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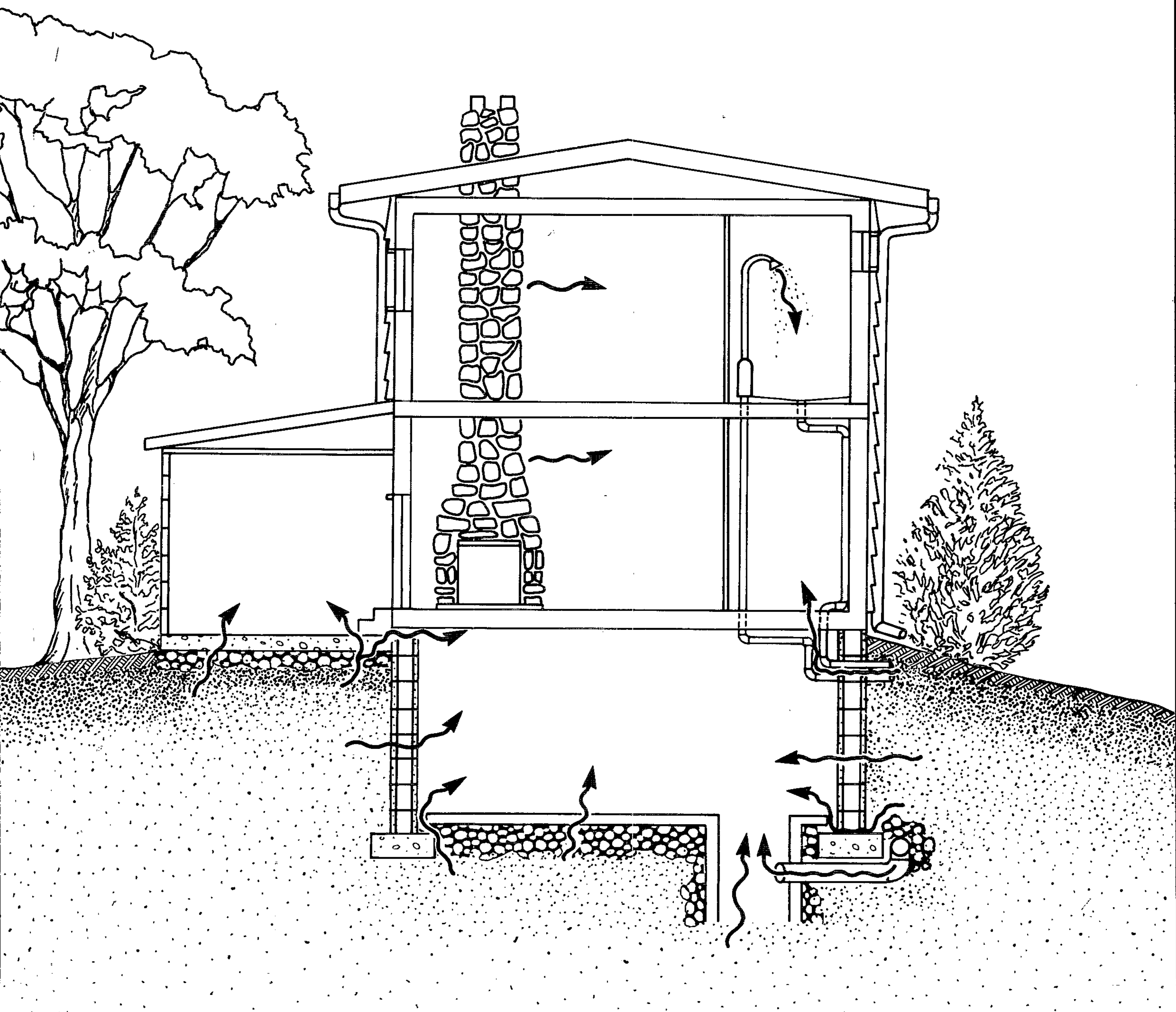
Radon Reduction Techniques for Detached Houses

Technical Guidance



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Air and Energy Engineering Research Laboratory
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This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of firms, trade names, or commercial products constitute endorsement or recommendation for use.

This document is availble to the public through the Center for Environmental Research Information, Distribution, 26 W. St. Clair, Cincinnati, OH 45268.

A brief overview of the material contained in this document is available in the booklet, "Radon Reduction Methods: A Homeowner's Guide," (OPA-86-005). For information on how to obtain a copy, check with your State radiological health program office (see Chapter 3 of this document).

FOREWORD

This document is intended to supply State radiological health officials, State environmental officials, and building contractors (and the concerned homeowners who seek their assistance) with information on how to modify houses to reduce indoor radon. This guidance is based on the results of documented tests by many research groups, with emphasis on the soil-gas removal techniques EPA tested in the Reading Prong (Pennsylvania).

Although radon mitigation is a new field, one fact is already clear: no two houses are alike. Because of subtle differences in house construction and radon source material, seemingly identical houses may require quite different approaches to controlling indoor radon.

Homeowners are cautioned against attempting installations themselves except in cases of low indoor radon levels (controllable with inexpensive methods). Much expense can be incurred before the inadequacy of a technique is evident. Thus, the services of a mitigation contractor, knowledgeable in house construction and the principles of radon entry, are usually required. Homeowners, or their contractors, may also find it advisable to seek the assistance of their State radiological health official (or environmental official, in some States) in interpreting the information presented here.

EPA's Office of Research and Development is widening the scope of its house testing as well as seeking more information on techniques that other research groups have used successfully. This publication will be revised as new information becomes available.

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ACKNOWLEDGMENTS

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We are indebted to the States of Maine, Minnesota, New Jersey, New York, Pennsylvania, and Washington, and to EPA Regions 2, 3, and 6 for their valuable comments.

Glossary

Air changes per hour (ach)—The movement of a volume of air in a given period of time; if a house has 1 air change per hour, it means that all of the air in the house will be replaced in a 1-hour period. Air changes also may be expressed in cubic feet per minute.

Alpha particle—A positively charged subatomic particle emitted during radioactive decay, indistinguishable from a helium atom nucleus and consisting of two protons and two neutrons.

Back-drafting—A condition where the normal direction of air flow through a pipe is reversed due to abnormal pressure changes at one end of the pipe. Examples include the reversal of smoke down rather than up a fireplace chimney when strong winds create a down draft, or a similar condition that may occur in a furnace (or other combustion appliance) stack or vent when the inside of a room or house becomes temporarily depressurized. Such depressurization may result in increased radon-containing soil gas being drawn into the indoor air space in response to the lowered pressure.

Barrier coating(s)—A layer of a material that acts to obstruct or prevent 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 sheetmetal or plastic channel ducts 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.

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

Contractor—A building trades professional who would work for profit to correct radon problems; a remediation expert. At the present time, training programs are underway to provide working professionals with the knowledge and experience necessary to control radon exposure problems. State radiological health offices will have lists of qualified professionals.

Crawl space—An area beneath some types of houses which are constructed so that the floor is raised slightly above the ground, leaving a crawl space between the two to allow access to utilities and other services. In contrast to slab-on-grade or basement construction houses.

Cubic feet per minute (cfm)—A measure of the volume of a substance flowing within a fixed period of time. With indoor air refers to the amount of air in cubic feet that is exchanged with outdoor air in a minute's time, or an air exchange rate.

Depressurization—A condition that occurs when the air pressure inside a house is lower than the air pressure outside. Normally houses are under slightly positive pressure. Depressurization can occur when household appliances that consume or exhaust house air, such as fireplaces or furnaces, are not supplied with enough makeup air. Radon-containing soil gas may be drawn into a house more rapidly under the depressurized condition.

Detached houses—Single family dwellings as opposed to apartments, duplexes, townhomes, 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.

Duct work—Any enclosed channel(s) or tubular passage(s), normally hidden above the ceiling, behind the walls, or under the floor for the passage of wiring or hot or cold air.

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

French drain (also 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.

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.

Header joist—Also called header plate or band 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 serves to maintain spacing between the floor joists.

Heat exchanger—A device used to transfer heat from one medium to another. Also called air-to-air heat recovery ventilators or heat recovery ventilators.

Heat recovery ventilators—Also known as air-to-air heat exchangers or heat exchangers.

Hollow-block walls, Block walls—A wall built of hollow rectangular masonry units arranged to provide an air space within the wall between the facing and backing tiers of the individual blocks. Typical construction for concrete block or cinder block foundations in detached houses.

House air—Synonymous with indoor air. That part of the atmosphere that occupies the space within the interior of a house.

Indoor air—That part of the atmosphere or air that occupies the space within the interior of a house or other building. Researchers have found that the quality of indoor air is affected by the construction materials (and other indoor activities) that make up the house, the location of the house, and the ventilation characteristics of the space.

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 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.

Makeup air—Air which is supplied directly by a small pipe to the vicinity of a combustion appliance, such as a furnace, clothes dryer, or fireplace, to replace the air that is used up in combustion or that rises out a vent due to the heat of combustion. Provision for makeup air can prevent the conditions of back-drafting and depressurization and thus prevent increased radon entry to the house.

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. Pico indicates an amount equal to one trillionth (10^{-12}) of the unit of measure.

Radionuclide—Any naturally occurring or artifically produced radioactive element or isotope.

Radon—A colorless, naturally occurring, radioactive, inert gaseous element formed by radioactive decay of radium atoms. Chemical symbol is Rn, atomic weight 222, half-life 3.82 days.

Radon progeny, Radon daughters—A term used to refer collectively to the intermediate products in the radon decay chain. Each "daughter" is an ultrafine radioactive particle that decays into another radioactive "daughter" until finally a stable nonradioactive lead molecule is formed and no further radioactivity is produced.

Riser, Trap and Riser—A riser is a vertical pipe, including pipes which allow warm air to flow from a furnace to second-story rooms or to allow sewer gas to exhaust from sewer systems to the outside air; typically not under pressure or with minimum fan (forced air) pressure. A trap is a bend (often S-shaped) in a water or ventilation system that holds water to form a barrier to gases which might otherwise rise up into the house. A trap and riser together are used to capture gas and route it to a chosen release point.

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

Slab, Slab-construction—A term used to describe a flat bed of concrete on which a house is built in some types of construction. Such houses typically do not have basements or crawl spaces.

Soakaway—A drainage device that allows water to slowly be absorbed into the soil or to drain away from the foundation of a house. The drainage water may be carried some distance away from the house to the soakaway through a pipe.

Soil gas—Those gaseous elements and compounds that occur in the small spaces between particles of the earth or soil. Rock can contain gas also. Such gases can move through or leave the soil or rock depending on changes in pressure. Radon is a gas which forms in the soil wherever radioactive decay of radium occurs.

Source strength—The intensity, power, or concentration of a chemical or action from its point of origin. In this report, refers to the general intensity of radon evolution from a specific soil- or rock-type beneath a house.

Stack effect—In houses and other buildings, the tendency toward displacement (caused by the difference in temperature) of internal heated air by unheated outside air due to the difference in density of outside and inside air. Similar to the air and gas in a duct, flue, or chimney rising when heated due to its lower density compared with that of surrounding air or gas.

Sump, Sump pump—A pit or hole in a basement designed to collect water, and from which such water is drained by means of a vertical-lift or sump pump.

Top voids, Block voids, Voids—Air space(s) created within masonry walls made of concrete block or cinder block. Top void specifically refers to the air space in the first 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.

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/Suction—Ventilation is the act of admitting fresh air into a space in order to replace stale or contaminated air, achieved by blowing air into the space. Similarly, suction represents the admission of fresh air into an interior space; however, the process is accomplished by lowering the pressure outside of the space thereby drawing the contaminated air outward.

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 (173 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*
°F	5/9(°F - 32)	°C
ft	30.48	cm
ft^2	0.09	m^2
ft^3	28.32	L
in.	2.54	cm

Section 1
Introduction

1.1 Purpose

This document provides a general review of potential indoor radon concerns and presents technical information to support the choice of techniques to reduce indoor radon concentrations where unacceptable levels are found.

1.2 Scope and Content

This technical guidance document is based on many existing sources of information and on recent U.S. Environmental Protection Agency (EPA) research experience. Used in conjunction with selected referenced reports, it provides building trade professionals and homeowners with the basis for an understanding of:

(1) The source and nature of radon emissions

(2) Common radon entry routes into houses

(3) Methods for preventing or reducing indoor radon concentrations.

Radon levels in houses can be reduced by four methods: 1) preventing the entry of radon gas into the house, 2) ventilating the air containing radon and its decay products from the structure, 3) removing the source of the radon, and 4) removing radon and/or its decay products from the indoor air. This guidance concentrates on the first two methods as they relate to radon entry from soil gas.

