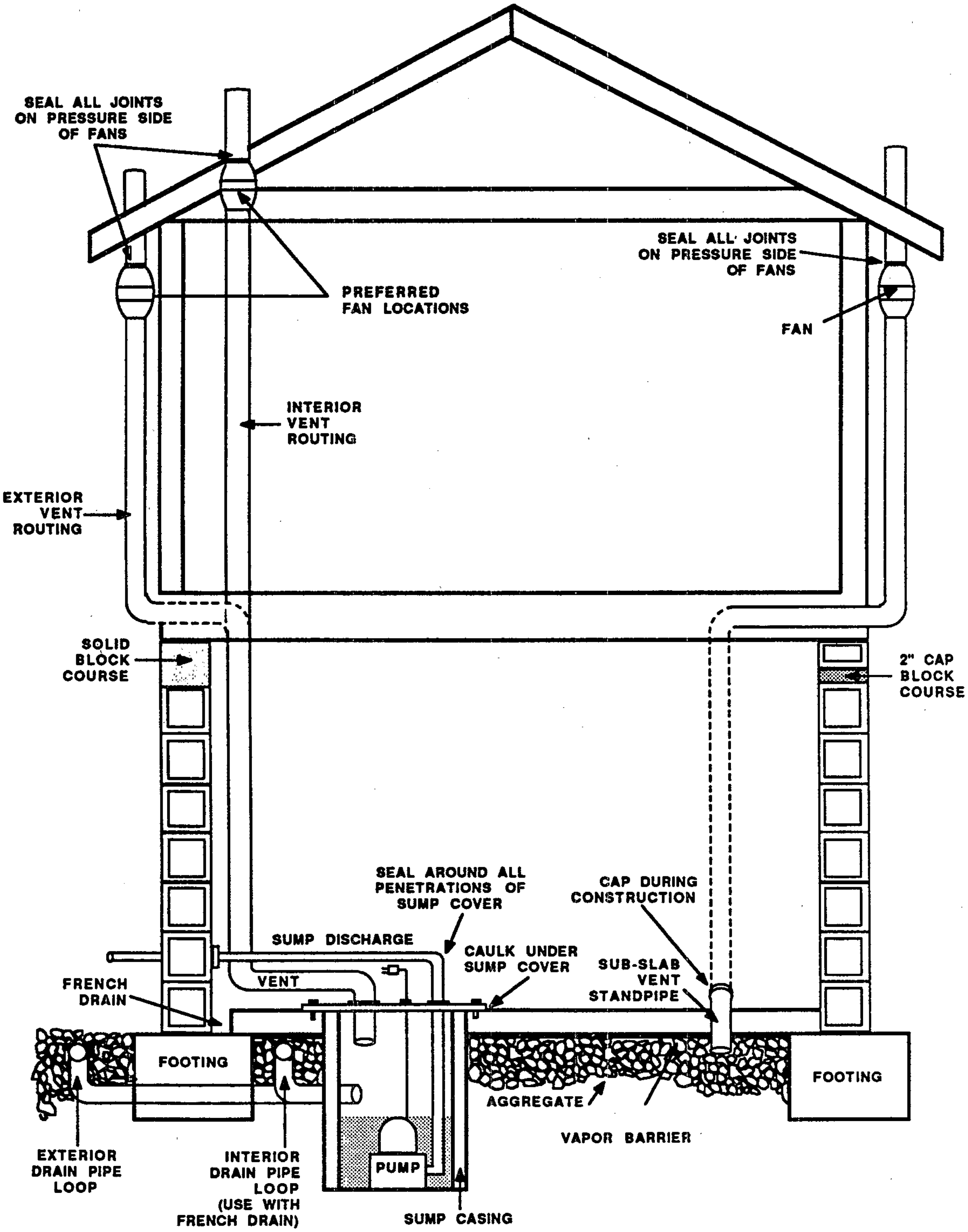
- Before pouring a slab, fill the entire sub-floor area with a layer (4 inches thick) of pea gravel or larger, clean aggregate to facilitate installation of a sub-slab ventilation system.
- Lay a continuous loop of perforated 4-inch diameter drain pipe around the inside perimeter of the foundation footing. Run the vent from this loop into the side of a closed sump that can, if necessary, be equipped with a fan-driven vent to the outside. In this configuration, the drain pipe loop can aid in water seepage control as well as radon reduction.
- As an alternative to the vented interior drain pipe loop, a similarly vented exterior loop can be laid outside the foundation footing.
- In areas where water seepage into below-grade spaces is not a problem and sump pumps are not installed, exterior or interior drain pipe loops can be stubbed-up outside the home or through the slab and can be available for use as sub-slab ventilation points if needed.
- The soil beneath a slab can also be ventilated using the following technique: Prior to pouring the slab, insert (in a vertical position) one or more short (12-inch) lengths of 4-inch minimum diameter PVC pipe into the sub-slab aggregate and cap the top end. After construction is complete, these standpipes can, if necessary, be uncapped and connected to one or more convection stacks or fan-driven vent pipes. When positioning these standpipes, choose locations permitting venting to the roof through already planned flue or plumbing chases, interior walls, or closets. In homes where flue or other chases are restricted in size or not easily accessible, it may be less expensive to go ahead—during the framing and rough-in plumbing/electric phase of construction—and complete the vent pipe hookup, temporarily terminating the vent in the attic along with an electric outlet for future fan installation. Experience has shown that in homes with higher radon levels—above 20 pCi/1—convection (passive) venting may not produce acceptable radon reductions. If lower radon levels are expected and passive venting is attempted, performance is improved by using a 6-inch diameter vent routed straight from the floor through the roof, with minimum bends.