This document does not address the fourth method—removing radon and/or its decay products from indoor air—due to incomplete data on the effectiveness of air cleaners in reducing the amount of radiation exposure to the lung. EPA, the Department of Energy, and radiation protection groups in several countries are currently conducting research on this topic. Although air cleaners have been shown to decrease the concentrations of airborne particulates and the radon decay products attached to those particulates, the devices may not decrease the concentration of unattached decay products. Since several studies indicate that the unattached decay products result in a higher absorbed radiation dose to the lung, the overall effectiveness of air cleaners in reducing the lung dose is uncertain, and is likely to be less than the effectiveness of air cleaners in reducing particulate levels. Results of further research on this topic will be reported to the private sector and the public.

Information on the risks of exposure to radon and why radon levels should be reduced in houses can be obtained from "A Citizen's Guide to Radon" (ORP86a), prepared by EPA's Office of Radiation Programs. More information about sampling and measuring levels of radon in houses can be found in EPA's "Interim Indoor Radon and Radon Decay Product Measurement Protocols" (ORP86b). A brief review of radon mitigation approaches can be found in "Radon Reduction Methods: A Homeowner's Guide" (ORD86), prepared by EPA's Office of Research and Development.

This document does not cover methods of dealing with radon in water, nor does it cover methods of handling building materials that emit radon, or sites contaminated with radon-emitting materials. Some of the methods described here, however, are applicable to any radon source. Programs conducted as a result of the Uranium Mill Tailing Radiation Control Act of 1978, and the Comprehensive Environmental Response, Compensation and Liability Act (Superfund) of 1980 have provided guidance on dealing with radon-emitting materials and contaminated sites.

To assist the reader in understanding the material presented here, this document contains a table summarizing salient information about each technique, detailed drawings where appropriate, a glossary of terms used in the document, and a list of State and Federal representatives who can provide assistance.

1.3 Radon and Its Sources

Sources and Natural Background Levels

Radon gas is a *naturally occurring* radioactive element, a radionuclide gas, found in soils and rocks that make up the earth's crust. Radon gas comes from the natural breakdown or decay of radium. Because radon is a gas, it can travel over considerable distances and through narrow passages before it also goes through radioactive decay. Thus, radon as a gas can move through the soil and water and into the atmosphere.

Technically, radon-222 is derived from the emission of alpha radiation from the decay of radium-226, as a step in the natural radioactive uranium-238 decay chain. As part of this decay chain, radon also eventually decays by releasing alpha radiation and is transformed into polonium-218, which decays further into lead-214; that is followed by a decay into bismuth-214 and then to polonium-214. A final decay and the end of this decay chain occurs when lead-210 decays into a stable, nonradioactive lead-206 molecule. These intermediate products in the radon decay chain are referred to collectively as radon decay products, radon progeny, or radon daughters.

The significance of this radioactive decay process is that the decay of radon and its progeny (polonium-218, lead-214, bismuth-214, and polonium-214) occurs within a relatively short period of time and results in the release of potentially harmful ionizing radiation. Radon, the only gaseous member of the decay chain, is highly mobile in the environment; therefore, it has the potential to increase human exposure to natural radiation. It is emphasized that the above process (generation of radon) is continually occurring wherever uranium-containing source material is found. Uranium-238 activity concentrations in soil are known to vary from background levels of around 0.6 pCi per gram (six-tenths of a picocurie per gram) to hundreds of pCi per gram in uranium ore bodies (NAS81). The curie is a measure of radioactivity; pico means one-trillionth (0.000000000001).

Where radon gas and its progeny, which are ultrafine particles, stay in soil and rock or are liberated to the outside air and diluted, their release does not have the health significance that they have when confined in indoor environments. Outdoor concentrations of radon are reported to average around 0.25 pCi per liter, and concentrations in areas with extensive mineralization are reported to be around 0.75 pCi per liter (Br83). The importance and extent of outside air dilution of radon emissions become apparent when one realizes that monitoring of radon activity in undiluted soil gas has revealed radon concentrations ranging from a few hundred to several thousand pCi per liter (Br83). Dilution with outside air, thus, is seen to produce 1,000- to 10,000-fold reductions in radon concentrations in breathable outside air.

Health Effects of Exposure to Radon

Much of our knowledge of the health significance of radon and its progeny is based on analysis of the effects of high exposures to radon and its progeny on underground miners (NAS81). Table 1, adapted from the National Academy of Science report, provides a comparison of representative exposures to radon and its progeny (NAS81). Major relevant findings from health studies emphasize that (NAS81):

(1) There is no doubt that sufficient doses of radon and its progeny can produce lung cancer in humans.

(2) It is generally believed that radon and radon progeny are responsible for most of the lung cancer risk to the general nonsmoking public.

(3) The cumulative exposures at which human cancer has been observed are generally 10 times higher than those characteristic of the normal indoor environment.

(4) Excess incidence of cancer has been associated with exposures that were 2 to 3 orders of magnitude (100 to 1000 times) greater than those found in normal indoor environments.

(5) The linear dose-response function relating cancer incidence to radiation exposure is the only generally accepted means of assessing the health significance of measured radon and radon progeny concentrations for radiation protection purposes.

Based on the preceding information, researchers believe that *the longer one lives in a high radon environment and the higher the radon level in that environment, the greater the risk of developing cancer.*

Indoor Levels of Radon

Based on our current knowledge, *radon and its progeny are believed to be harmful at all exposure levels,* with the risk of cancer increasing with increasing exposures. Thus, *EPA guidance for homeowners calls for homeowners to take increasingly expeditious action to reduce exposure to proportionately higher levels of indoor radon concentrations* (ORP86a).

Beginning in the late 1970s, as interest increased in energy conservation in both new and existing buildings, many researchers started studies to determine how increasingly popular weatherization and house tightening techniques affect indoor air quality. Some of these studies established indoor air quality baseline (starting) conditions before installing energy-saving measures. Some studies found significant information about radon concentrations in the indoor air

Table 1. Representative Exposures to Radon-222 Progeny

Location	Working Level, WL[a,b]
Pre-1960 Mines	1 to 20
Outdoors	00.001
Indoors	00.01

[a]Working level (WL) is a measure of exposure rate to radon progeny defined as the quantity of short-lived progeny that will result in 1.3 x 105 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 (173 hrs) is 1 WLM.
[b]Working level measurements measure the activity of radon-222 progeny. Under equilibrium conditions of radon and its progeny, 1 WL equals the activity of 100 pCi per liter of air. At the characteristic equilibrium (50%) found in most indoor environments 1 WL equals 200 pCi per liter.

of certain houses. Studies showed radon concentrations in residences significantly above those found in the outdoor environment. Recent monitoring of houses in the Reading Prong (Pennsylvania) area of the United States revealed concentrations ranging from 0.1 to 10 WL in a number of houses.

Table 2 presents a comparison of the health risks and the calculated reductions needed to lower these health risks to a level associated with a 0.02 WL concentration of radon.

Reported incidences of high radon and radon progeny concentrations in houses have focused attention on the need to identify, in a short time frame, effective approaches to reducing indoor radon concentrations to the minimum levels practically obtainable.

Table 2. A Comparison of Health Risks and Percentage Reductions in Measured Concentrations Needed To Reach 0.02 WL

Measured Concentrations, WL	Risk of Death from Lung Cancer at Measured Concentrations	Percentage Reduction in Measured Concentration Needed to Attain 0.02 WL
10.0	>75 times normal[a]	99.8
1.0	75 times normal	98
0.2	30 times normal	90
0.1	15 times normal	80
0.02	3 times normal	0

[a]Normal = national average lung cancer incidence for nonsmokers.

Methods for Measuring Radon Levels

The homeowner who wishes to know definitely whether a particular house contains unacceptable levels of radon gas and its radioactive progeny must either monitor the house personally or have it monitored professionally. *Expert guidance by health and radiation officials can be particularly valuable before any monitoring program is conducted.*

Radon measurements should be taken as part of a well-planned mitigation program (ORP86a). Indoor house conditions should be stabilized with the house closed and after sufficient time has been allowed for the radon concentrations to stabilize. Ventilation rates should be as low as possible throughout the house; i.e., exhaust fans and air conditioners should be turned off, and windows, doors, and basement or crawl space openings should remain closed. No matter which of several available types of instruments are to be used, the instrument(s) should be placed in the area of the house closest to the underlying soil.

Relatively simple-to-use and inexpensive measurement devices are available to determine indoor radon levels; these include the charcoal canister and the alpha track-etch detector. These devices are typically deployed for 3 days and 1 to 3 months, respectively; and thus, they provide integrated radon concentration measurements (integrated over time). Longer averaging time measurements have the advantage of being more representative of annual radon exposures and more applicable to evaluating overall performance of installed radon control techniques. Longer term measurements have the disadvantage, for screening purposes, of delaying identification of possibly unacceptable living area radon levels.

Professional public or private services can measure radon and radon progeny concentrations by using a variety of highly instrumental methods. Examples of two such approaches include use of the Continuous Working Level Monitor (CWLM) and the Radon Progeny Integrating Sampling Unit (RPISU). These instruments have recommended minimum sampling times of 24 hours and 72 hours, respectively (ORP86b). Professional services can provide enhanced accuracy and precision of results, but with higher costs typically.

A homeowner may wish to select an inexpensive and rapid method for an initial or screening measurement, using a method such as the charcoal detector. When a measurement reported from such a screening test results in a value far above or far below the range of concern, decisions can be made with regard to the need to develop a plan for mitigation. Obviously, a very low measurement can relieve the homeowner's concern, while a very high measurement can indicate the need for expeditious action. If a screening measurement indicates an intermediate level or a level near the target level for action, the homeowner may wish to obtain more extensive and sophisticated measurements for better determination of the actual radon levels in the house and for help in deciding upon remedial action.

For the homeowner contemplating remedial action, accurate, reproducible, and representative results are important to provide a basis for appropriate method selection for mitigation. Comparable quality measurements also are needed to confirm the degree of success of any mitigation action taken.

Radon Entry and Buildup in House Air

For the Nation as a whole, measured radon and radon progeny concentrations vary from house to house by a factor of several thousand. For example, radon progeny concentrations vary from 0.0007 to greater than 10 WL. This variation in radon levels found nationally also is found on a local scale, which shows that indoor radon concentrations in apparently similar houses in proximity to one another can be quite different.

The physical relationship between the major sources of radon and the indoor structure of a house is illustrated in Figure 1. Common entry routes for radon gas into the house are shown. *Principal entry points* *for radon into the house include*: 1) *soil and rock* surrounding the house, Routes A-H; 2) potable (*drinking water*), Route J; and 3) *natural building materials* used in the house, Route I. The soil is generally believed to be the most important contributor of indoor radon in typical detached houses, followed by outdoor air, potable (drinking) water, and building materials.

Figure 1. Major radon entry routes into detached houses.

Key to Major Radon Entry Routes

Soil Gas

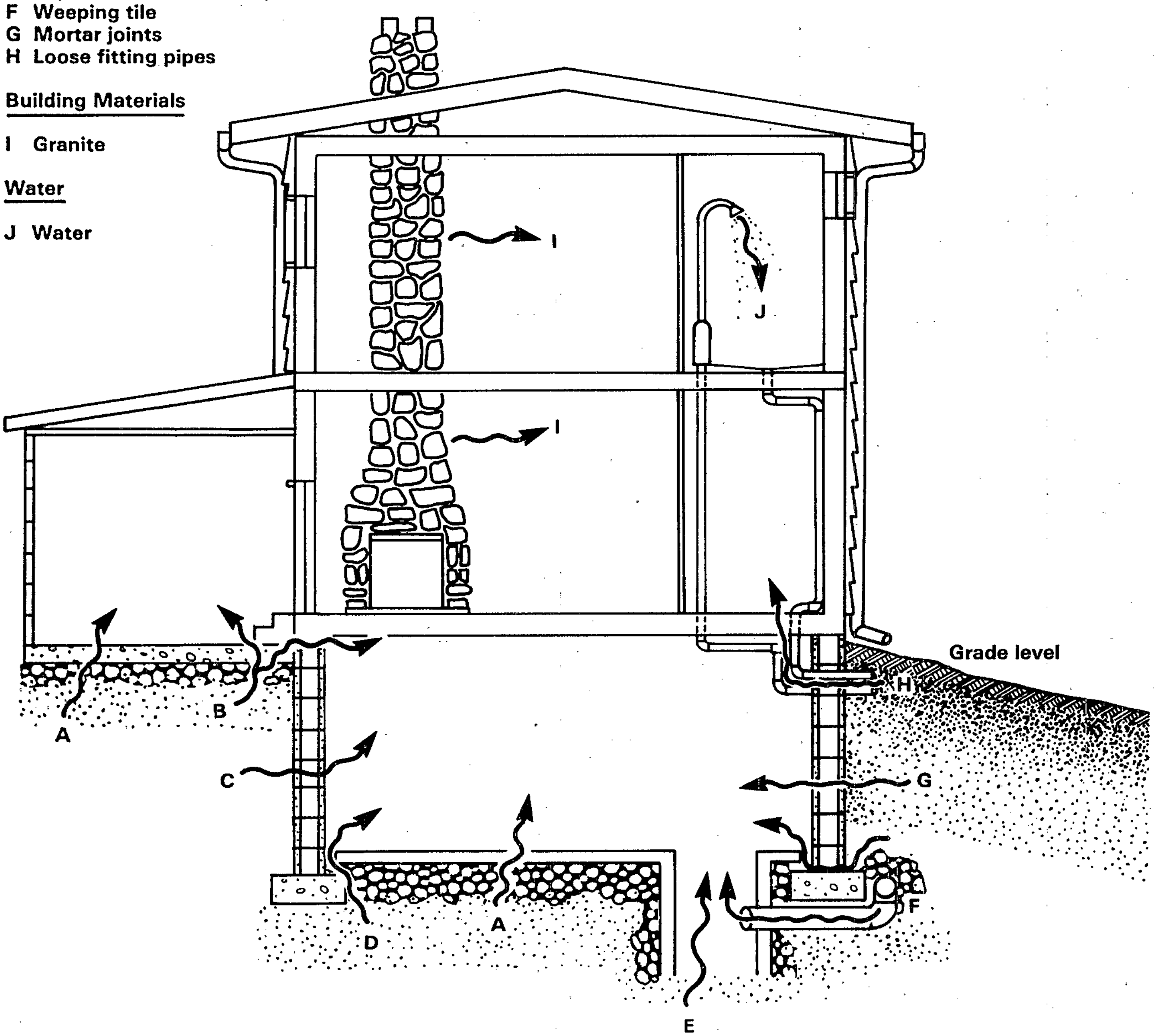
A Cracks in concrete slab
B Cracks between poured concrete (slab) and blocks
C Pores and cracks in concrete blocks
D Slab-footing joints
E Exposed soil, as in sump
F Weeping tile
G Mortar joints
H Loose fitting pipes

Building Materials

I Granite

Water

J Water



Section 2
Indoor Radon Reduction Approaches

2.1 Overview of Radon Reduction Methods

When radon is known to have entered a house and to have accumulated in unacceptable concentrations, a homeowner may take *effective action* to reduce concentration levels. Indoor radon exposure to occupants of a house may be reduced by 1) *preventing or reducing radon entry into the house* or 2) *removing the radon after it has entered the house.*

With reference to Figure 1, examples of principal methods of preventing radon entry into a house are:

(1) Sealing and closing of all pores, voids, open joints, and exposed earth that permit soil-gas-borne radon to enter a house. Entry routes A through H in Figure 1 illustrate cases where sealing would be an essential first step in reducing radon entry.

(2) Reversing the predominant direction of soil-gas-borne radon flows so that air movement is from the house to the soil and outside air. This could be accomplished by locating a uniformly exhausting ventilation system around a house's perimeter or under a basement slab. The main cause of radon entry from soils is pressure-driven air flows. Because houses are generally at slightly lower pressures, especially in the winter season, than the soils surrounding or underneath them, radon/soil gas flows will be from the soil to the house. Thus, reversing this pressure-driven flow requires control techniques that lower the soil air pressure relative to that of the house or raise the house pressure relative to that of the soil.

(3) Avoiding use of water supplies containing radon or removing radon from potable water supplies through the use of aeration or carbon adsorption removal techniques.

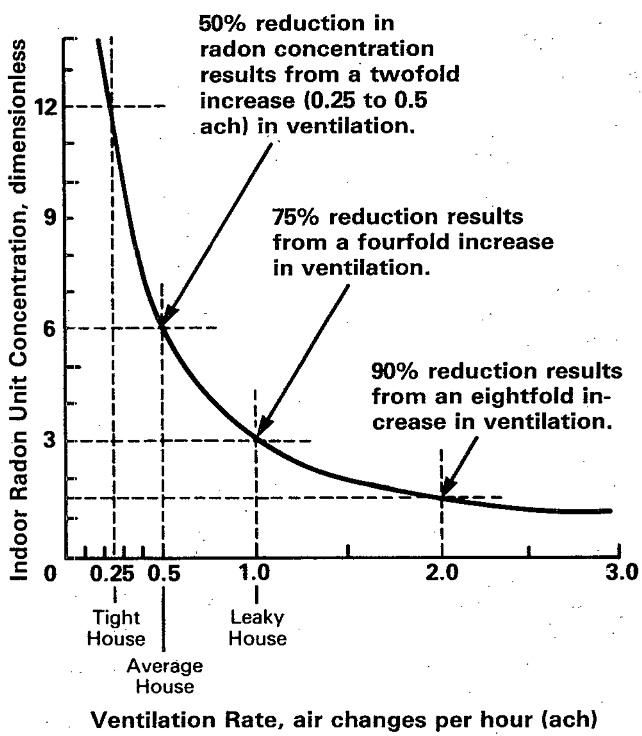
(4) Avoiding use of building materials that may contain radium and release radon.

Currently, the only effective method for removing radon after it has entered a house is by *ventilating the affected living space*. Ventilation entails bringing outside air into the living areas, basements, or crawl spaces to displace and replace an equal volume of indoor air and to mix with undisplaced indoor air (thus diluting radon concentrations). Where outside air radon concentrations are much lower than indoor concentrations (as they generally are by up to a factor of 1000), indoor radon can be reduced substantially by increasing normal house ventilation rates.

The effect of increasing ventilation rates for houses over a typical range of 0.2 to 2.0 air changes per hour (ach) is shown in Figure 2. This figure shows four important characteristics associated with the use of ventilation for radon removal:

(1) The utility of ventilation to reduce indoor radon levels decreases with increasing ventilation rates. This means that ventilation is more cost-effective for tight houses (i.e., low air change—less than 0.5 ach).

Figure 2. Effect of ventilation on indoor radon concentrations.



(2) Increasing ventilation rates from 0.25 to 2.0 ach can yield about 90 percent reductions in indoor radon levels.

(3) Use of ventilation, even at very high air change rates, will not effectively reduce indoor radon levels below a finite level determined by the radon source strength and entry rates.

(4) While in theory ventilation can be used to effectively and efficiently reduce indoor radon concentrations, practical field experience has identified such implementation problems as difficulty in operating ventilation systems so that they do not further reduce indoor air pressure and induce pressure-driven radon entry.

Table 3 summarizes radon reduction methods that can effectively reduce indoor radon concentrations in houses. The points summarized in this table are described in more detail and specific applications are discussed in the remainder of this section. Each method for radon level reduction makes use of either house ventilation/air exchange (e.g., forced air ventilation with heat recovery) or control of radon at its source (e.g., collection and exhausting of soil gas).

Table 3 shows that *house ventilation control techniques generally can reduce indoor radon concentration by as much as 90 percent on an annual basis* (Natural Ventilation, Forced Air Ventilation, and Forced Air Ventilation with Heat Recovery). The table also indicates that climatic conditions typical of much of the country are such that these techniques may pose significant comfort or economic cost penalties. Significant energy (and, therefore, operating cost) savings can be achieved by use of forced air ventilation with heat recovery (as indicated by comparison of heating costs of forced air ventilation with and without heat recovery).

Methods that *prevent radon entry* into the house by collection of soil-gas-borne radon at its source *have been demonstrated to produce reductions from 98 to 99+ percent*. These methods include Drain Tile Soil Ventilation, Active Ventilation of Hollow-block Basement Walls, and Ventilation of Sub-slab. Achieving these kinds of radon reductions depends on house design and technical limitations posed by the installation and operation of a complete soil-gas collection system.

The method for Active Avoidance of House Depressurization addresses the need to avoid worsening an existing radon entry problem by providing a supply of outside air to home appliances that use and exhaust indoor air or by supplying natural or forced air considering the air balance. Because such appliances (e.g., furnaces, fireplaces, dryers, and exhaust fans) are used only intermittently (sometimes only seasonally), expected annual average reductions are estimated to be 10 percent. However, during the actual time-of-use of the appliance (e.g., use of a fireplace for 12 hours), radon concentration may be reduced as much as 50 percent by avoiding house depressurization effects.

With the exception of the sealing techniques all the methods represented in Table 3 are judged to have moderate to high confidence levels. The basis for the estimated reductions is supported by some field experience and is consistent with control theory. The operating conditions and applicability of the methods are derived from actual experience reported in the technical literature on radon control.

Natural and Forced Air Ventilation without heat recovery are limited in a very practical way by considerations of human comfort and the potential energy penalties for heating and air conditioning costs needed to maintain comfort. These methods are very climate and weather dependent. House occupants must actively manage ventilation systems on a daily basis. Even with active management, short-term fluctuations in the effectiveness of these systems should be expected. Nevertheless, a conscientious homeowner can achieve significant reductions of radon levels by these ventilation methods. These techniques are particularly effective in one time situations (e.g., clearing radon from a temporarily or seasonally closed, uninhabited house).

Where possible, estimates of installation and annual operating costs for the methods were taken from specific radon control studies. Estimated increases in the cost of house heating with the ventilation techniques are based on the assumption that heating costs will increase in direct relationship to increased ventilation (air exchange rates). Installation costs include both equipment purchase costs and, where necessary, contractor installation. It is presumed that all methods described should be installed by professional contractors trained in radon mitigation to ensure that the installed systems will operate with maximum effectiveness, although some preliminary actions are suited to do-it-yourself installation by knowledgeable homeowners. *A homeowner considering installation of any of the techniques described in this document is encouraged to solicit several independent technical opinions as to the design specifics of any method and its applicability to the situation in his/her specific house.*

The reader is cautioned not to interpret the separate discussions of seemingly independent radon reduction techniques to mean that the techniques cannot or should not be used in combination. Indeed, where large reductions in indoor radon levels need to be accomplished and this must be done in the most economical way, *simultaneous application of two or three radon reduction techniques may be appropriate and should be considered.*

Table 3. Summary of Radon Reduction Techniques

Method	Principle of Operation	House Types Applicable	Estimated Annual Avg. Concentration Reduction, %	Confidence in Effectiveness	Operating Conditions and Applicability	Estimated Installation and Annual Operating costs	Sources of Information
Natural ventilation	Air exchange causing replacement and dilution of indoor air with outdoor air by uniformly opening windows and vents	All[a]	90[b]	Moderate	Open windows and air vents uniformly around house Air exchange rates up to 2 ach may be attained May require energy and comfort penalties and/or loss of living space use	No installation cost Operating costs for additional heating are estimated to range up to a 3.4-fold increase from normal (0.25 ach) ventilation conditions[c]	Be84, ASHRAE85, DOC82
Forced air ventilation	Air exchange causing replacement and dilution of indoor air with outdoor air by the use of fans located in windows or vent openings	All	90[b]	Moderate	Continuous operation of a central fan with fresh air makeup, window fans, or local exhaust fans Forced air ventilation can be used to increase air exchange rates rates up to 2 ach May require energy and comfort penalties and/or loss of living space use	Installation costs range up to $150 Operating costs range up to $100 for fan energy and up to a 3.4-fold increase in normal (0.25 ach) heating energy costs[c]	Be84, Go83, ASHRAE85, DOC82
Forced air ventilation with heat recovery	Air exchange causing replacement and dilution of indoor air with outdoor air by the use of a fan powered ventilation system	All	96[d]	Moderate to high	Continuous operation of units rated at 25-240 cubic feet per minute (cfm) Air exchange increased from 0.25 to 2 ach In cold climates units can recover up to 70% of heat that would be lost through house ventilation without heat recovery	Installation costs range from $400 to $1500 for 25-240 cfm units Operating costs range up to $100 for fan energy plus up to 1.4-fold increase in heating costs assuming a 70% efficient heat recovery[c]	Be84, CR86, NYSERDA85, Na81, We86b
Active avoidance of house depressurization	Provide clean makeup air to household appliances which exhaust or consume indoor air	All	0-10[e]	Moderate[f]	Provide outside makeup air to appliances such as furnaces, fireplaces, clothes dryers, and room exhaust fans	Installation costs of small dampered duct work should be minimal Operating benefits may result from using outdoor air for combustion sources	Na85