  Drilling 4-inch holes through finished slabs for insertion of vent pipes is an alternative to this technique.
- To create the necessary convection flow, radon prevention techniques that involve passive venting normally require stacks that pass through the floors and roof. When active (fan-driven) systems are installed, venting through to the roof is still preferred. Recognizing, however, that active systems can be vented through the band joist or below-grade walls to the outside, it is considered advisable in such active systems to position the exit point of the vent pipe at or above the eave line of the roof and away from any doors or windows. This will preclude any possible recirculation of air containing concentrated radon gas back into the house.
- In homes where an active (fan-driven) sub-slab ventilation system has been installed, it may be necessary to provide make-up air to avoid back drafting.



METHODS TO REDUCE THE VACUUM EFFECT

Figure 3



METHODS TO FACILITATE POST-CONSTRUCTION RADON REMOVAL

Figure 4

Source of Information

If you would like further information or explanation on any of the points mentioned in this booklet, you should contact your State radiation protection office or home builders association.

If you have difficulty locating these offices, you may call your EPA regional office listed below. They will be happy to provide you with the name, address, and telephone number of these contacts.

STATE-EPA REGION

Alabama-4
Alaska-10
Arizona-9
Arkansas-6
California-9
Colorado-8
Connecticut-1
Delaware-3
District of Columbia-3
Florida-4
Georgia-4
Hawaii-9
Idaho-10
Illinois-5
Indiana-5
Maryland-3
Massachusetts-1
Michigan-5
Minnesota-5
Mississippi-4
Missouri-7
Montana-8
Maine-1
New York-2
North Dakota-8
Oklahoma-6
Oregon-10
Ohio-5
Pensylvania-3
Rhode Island-1
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EPA Region 5
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1445 Ross Avenue
Dallas, TX 75202
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EPA Region 7
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(913) 236-2893

EPA Region 8
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Denver, CO 80202
(303) 293-1648

EPA Region 9
215 Fremont Street
San Francisco, CA 94105
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EPA Region 10
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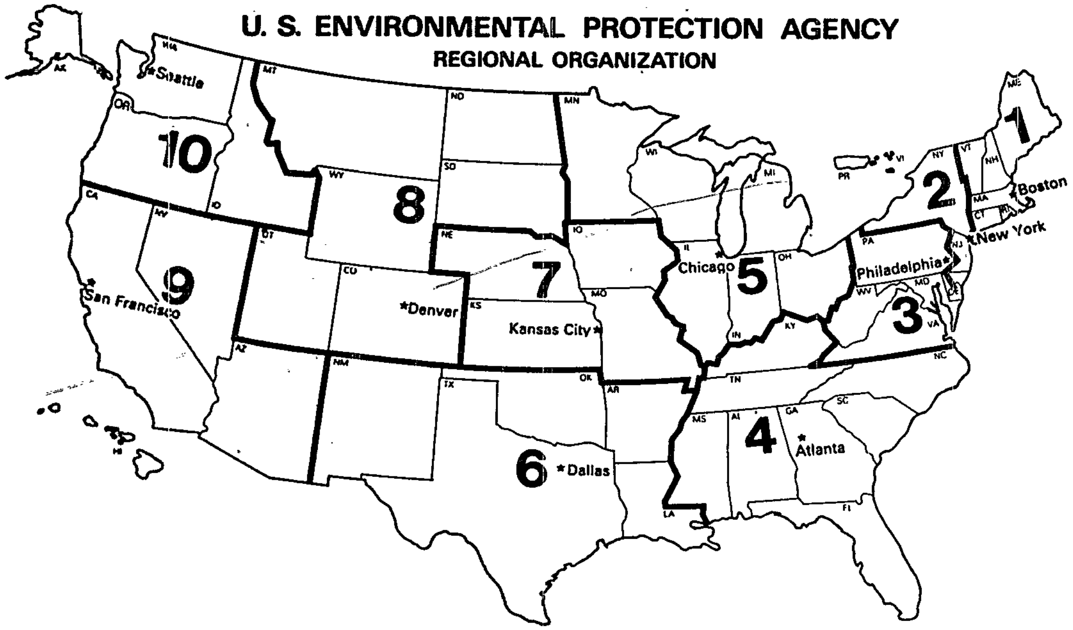

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