Table 3. ***(Continued)***

Method	Principle of Operation	House Types Applicable	Estimated Annual Avg. Concentration Reduction, %	Confidence in Effectiveness	Operating Conditions and Applicability	Estimated Installation and Annual Operating costs	Sources of Information
Sealing major radon sources	Use gas-proof barriers to close off and exhaust ventilate sources of soil-gas-borne radon	All	Local exhaust of the source may produce significant house-wide reductions	Extremely case specific	Areas of major soil-gas entry such as cold rooms, exposed earth, sumps, or basement drains may be sealed and ventilated by exhausting collected air to the outside	Most jobs could be accomplished for less than $100 Operating costs for a small fan would be minimal	Sc85b, Na85, NYSERDA85
Sealing radon entry routes	Use gas-proof sealants to prevent soil-gas-borne radon entry	All	30-90	Extremely case Specific	All noticeable interior cracks, cold joints, openings around services, and pores in basement walls and floors should be sealed with appropriate materials	Installation costs range between $300 and $500	NYSERDA85, Sc83
Drain tile soil ventilation	Continuously collect, dilute, and exhaust soil-gas-borne radon from the footing perimeter of houses	BB PCB S	Up to 98	Moderate[g]	Continuous collection of soil-gas-borne radon using a 160 cfm fan to exhaust a perimeter drain tile Applicable to houses with a complete perimeter footing level drain tile system and with no interior block walls resting on sub-slab footings	Installation cost is $1200 by contractor Operating costs are $15 for fan energy and up to $125 for supplemental heating	He86
Active ventilation of hollow-block basement walls	Continually collect, dilute, and exhaust soil-gas-borne radon from hollow-block basement walls	BB	Up to 99+	Moderate to high	Continuous collection of soil-gas-borne radon using one 250 cfm fan to exhaust all hollow-block perimeter basement walls Baseboard wall collection and exhaust system used in houses with French (channel) drains	Installation costs for a single suction and exhaust point system is $2500 (contractor installed in unfinished basement) Installation cost for a baseboard wall collection system is $5000 (contractor installed in unfinished basement) Operating costs are $15 for fan energy and up to $125 for supplemental heating	He86

Table 3. ***(Continued)***

Method	Principle of Operation	House Types Applicable	Estimated Annual Avg. Concentration Reduction,%	Confidence in Effectiveness	Operating Conditions and Applicability	Estimated Installation and Annual Operating costs	Sources of Information
Sub-slab soil ventilation	Continually collect and exhaust soil-gas-borne radon from the aggregate or soil under the concrete slab	BB PCB S	80-90, as high as 99 in some cases	Moderate to high	Continuous collection of soil-gas-borne radon using one fan (~100 cfm, ≥0.4 in.; H_2O suction) to exhaust aggregate or soil under slab For individual suction point approach, roughly one suction point per 500 sq ft of slab area Piping network under slab is another approach, might permit adequate ventilation without power-driven fan	Installation cost for individual suction point approach is about $2000 (contractor installed) Installation costs for retrofit sub-slab piping network would be over $5000 (contractor installed) Operating costs are $15 for fan energy (if used) and up to $125 for supplemental heating	Er84, Br86b, NYSERDA85, Sa84, He86, Sc86

[a]BB (Block basement) houses with hollow-block (concrete block or cinder block) basement or partial basement, finished or unfinished
PCB (Poured concrete basement) houses with full or partial, finished or unfinished poured-concrete walls
C (Crawl space) houses built on a crawl space
S (Slab, or slab-on-grade) houses built on concrete slabs.

[b]Field studies have validated the calculated effectiveness of fourfold to eightfold increases in air exchange rates to produce up to 90 percent reductions in indoor radon.

[c]Operating costs are ascribed to increases in heating costs based on ventilating at 2 ach the randon source level; as an example, the basement with 1) no supplementary heating or 2) supplementary heating to the comfort range. It is assumed the basement requires 40 percent of the heating load and if not heated would through leakage still increase whole house energy requirements by 20 percent. Operating costs are based on fan sizes needed to produce up to 2 ach of a 30x30x8 ft (7200 cu ft) basement or an eightfold increase in ventilation rate.

[d]Recent radon mitigation studies of 10 inlet/outlet balanced mechanical ventilation systems have reported radon reduction up to 96 percent in basements. These studies indicate air exchange rates were increased from 0.25 to 1.3 ach.

[e]This estimate assumes that depressurizing appliances (i.e., local exhaust fans, clothes dryers, furnaces, and fireplaces) are used no more than 20 percent of the time over a year. This suggests that during the heating season use of furnaces and fireplaces with provision of makeup air may reduce indoor radon levels by up to 50 percent.

[f]Studies indicate that significant entry of soil-gas-borne radon is induced by pressure differences between the soil and indoor environment. Specific radon entry effects of specific pressurization and depressurization are also dependent on source strengths, soil conditions, the completeness of house sealing against radon, and baseline house ventilation rates.

[g]Ongoing studies indicate that where a house's drain tile collection system is complete (i.e., it goes around the whole house perimeter) and the house has no interior hollow-block walls resting on sub-slab footings, high radon entry reduction can be achieved.

Application of the techniques addressed in this document to a specific house *should be discussed with knowledgeable State or Federal government personnel to obtain the benefit of the most up-to-date information with regard to the performance of currently available radon reduction techniques or systems* (combinations of techniques).

2.2 Natural and Forced Air Ventilation

Principle of Operation

Natural ventilation refers to the exchange of indoor air for outdoor air that occurs in response to and is driven by natural forces. The major forces driving natural ventilation are winds and pressure and temperature differences between the indoor and outdoor atmospheres. Natural ventilation in a house takes place through all passageways, however small, that connect the inside air to the outdoors. Thus some exchange of indoor air with outdoor air occurs even when doors and windows are closed. This baseline ventilation, present in all buildings, is called infiltration.

Forced air or mechanical ventilation relies on the use of fans to force an increase in house air exchange rates by 1) blowing in outside air or 2) exhausting indoor air with the assurance that it will be replaced by cleaner air from the outside.

In most American houses in normal use, the annual average ventilation rate is about 1.0 air change per hour (ach). Newer houses, built with a concern for reducing heating and cooling energy costs, may have air exchange rates as low as 0.1 ach (one-tenth of an air change per hour), and older houses may have air exchange rates as high as 2.0 ach. Houses with high air exchange rates probably would not be suitable for the ventilation approach to radon mitigation.

The ventilation approach relies on achieving reductions in indoor radon levels from a constantly emitting radon source that are in direct proportion to increases in ventilation rates. This reduction is due to both the removal of radon-laden air and the dilution of the total indoor volume with the clean incoming air. This relationship is shown in Figure 2. Over the typical house ventilation rates of 0.25 to 2.0 ach, each doubling of the ventilation rate reduces indoor radon concentrations by a factor of 2. For example, if energy and human comfort cost penalties were not a consideration, ventilation could be used to reduce a 0.1 WL indoor concentration to about 0.02 WL by increasing house ventilation rates from 0.25 to 1.0 ach, or to about 0.01 WL by increasing the house ventilation rate to 2.0 ach.

Applicability

In practice the application of ventilation, whether natural or forced air, to reduce indoor radon concentration is limited by the energy penalty imposed by the need to maintain human comfort conditions at potentially high ventilation rates, especially in the winter. Human comfort is a somewhat subjective determination, but temperatures between 68° and 78°F* with relative humidities between 30 and 70 percent are generally comfortable to most people (ASHRAE85). Considering only the temperature criterion and data on heating and cooling degree days (DOC82), it is estimated that nationally (and in the Mid-Atlantic States of New York, Pennsylvania, and New Jersey in particular) natural or forced air ventilation could be used to reduce indoor radon concentrations up to 4 months per year with little or no comfort penalty.

If a homeowner were willing to 1) accept a comfort penalty, 2) offset this comfort penalty by closing off and limiting use of a ventilated radon source area such as a basement, or 3) incur a supplemental heating or cooling cost, greater application of ventilation as a technique for reducing indoor radon levels would be possible. Current experience with the use of ventilation (in pressure-balanced, heat-recovery systems) suggests that ventilation can effectively reduce moderately high basement radon levels (up to 20 pCi per liter) to levels below 4 pCi per liter (NYSERDA85, We86a).

Confidence

Ventilation as a technique for reducing airborne concentration has a proven performance (and thus a high confidence level) under *controlled ventilation*; that is, where ventilating air can be distributed or mixed with indoor air at controlled and quantifiable rates (ASHRAE81).

Forced air ventilation with the proper placement of fans, or with inlet and exhausting forced air duct work, can be expected to meet controlled ventilation conditions; therefore, the confidence level in its performance is high.

The radon-reduction effectiveness of natural ventilation has a low to moderate confidence level if for no other reason than it varies with the weather and its only control is by opening or closing windows.

Installation, Operation, and Maintenance

The ability of any radon-reduction technique to provide reliable performance depends greatly on a systematic and understandable definition of the operating conditions required.

The effectiveness of natural ventilation is dependent on ensuring uniform ventilation throughout all portions of the house with elevated radon concentrations; for example, as found in crawl spaces or basements. Thus, the space to be ventilated should have

*Readers more familiar with metric units may use the conversion factors in the front matter of this report.

windows and vents completely around it, and they all should be opened to the same degree.

Although natural ventilation clearly depends on and varies with weather conditions, its minimum performance level, which is unique to each house, should be demonstrated and quantified to ensure that natural ventilation is not relied upon, even temporarily, to reduce radon concentrations to levels beyond its capability.

The air distribution and ventilation rates of forced air ventilation of a basement or larger space can be controlled by the size and location of fans and the use of louvered air deflectors. Extrapolations from and experience with small chambers and room-sized spaces suggest the need for two or three fans rated at twice the air-moving capacity nominally desired.

The design, implementation, or operation of a control strategy based on ventilation requires an understanding of the dynamics of radon entry into a house, as well as the dynamics of air distribution within the house. For example, adding ventilation that creates a negative pressure on a basement area actually may increase the entry rate of soil-gas-borne radon and cause increased radon concentrations in areas remote from the basement. Both natural and forced air ventilation can produce this unwanted effect if the inlets and outlets are improperly located (e.g., opening the upstairs windows or using an attic fan may be a mistake in some situations).

Estimate of Costs

No installation cost is assumed with natural ventilation in its simplest application. Minor costs, however, could occur in securing house windows in fixed, open positions. The need for acquiring additional protective devices for occupants of a house with open windows can result in specific environments where security, insect pests, or cold temperatures are at issue. Relocation of services in areas which are closed off to adequately heated spaces may also be required.

Operating costs for the natural ventilation method can run from none (if the technique is used only when outdoor temperatures and humidities are within comfort criteria or the homeowner is willing to accept comfort penalties or to close off parts of the house) to a range of from 1.2- to 3.4-fold increases in heating costs incurred by, for example, ventilating a basement space year-round and supplementing heat loss from the upper floor or increasing basement air heating to maintain comfortable conditions in the basement. These estimates for supplementary heating are based on increasing basement ventilation rates eightfold with a basement that normally incurs 40 percent of the house heating load.

Forced air installation costs were estimated to be no more than $150 for the purchase of fans with an air-moving capacity of approximately 240 cfm. If new wiring, duct work, dampers, filters, or automatic smoke alarm cutoffs are desired, installation costs increase substantially. Annual operating costs for the forced air ventilation technique were estimated to be $100 for fan energy (Be84) and from none (if the technique is used only when outdoor temperatures and humidities are within comfort criteria or the homeowner is willing to accept comfort penalties) to a range of 1.2- to 3.4-fold increases in heating costs incurred by ventilating a basement space year-round and supplementing heat lost from the upper floor or increasing basement air heating to maintain comfort criteria conditions.

2.3 Forced Air Ventilation with Heat Recovery

Principle of Operation

Forced air ventilation with heat recovery is a technique for bringing outside air into a house, exhausting radon-contaminated indoor air, and transferring or recovering the heat from the exhaust air to the cleaner incoming air. Fans provide controlled steady flows of ventilating and exhaust air.

As explained in Section 2.2 indoor radon concentrations are reduced by replacing the indoor air with clean outside air. Mixing of the clean outside air with the indoor air that is not exhausted dilutes the indoor radon concentrations. As the rates of air exchange (air changes per hour) are increased indoor radon concentrations are decreased, as shown earlier in Figure 2.

Section 2.2 also addresses the practical considerations of comfort and the cost of providing supplemental heating to offset loss of comfort during the use of ventilation. Heat recovery between exhaust and inlet ventilating air thus becomes an important feature in extending the applicability of ventilation.

Heat recovery basically entails the transfer of heat energy from warm sources to cold sources. The rate of heat transfer is related to the temperature difference of the two sources. The incoming colder clean air is heated by contact with a heat transfer surface that has been warmed by the exhausting warm indoor air. The greater the temperature difference is between the ventilating air and the exhausting air, the more effective the heat transfer.

Applicability

The application of forced air ventilation with heat recovery has its greatest potential in low-ventilation-rate (tight) houses in cold climates. These conditions maximize the effectiveness of the ventilation and heat recovery mechanisms. For the most part, this approach has been used in houses with moderately elevated radon levels (less than 0.1 WL) (We86, Na85). Ventilating capacities of commercially available "heat-recovery ventilators" identified by Consumer Reports (CR86) vary from about 25 to 240 cfm, and heat recoveries range from 15 to 70 percent at 5° and 45°F, respectively.

Confidence

Forced air ventilation with heat recovery is a proven technique for reducing indoor air pollutant concentrations in direct relation to the ventilating rates. Heat recoveries up to 70 percent are possible. Confidence in the effectiveness of this technique should be high.

Installation, Operation, and Maintenance

Commercially available forced air ventilation systems with heat recovery vary in size from room or window units to systems that ventilate the whole house. For the purpose of radon reduction, the whole-house systems probably would be placed in basements and run automatically. These systems require their own duct work for collection and distribution of outdoor air and the collection and exhausting of indoor air. Generally, existing windows can be used for air intake and exhaust purposes.

The particular heating and ventilating system decided upon and information regarding the source strength and radon entry path into the house will dictate the precise location, size, and configuration of the ventilation system duct work.

Estimate of Costs

Installation costs will vary with the size (ventilating capacity) and complexity of the system to be installed. Estimates indicate that costs of commercial units can range from $400 to $1500 for rated air-moving capacities of 25 to 240 cfm. A 240-cfm capacity would be needed, for example, to ventilate a 30 x 30 x 8 ft (7200 cu ft) basement at a rate of 2 ach. If the basement's original ventilation rate was 0.25 ach, this increased ventilation could reduce radon levels by approximately 90 percent.

The operating cost of a 240-cfm system is estimated to be $100 per year for fan energy. If the basement is just ventilated with the system (no makeup heat added), whole-house heating costs could still increase by 20 percent because of the heat loss to the ventilated basement. In cold climates, this would limit the use of the basement and can require the insulation of utility services. If makeup or supplemental heat is added to the basement, whole-house heating costs could increase 1.4-fold; i.e., about 40 percent.

2.4 Active Avoidance of House Depressurization

Principle of Operation

The house living space may be depressurized when certain household appliances that use and exhaust house air to the outside are used and when unbalanced natural or forced air ventilation is applied. Depressurization of a house occurs naturally in the winter as a result of the rising of heated indoor air and its loss or exfiltration to the outdoors. This is called the "stack (as in smoke-stack) effect." The winter stack effect or depressurization in houses is believed to be the main cause of increased soil-borne radon entry.

Any additional cause of depressurization, especially in the radon source entry spaces (e.g., basements or rooms abutting or directly on soil), can also contribute to increased radon entry. Thus, if additional depressurization activities can be limited or modified by the direct provision of outside makeup (combustion or exhaust) air, increased radon entry can be avoided.

Applicability

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE81) has recommended the provision of outside makeup air for combustion appliances, such as furnaces and water heaters, since 1981. They believe that outside makeup air is necessary to ensure the effective and controlled ventilation needed for acceptable indoor air quality. Other appliances affecting indoor air ventilation (e.g., intermittently used local exhaust fans) are not mentioned by ASHRAE and are clearly not as important as combustion appliances in effecting ventilation or house depressurization. Where depressurization and ventilation effects have been documented, it was during the use of combustion appliances (Na85, Sc85a).

Confidence

The major consequence of providing makeup or combustion air to household appliances is to prevent additional house depressurization and hence to prevent increasing pressure-driven flows of soil-gas-borne radon into the house. While there is high confidence that the pressure-driven flow of soil-gas-borne radon into the house is the major radon entry mechanism, quantitative evidence of the radon-reduction benefit of avoiding appliance depressurization effects is variable, 0 to 50 percent (Na85). The variability probably reflects the specific appliance's operating conditions, varying indoor conditions, and differences in radon source strength.

Installation, Operation, and Maintenance

Because of the potential for significant seasonal radon reduction benefits and improvements in the quality of the whole-house ventilation performance, installation of homeowner- or contractor-installed duct work for supplying outside air to major indoor combustion appliances is encouraged. Additional guidance in this area can be found in U.S. Department of Energy report DOE/CE/15095 (DOE86).

Estimate of Costs

Installation costs will be associated with providing small dampered duct work systems for indoor air consuming appliances, such as furnaces, fireplaces, and (perhaps) clothes dryers.

2.5 Sealing Major Radon Sources

Principle of Operation

Exposed soil and rock under, around, or within a house can be a major source and entry route for radon into the living area of a house. These areas should be closed, sealed, and (if necessary) exhaust-ventilated to the outdoors to prevent soil-gas-borne radon entry into the house.

Applicability

Exposed earth, as in basement cold rooms or water drainage sump areas, is a prime target for 1) excavation of fill and replacement with a concrete cap; or 2) at least capping of those areas with an impermeable covering such as aluminum sheet metal, sealing of all cover joints, and forced air exhausting of any below-grade air space (such as that found in a sump pump cavity).

Confidence

Theoretically, locating, capping, and sealing major potential sources of soil-gas-borne radon entry should have significant radon reduction benefits. Several studies indicate that pressure-driven soil-gas-borne radon entry into a tightly sealed energy efficient house is effectively prohibited or significantly reduced in houses with radon levels of 30 to 70 pCi per liter by sealing of all visible cracks and gaps between floor, walls, and service pipes entering a basement (Ho85, NYSERDA85). Most researchers in the radon research community, however, would probably caution that, while better barriers, sealants, and construction techniques can have a significant effect on radon entry rates, *this beneficial effect will be limited in degree and in duration of control.* Even imperceptible movements of a house's understructure can create small imperfections that appear to be adequate pathways for the entry of soil-gas-borne radon (Ne85).

If a moderate to high confidence level is to be assigned to the control of radon entry through localized major soil gas sources, such confidence will be attributable to a system that effectively caps and seals the source and uses a small-capacity fan to exhaust the capped source space. The potential benefit of exhausting a capped sump has been demonstrated in studies where variations in concentrations at a sump pump cover corresponded to variations in average house concentrations for the same time period (Na85, NYSERDA85).

Installation, Operation, and Maintenance

Figure 3 shows a possible sump ventilation arrangement. A tight-fitting cover is placed over the sump, and the sump is exhausted to the outside by a small fan. Although the immediate purpose is to exhaust the radon that enters the sump from the surrounding soil, Figure 3 shows that the fan suction produced in the sump may be transmitted through the attached weeping tile drainage system and diminish the radon soil gas concentration for some distance from the sump.

Estimate of Costs

Such a sump ventilation system should cost less than $100 (Sc85b); however, variations of this system with increased soil gas removal capacities can cost up to $1200. See Section 2.7.

2.6 Sealing Radon Entry Routes

Principle of Operation

Radon entry with soil gas can be prevented by sealing all cracks, openings, or other voids in the house structure that provide pathways for gas flows from the soil to the house interior. Sealing of potential soil-gas-borne radon entry routes is often considered as an initial radon reduction approach, especially in houses with marginal problems. It is often implemented in conjunction with other radon-reduction strategies.

The discussion of sealing is limited to the closing off of small soil-gas entry routes. Major entry routes (e.g., sumps, drains, or soil outcroppings in cold rooms) are addressed in Section 2.5. Sump and channel or French drains are also discussed in Section 2.8.

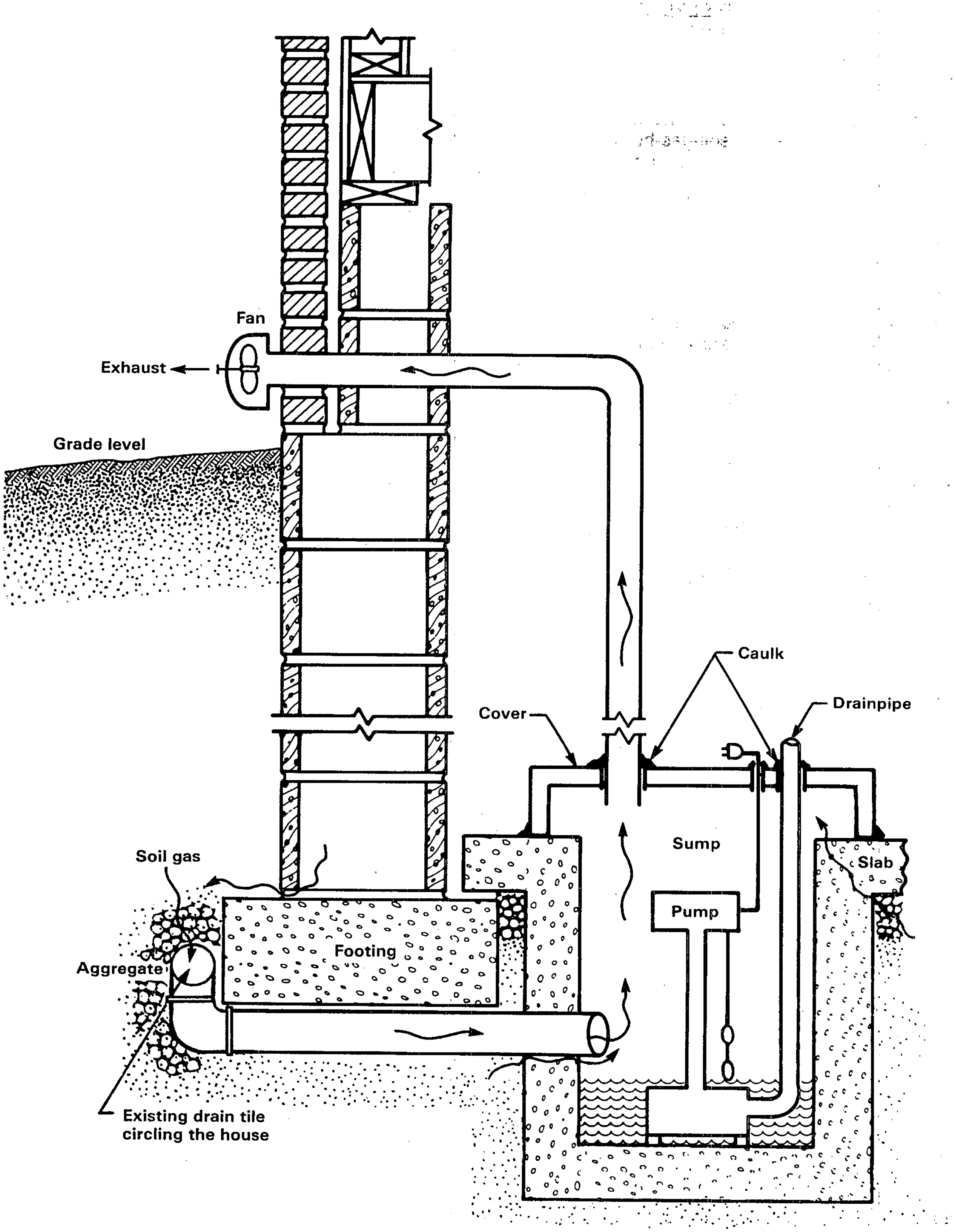
Applicability

The practical applicability of sealing is generally limited by the knowledge of and access to all small soil gas entry routes. In existing houses, limited access is a major impediment to complete sealing without significant expense.

Confidence

Current experience dictates that only a low confidence level can be assigned to the use of sealing in existing houses for the prevention of soil-gas-borne radon entry. A homeowner should not expect sealing of all noticeable cracks or openings to eliminate an indoor radon problem. The potential effectiveness of

Figure 3. Drain tile ventilation where tile drains to sump.



sealing as a means of significantly reducing indoor radon concentration has been demonstrated in the 30 to 90 percent range (NYSERDA85, Sc83). These studies emphasize the uncertainty of successful control with comparable sealing efforts in apparently similar house situations.

Installation, Operation, and Maintenance

Table 4 is a checklist of soil-gas-borne radon entry routes through walls and floors into the house.

The method most commonly used to seal floor and wall cracks and utility openings involves enlarging the existing crack or opening to dimensions sufficient to allow filling with a grout, caulk, or sealant. These compounds must be compatible, gas-proof, and nonshrinking. Wall and floor joints are sealed by a variety of methods. The most common are a polyurethane membrane sealant and protective cover or a nonshrink grout with a protective concrete cap.

Radon flow through porous walls, especially block walls, and floors can be reduced by the use of interior and exterior barrier coatings. In general, sealants cannot be applied to exterior wall surfaces of existing houses inexpensively. Thus, walls are usually sealed by applying epoxy sealants or waterproof paints to interior surfaces. Proper sealing of these entry points generally requires meticulous surface preparation and quality control in the application of appropriate sealants.

Table 4. Soil-Gas-Borne Radon Entry Routes

Category	Description
Block or concrete wall	Pores in block Mortar joint cracks between blocks Openings in top course of block Utility openings through walls Cracks in wall Gaps between block and brickwork surrounding basement fireplaces
Concrete floor	Cold joints in poured floor Cracks in floor slab Wall and floor joints on footings Utility openings

Estimate of Costs

Many sealing jobs can be accomplished for a materials cost of less than $100. Comprehensive, whole-house efforts have cost up to $500 (Sc83).

2.7 Drain Tile Soil Ventilation

Principle of Operation

Perforated drain tiles surround part or all of some houses in the vicinity of the footings to drain moisture away from the foundation. The water collected in the drain tiles is generally routed either to an above-grade soakaway remote from the house or to a sump in the basement. It is believed that a significant amount of the radon-containing soil gas entering a house may be gaining access through openings in the vicinity of the footings; e.g., through the exterior mortar joint between the block and the footings, through other mortar joint cracks, through block pores in the exterior face of block wall near the footings, or through the crack between the interior face of the blocks and the concrete slab. Drain tile ventilation involves drawing suction on the drain tiles by use of a fan in an effort to draw soil gas away from these potential entry routes. Depending on the permeability of the soil and of the aggregate beneath the slab, drain tile ventilation can also ventilate portions (or all) of the area underneath the slab and the soil well above the level of the footings.

The advantage of drain tile ventilation is that it is the least expensive and least obtrusive active soil ventilation approach potentially capable of significantly reducing radon levels. Its disadvantage is its limited applicability, as discussed in the following subsection.

Applicability

It would be fairly expensive to install drain tiles around a house that did not have them installed during construction; therefore, the practical application of drain tile ventilation may be limited to houses already having drain tiles in place. Data acquired by EPA in testing this technique on seven houses suggest that the technique offers reasonable potential for substantial, year-round reductions in radon *only* when the drain tiles are *known* to extend around the entire perimeter of the house and to be basically open and connected. This is necessary to ensure that the ventilation is treating the entire footing region. If some portion of the perimeter does not include drain tiles—or if the tiles are damaged or blocked with silt—that portion of the perimeter will not be effectively treated. Another potential problem concerns houses having interior block walls in the basement that rest on footings underneath the concrete slab (e.g., walls that divide the basement into sections or separate the basement from an attached garage). Such "interior" footings generally do not include drain tiles; only the exterior perimeter footings do. Thus, such interior footings provide a potential access route for soil gas into the house, an entry route that cannot be treated reliably with house perimeter drain tile ventilation. EPA's data do show, however, that as long as the perimeter drain tile system is complete, drain tile ventilation can sometimes produce significant reductions of indoor radon on houses with interior block walls. These interior walls would, however, increase the risk of reduced performance. Drain tile ventilation would be an especially logical choice in houses with "finished" basements, as the practicality of installing control measures inside the house is reduced.

To date testing of the drain tile ventilation technique has focused primarily on houses with concrete block basements. In view of the principle of operation, however, this technique may also offer reasonable potential for reducing radon in houses of other substructure types.

In summary, drain tile ventilation would be most applicable to 1) houses known to have a complete drain tile system in place, and 2) preferably (although not necessarily) houses that do not have interior basement walls that penetrate the slab to rest on footings.

If a homeowner is uncertain as to whether the drain tile system is complete or might be blocked by silt, drain tile ventilation may not be a wise approach. The fact that the technique is sufficiently attractive (i.e., has the potential to produce significant radon reductions at fairly low cost with an unobtrusive installation) may lead some homeowners who believe their drain tiles are reasonably likely to form a complete loop to try this approach before attempting a more expensive one.

Confidence

To date, EPA has tested drain tile ventilation in seven houses all of which have concrete block basements (He86). In all cases, the tiles drained to an above-grade soakaway. Three of these houses are known to have drain tile systems that completely surround the house. The results obtained at these three houses are shown in Table 5.

Table 5. Results Obtained With Drain Tile Systems in Three Test Houses

	Concentration before technique installed, WL		Concentration after technique installed, WL	
House No.	Early 1985	July/ Aug. 1985	July/ Aug. 1985	Nov./ Dec. 1985
10	1.1-3.1	0.46-1.5	0.02-0.04	0.005-0.03
12	0.22	0.03-0.10	0.005-0.01	0.01-0.03
15	0.17	0.02-0.50	0.01-0.02	0.01-0.03

These radon level ranges are generally based on 1 to 2 days of continuous radon monitoring by EPA during the months indicated. The exception is the column presenting early 1985 data before mitigation technique installation; these results are based on 5-minute grab samples (and sometimes on longer-term integrated measurements) by the Pennsylvania Department of Environmental Resources. House No. 10, which has an interior block wall, illustrates that the technique can, at least in some cases, provide reasonable reductions even under these conditions. The good performance in House No. 10 suggests that the ventilation effect of the drain tile system in this case must have extended under much or all of the slab. These data indicate that, under favorable conditions, the drain tile ventilation technique can provide reasonably high levels of radon reduction and that these reductions can be sustained during the winter when the natural stack effect created in the house gives the control technique its greatest challenge.

Levels of radon in House No. 10 peaked to 0.05 WL when the clothes washer and dryer in the basement were used. This reflects either the effects of basement depressurization caused by the dryer or the contribution of additional radon from the 35,000-pCi per liter well water used in the washer. Radon levels in House No. 12 peaked to 0.05 WL when the fireplace was operating (which caused depressurization of the basement). These results suggest that drain tile ventilation may be somewhat vulnerable to increases in soil gas influx when the house is depressurized.

At the other four houses on which EPA tested drain tile ventilation, the drain tiles were known not to extend around the full perimeter. In these four houses, reductions of 74 to 98 percent were observed during the summer (based on a comparison of EPA's summer premitigation data and summer post-mitigation data); summer premitigation levels of 0.12 to 1.6 WL were reduced to 0.01 to 0.08 WL. With the onset of cold weather, however, the levels began to increase (0.06 to 1.0 WL), which indicates that the technique cannot maintain reasonably low levels year-round in houses that do not have complete drain tile systems.

Although EPA's testing in the three houses having complete drain tile loops draining to a soakaway showed consistently significant reductions in radon levels, further tests on additional houses (including more houses with interior walls) would be necessary before a high statistical confidence level of success could be established in a variety of houses with complete drain tile systems. Further, EPA's measurements in the three houses where this approach was successful were relatively short-term (1 to 2 days of continuous monitoring on two occasions). Longer-term (2-month) monitoring and observation of system performance for a full year or longer are needed for better confirmation of performance.

Other investigations have tested drain tile ventilation in situations where the tiles drain to a sump inside the basement (Na85). Of three houses with a footing drain/sump ventilation system, one had a poured concrete basement, one had a concrete block basement, and one had a combination block basement plus crawl space. The drain tiles for the last house were known not to extend entirely around the perimeter; however, how far the tiles extended in the other two 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 three 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 (Na85).

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

Based on the aforementioned considerations, the confidence level in the performance of the drain tile ventilation approach is considered to be "moderate."

Design and Installation

Figure 4 shows a drain tile ventilation system (where the tiles drain to an above-grade soakaway). The drain tile, including the line running to the soakaway, must be already in place. The ventilation system in Figure 4 consists of the water trap and riser(s) (which are in the existing line to the soakaway) and the fan. The water trap ensures that the fan effectively draws suction on the drain tiles. Without the trap, the fan would simply draw outside air up from the soakaway and have no significant radon reduction impact. Most of EPA's experience to date has been with houses where the tiles drain to a soakaway. If the tiles drain instead to an inside sump, the drain tiles can be ventilated by covering and drawing suction on the sump. One sump ventilation approach is illustrated in Figure 3. Other sump ventilation configurations have been tested by other investigators (e.g., flat rather than raised cover, fan inside the house with exhaust piping leading outside).

Locating Line to Soakaway

The following general description of the ventilation design features focuses on the soakaway system (Figure 4). In preparation for installation of a soakaway system, the contractor must first locate the position of the drain line to the soakaway and then dig down to expose the line at the point where the trap and riser are to be installed (Figure 4). A complete drain tile system consists of a continuous loop around the perimeter of the house (at footing level) with a discharge drain tile line tapping out of the loop at some point to run to the soakaway; it is in this drain line (not in the loop itself) that the vent system should be installed. The position of the discharge line can initially be estimated by locating the point at which the line comes above grade at the soakaway and then visually tracing the likely path of the line from the point back to the house.

The ventilation system can be installed at any point in the drain line. The advantages of installing the system at a point remote from the house are reduced fan noises in the house, a more aesthetically appealing installation, and less digging because the line may be closer to grade level at a remote point. In addition, the release of the fan exhaust, which could contain high levels of radon, would be remote from the house. On the other hand, the long length of drain tile required between the fan and the loop around the house could result in a potentially significant pressure drop which would make the fan less effective in maintaining suction in the loop around the house and thus reduce the system's performance. Also, 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 and prevent proper drainage during winter months. Based on these considerations, the ventilation system should be installed at some reasonable distance from the house—perhaps up to 20 ft.

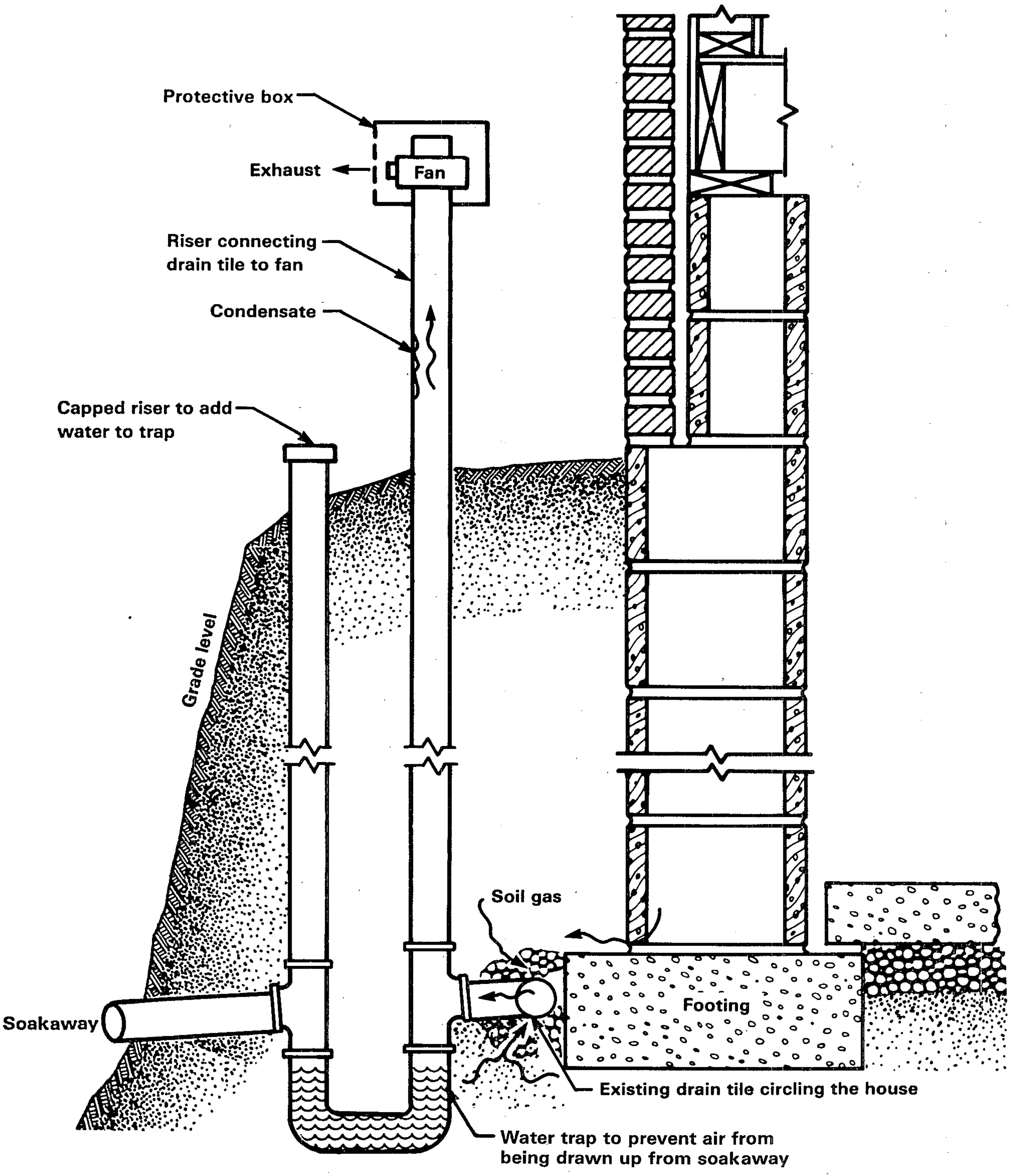
Trap and Riser(s) Installation

To install the trap and riser(s) after the proper point in the drain tile line is exposed, the contractor must sever the tile and remove a section so that the trap/riser assembly can be inserted. In the EPA testing, the trap and riser(s) consisted of 4-in. Schedule 40 plastic sewer pipe. The trap itself can be purchased as a unit or assembled from elbows and tees cemented together. Details on how the trap is fabricated are not crucial as long as it serves the purpose of preventing outside air from being drawn up from the soakaway. 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 (e.g., by a clamp over a rubber sleeve) so that there is no break that permits silting or otherwise prevents effective suction from being drawn on the drain tile loop.

The riser to support the fan must be on the house side of the trap. It should protrude some distance (perhaps 2 to 3 ft) above grade level to provide reasonable clearance for the fan and to permit proper condensation of moisture during the winter. The soil gas contains moisture and is relatively warm compared with winter air temperatures; thus, moisture can condense and freeze up the fan unless much of it is condensed in the riser.

Although the riser shown on the opposite side of the trap from the fan is optional, it would ensure that the trap always contains water, even in prolonged dry weather. Were the trap ever to dry out, the ventilation system would become ineffective. This second riser should extend above ground only far enough for convenient access and should always be

Figure 4. Drain tile ventilation where tile drains to soakaway.



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.

Fan Selection and Mounting
The fan needed to draw suction on the drain tiles is fairly small (relative to a central furnace fan). Although a wide variety of fans can be considered, the fans used in the EPA testing were 0.03-hp (25-W), 160-cfm centrifugal fans (maximum capacity) capable of drawing up to 1 in. of water suction before stalling. These fans actually operated at about 80 cfm and 0.2 in. of water during the EPA study. The fan must be large enough (both in terms of flow rate and suction capability) to draw reasonable suction on the drain tiles. Fans of this type can cost between $40 and $100.

The fan must be mounted to draw suction on the drain tiles (i.e., *not* mounted in the reverse direction to blow air down into the tiles). The preferred mounting is directly on the pipe. In some of EPA's initial installations, the fan was in a protective box that stood on the ground near the riser and was connected to the riser by flexible ducting; however, this configuration resulted in increased pressure drops (and, consequently, less effective suction on the drain tiles) as well as condensate buildup and plugging in low sections of the flexible ducting in cold weather. Figure 4 shows the fan mounted directly on top of the riser and enclosed within a protective box. This configuration minimizes pressure drop in the riser/fan connection arrangement by eliminating all bends in the pipe and ducting. Some fans can be purchased with a protective enclosure similar to that shown in Figure 4. Such a protective box also can be fabricated separately. The exhaust should be covered with a screen to prevent children and pets from reaching the blades and to keep out debris. Electrical connections to the fan should be wired according to code to avoid electrical hazards.

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, the fan will simply draw outside air through itself and will not draw effective suction on the drain tiles.

Operation and Maintenance
The operating and maintenance requirements for the drain tile ventilation system consist of regular inspections by the homeowner to ensure that 1) the fan is operating properly (e.g., is not iced up or broken), 2) the trap is full of water, and 3) any seals are still intact (e.g., where the fan is mounted onto the riser). Maintenance would include routine maintenance to the fan motor (e.g., oiling), replacement of the fan as needed, addition of water to the trap, and the repair of any broken seals.

Estimate of Costs
Based on EPA's experience in installing drain tile ventilation systems in seven houses, it is estimated that a private homeowner might have to pay about $1200 to have a contractor install a system. This estimate assumes that the house and drain tile installation present no unusual difficulties and that the job is completed without the added expense of a "radon mitigation expert" to oversee the contractor's work. The estimate includes both materials and labor. Most of the cost is the manual labor required for digging down to expose part of the discharge line.

Some homeowners may be able to install the drain tile ventilation system themselves. This approach would limit the cost to materials; i.e., the fan, the sewer pipe, and some incidentals. The material cost alone should not exceed $300.

Operating costs would include the electricity to run the fan and possibly a heating penalty because of the increased ventilation in the house (assuming that the gas drawn out of the drain tiles by the fan is made up partly by house air that has been drawn out through the block walls near the footings). Occasional replacement of the fan would also be an operation and maintenance cost. The cost of electricity to run a 0.03-hp (25-W) fan 365 days per year would be about $15. Assuming that the system increases house ventilation by roughly 50 cfm, the cost of heating 50 cfm of outside air to house temperature throughout the winter would be about $125. Thus, the total operating cost would be about $140 per year. Experience to date is insufficient to estimate how often the fan might have to be replaced; a new fan would likely cost between $40 and $100.

2.8 Active Ventilation of Hollow-Block Basement Walls

Principle of Operation
The centers of concrete blocks used to construct many basement walls contain voids. These voids generally are interconnected both vertically and horizontally within a wall. Soil gas that enters the wall through mortar joint cracks or pores in the exterior face can travel through the wall by means of these interconnected voids, and can enter the basement through the voids in the top course of block or through holes, mortar joint cracks, and pores in the interior face of the blocks. The principle of block wall ventilation is to sweep the soil gas out of these voids by drawing suction on (or by blowing air into) this void network. When the wall ventilation system operates to draw suction, the void network within the block wall is maintained at a pressure lower than that in the basement; hence, the flow of any radon-containing soil gas that has leaked through the block pores or through other inaccessible and unsealed openings will be outward with the basement air rather than into the basement.

Two approaches have been considered for implementing block wall ventilation. In one 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 (pipe-wall ventilation approach). In the second approach, 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 (baseboard duct approach). The baseboard duct approach produces a more uniform ventilation of the walls, and may be more aesthetic in some cases, but it is approximately twice as expensive as ventilation achieved by using single suction points in each wall.

Regardless of which of these approaches is used it is crucial that all big openings in the walls be closed. These openings include voids in the top course of block, the gap between the interior block and any exterior brick veneer, and large unsealed holes around utility penetrations through the walls. In principle, small fans have sufficient capacity to handle the relatively small air leakage that will occur through small cracks, block pores, etc. In fact, the whole premise of active wall ventilation is that these little cracks and openings are probably too numerous and inaccessible to seal completely with caulk, epoxy, or mortar, so a fan is used to ensure that soil gas will not flow into the basement through these routes. The fans that can realistically be considered for these two approaches are too small to handle the air flows that could enter the walls through big openings. If the big openings are left unclosed, the entire fan capacity would be consumed in drawing house air (or outside air) through the big openings, and the fan would not be able to maintain adequate suction on the entire void network. Thus, radon reduction could be quite limited.

Applicability

Obviously, this technique applies only to houses with basements constructed with hollow-block walls (concrete block or cinder block). The data obtained by EPA during the testing of wall ventilation on eight houses have shown that this technique produces consistently high reductions in radon only when major openings in the blocks can be effectively closed; otherwise, the technique cannot properly ventilate the wall. In some houses, such effective wall closure is very difficult to achieve; in these houses, the expense involved in trying to accomplish such closure could be prohibitive.

The baseboard duct approach to wall ventilation is particularly applicable in block basements having French drains (also called channel drains) with a 1- or 2-in. gap between the block wall and the concrete slab around the perimeter inside the basement for water drainage purposes. In these houses, the baseboard duct (which would cover the drain) would ventilate not only the wall voids (via the holes drilled into the walls), but also the aggregate underneath the slab. This gap in the slab is a potentially important entry route for soil gas into the basement; thus, the baseboard duct approach is particularly appropriate as it addresses this entry route.

To draw suction on or pressurize the wall void network effectively requires that the major openings in the wall be closed. If large openings (such as the voids in the top course of block) are left open, a fan used for suction would simply draw basement air into the openings close to the fan and exhaust it; the fan probably would *not* effectively draw soil gas out of the wall. In other words, any fan of reasonable capacity would be unable to maintain the wall void network at a lower pressure than the basement, particularly during winter, if there were major openings through which large quantities of house (indoor) or outdoor air could leak into the network. Some houses are constructed in a manner that limits major openings to those that can be closed fairly readily.

An example of a house that is particularly suitable for the wall ventilation system is one where:

(1) All concrete block walls (including any interior walls that penetrate the floor slab and rest on footings as well as perimeter walls) have a top course with the voids reasonably accessible for being mortared and closed

(2) There is no exterior brick veneer

(3) There is no fireplace or chimney structure within any block wall.

By comparison, effective closure of voids could be difficult in houses where the top voids are rendered inaccessible by a sill plate. In houses with exterior veneer on one or more walls, a gap is usually present between the exterior veneer and the interior sheathing or block that connects to the wall voids but is inaccessible for effective closure. Fireplace structures can contain accessible but totally concealed openings at points within the wall.

EPA's testing of three houses considered suitable by the above definition showed very high levels of sustained radon reduction. Testing in several less suitable houses (i.e., houses having one or more of the difficulties discussed in the previous paragraph) demonstrated that reasonably high levels of reduction were generally achieved in the summer, but these reductions were lost again with the onset of cold weather. EPA is currently working to define approaches for achieving good year-round performance with wall ventilation on houses in which effective closure is more difficult to achieve. Currently, however, high sustained levels of reduction can be confidently expected only on suitable houses.

In summary, wall ventilation would be most applicable to:

(1) Concrete block basement houses that have reasonably accessible top voids, no exterior brick veneer, and no fireplace structure within a block wall

(2) Houses fitting the above description, but with French drains (in which case the baseboard duct variation is particularly appropriate).

The wall ventilation system (whether the pipe-wall ventilation approach or the baseboard duct approach is selected) can be designed and operated with suction or ventilation on the hollow-block wall voids. If the wall ventilation system operates by suction, the void network is maintained at a pressure lower than both the basement and the surrounding soil. Any soil gas that penetrates into the wall (through cracks and pores in the exterior face) is drawn out by the fan. If there are small unsealed cracks or holes in the interior face of the basement wall (e.g., small mortar joint cracks), the gas flow will consist of basement air flowing *into* the cracks (and out through the fan) rather than soil gas flowing into the basement. The gas flow through the pores of the blocks also will be in the direction of basement air entering the blocks, and thus keep radon out of the basement.

Based on EPA's experience, the subsequent discussions on maintaining hollow-block wall ventilation for radon reduction focus on the operation of the system under suction. As mentioned earlier the system could be operated to blow into the walls and thus maintain the hollow-block wall voids under pressure. In this case, the voids would be at a pressure higher than the surrounding soil gas. Any air flow across the exterior face of the block would be clean outside air (from the fan) flowing out into the soil rather than radon-containing soil gas entering the block voids. Essentially all of the subsequent discussion of wall ventilation design would be equally applicable to depressurization or pressurization of the void network.

Confidence

EPA has tested wall ventilation in eight concrete block basement houses to date: six use pipe-wall ventilation and the other two use baseboard ducts (He86). In all of this testing, the fans were operated to draw suction on the walls (not to pressurize the walls). Three of the six single-pipe wall ventilation houses lent themselves to effective closure (although a portion of one wall of House No. 14A has veneer). Testing results on these three houses are shown in Table 6.

Table 6. Results Obtained With Wall Ventilation In Three Test Houses

House No.	Concentration before technique installed, WL: Early 1985	July/ Aug. 1985	Concentration after technique installed, WL: July/ Aug. 1985	Nov./ Dec. 1985
3A	1.7 - 3.0	4.2 - 7.4	0.005 - 0.01	0.005 - 0.01
8	0.13 - 1.7	0.26 - 0.80	0.005 - 0.02	0.01 - 0.02
14A	0.12 - 0.42	0.26 - 0.34	Not available	0.005

Except for the early 1985 premitigation values, these values are each based on 1 or 2 days of continuous radon monitoring by EPA during the months indicated; the early 1985 results are based on both grab sampling and longer-term integrated measurements by the Pennsylvania Department of Environmental Resources (PDER85). These data demonstrate that very high radon reductions can be achieved and sustained into the cold weather months if effective closure of major wall openings is achieved.

In the remaining five houses, which were less suitable for effective closure, the wall ventilation installations were able to achieve reductions of between 81 and 99 percent during the summer months but were unable to maintain this performance into the cold weather months. The premitigation levels measured by EPA in July and August (0.14 to 2.4 WL) in these five houses were reduced to 0.005 to 0.06 WL in the summer after the technique was installed, but the levels increased to 0.05 to 1.0 WL when followup measurements were made in November and December. Each of these five houses had significant unclosed openings in the block walls (three of them had brick veneer on three or four walls). EPA is currently exploring effective ways of applying wall ventilation to these more complex houses. Technique modifications under study include additional fan capacity, redesigned ducting, and ways of sealing inaccessible wall openings.

EPA's testing in the three houses that were suitable for effective wall closure demonstrated that very high radon reductions can be achieved and maintained in such houses. Nonetheless, demonstrations are needed on a variety of additional suitable houses to increase confidence in the reliability of the technique and to identify other house design features that could result in sufficient inaccessible wall openings to reduce wall ventilation performance. Furthermore, EPA's measurements in the three houses where this approach was successful have been relatively short-term (1 to 2 days of continuous monitoring); longer-term (2-month) monitoring and observation of system performance for a year or longer are needed to confirm these results. Based on these considerations, it is believed that there can be moderate to high confidence that suitable houses can be identified for the successful application of wall ventilation for the reduction of indoor radon levels.

Even in less suitable houses with inaccessible top voids, exterior veneer and/or a fireplace structure, it is still possible that wall ventilation can work successfully (e.g., through increased fan capacity and/or special closure efforts); however, EPA has not yet demonstrated consistently high radon reductions in such houses. Thus, the confidence in the performance of wall ventilation in these houses must be considered low to moderate at present.

Some question exists as to how well wall ventilation ventilates the aggregate under the concrete slab at points remote from the wall. The ability of wall ventilation to provide such sub-slab ventilation depends on the effectiveness of communication between the bottom course of block and the sub-slab (i.e., the nature of the mortaring and slab-pouring when the house was built), the condition of the aggregate, the extent of slab cracks, and the size of the ventilation fan. The baseboard duct approach may provide a greater potential for simultaneous ventilation of the sub-slab, especially when the duct is laid over a French drain.

Design and Installation (Pipe-Wall Ventilation Approach)

A wall ventilation system using the pipe-wall ventilation method is shown in Figure 5. In this system, generally one pipe (sometimes two) would be embedded in each wall to ventilate the void network. Figure 5 depicts the system as drawing suction on the wall.

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 those 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 (i.e., is essentially open to the basement or to other parts of the home), the block walls around the crawl space also must be vented. The concern with above-grade and interior walls arises because the mortar joint between the bottom course of block and the footings appears to be a major entry route for soil gas into the void network; thus, *any* block wall that contacts footings can serve as a chimney for soil gas to flow into the home, even if the exterior face of the block does not appear to contact the soil.

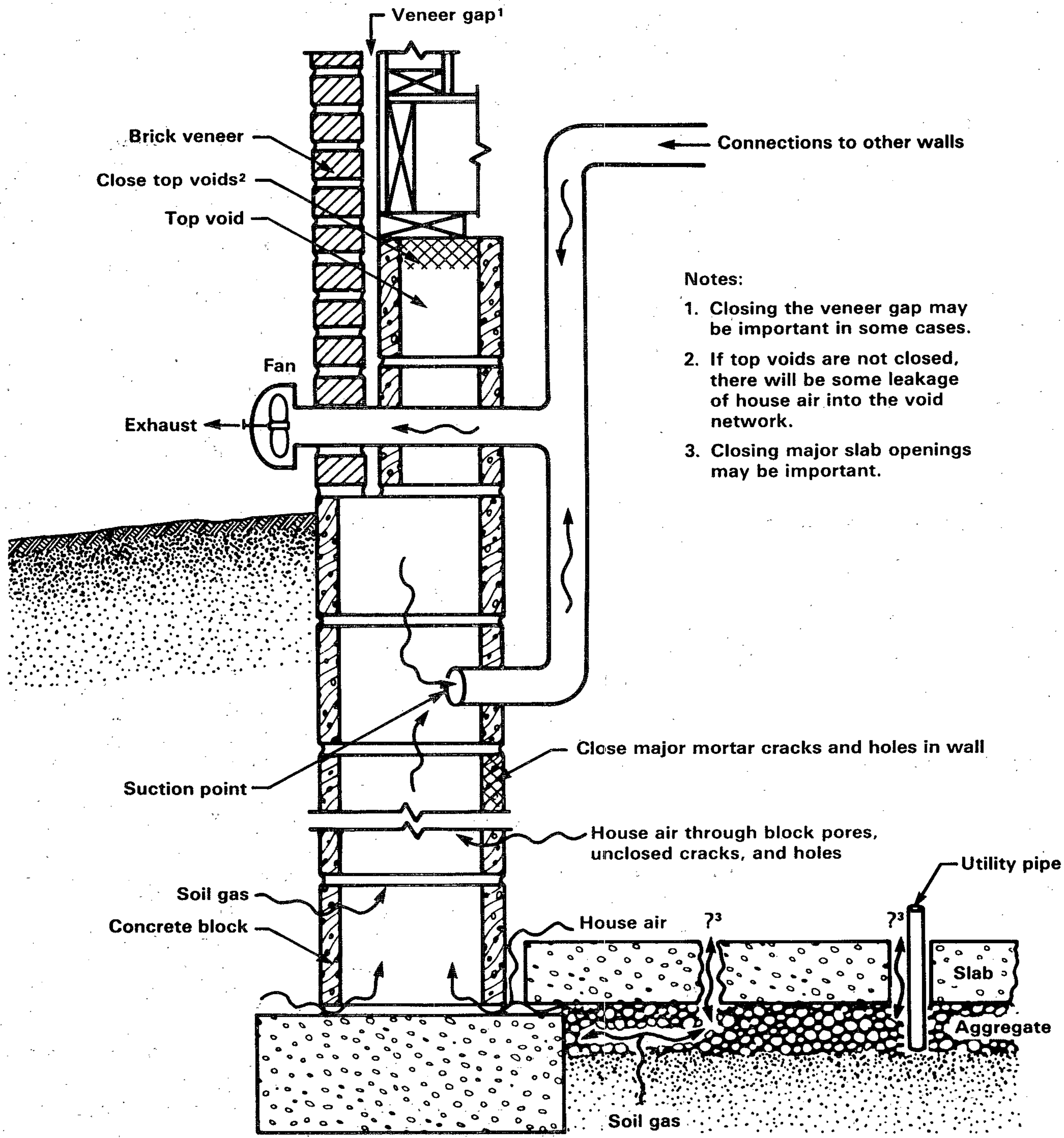
Number and Location of Wall Suction Points

In the three houses where EPA experienced the greatest success with wall ventilation, one suction point per wall was generally adequate. At least one suction point per wall is necessary because there is no guarantee that effective communication has been maintained between the voids in turning a corner. The mason who laid the block during construction might have applied the mortar and laid the block in a manner that would prevent suction on one wall from being effectively transmitted to the adjoining wall. If there is reason to believe that a particular wall could be subject to greater leakage of basement or outside air (e.g., due to the presence of brick veneer on the exterior of that wall) and thus the pipe into the wall could be handling a larger than average air flow, a second suction point would probably be advisable. If a segment of a particular wall is offset from the remainder of that wall (e.g., by a pair of right-angle turns in the block), that offset segment probably should have a suction point of its own, again because the suction in the main part of the wall might not effectively turn the corner.

It appears reasonable to locate a single suction point approximately in the linear center of the wall (or the segment of wall) that it is meant to treat. A rule of thumb applied in the EPA testing was to use one suction point for each 24 ft of wall length (i.e., 12 ft on either side of the suction point). When the wall was longer than 24 ft, two suction points were provided. If multiple points are used in a given wall, logical placement would be approximately one-quarter of the wall length from each end of the wall. In terms of height, it is generally advantageous to place the suction points as close to the floor as possible in order to sweep the top courses of voids with clean air entering through any leaks (rather than drawing soil gas up into the void network). Often practicality or aesthetics may prohibit placement of the suction points near the floor; in this case, it is acceptable to place them higher. In a house where effective closure of wall openings is possible, the height of the points should not be important.

The suction points may be located either inside or outside the basement. Figure 5 shows them inside the basement and connected to an outdoor fan. Inside installation is generally more simple 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 panelling and putting a piping network inside the living area. If a basement wall is partially above grade, access to the block voids from outdoors should not be a problem. Outside installation would simply involve drilling halfway into the blocks from the outside rather than the inside and mounting the pipe outside. When a basement is largely below grade, outside mounting would require the digging of a small well against the exterior basement wall, similar to a basement win-

Figure 5. Wall ventilation with individual suction points in each wall.



Notes:

1. Closing the veneer gap may be important in some cases.
2. If top voids are not closed, there will be some leakage of house air into the void network.
3. Closing major slab openings may be important.

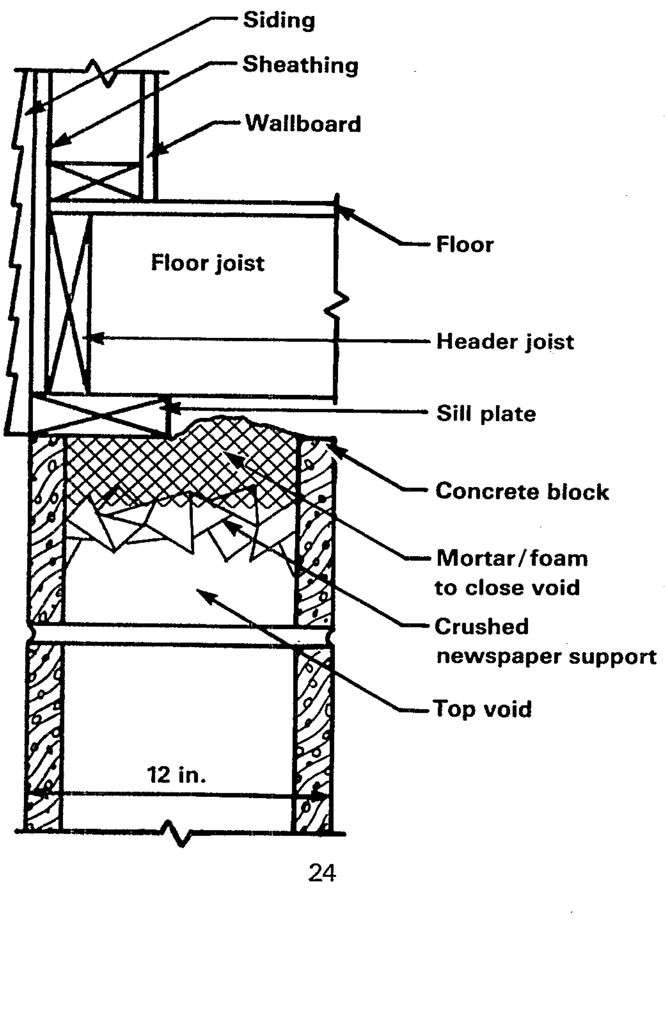
dow well, to provide access. If desired, such a well could be filled in after the piping was mounted and brought above grade. For interior walls, of course, the only option is to make the penetration inside the basement. The least obtrusive approach for making this penetration (and installing the piping) is a house-specific decision.

Closing Major Wall Openings—Top Voids

The voids in the top course of block interconnect with all of the other voids inside the wall and must be adequately closed; otherwise, the wall ventilation system will be unable to maintain the void network reliably at a pressure lower than the basement. In cases where these top voids were capped with solid block during construction, an effective closure is almost ensured. This situation did not occur, however, in most of the houses that EPA inspected in eastern Pennsylvania.

In some houses the top voids are sufficiently accessible for a person to reach down into the voids. This situation can occur when 12-in.-wide blocks have been used and the sill plate is sufficiently small that much of the void is exposed (see Figure 6). Voids

Figure 6. Closing top void when a fair amount of the void is exposed.



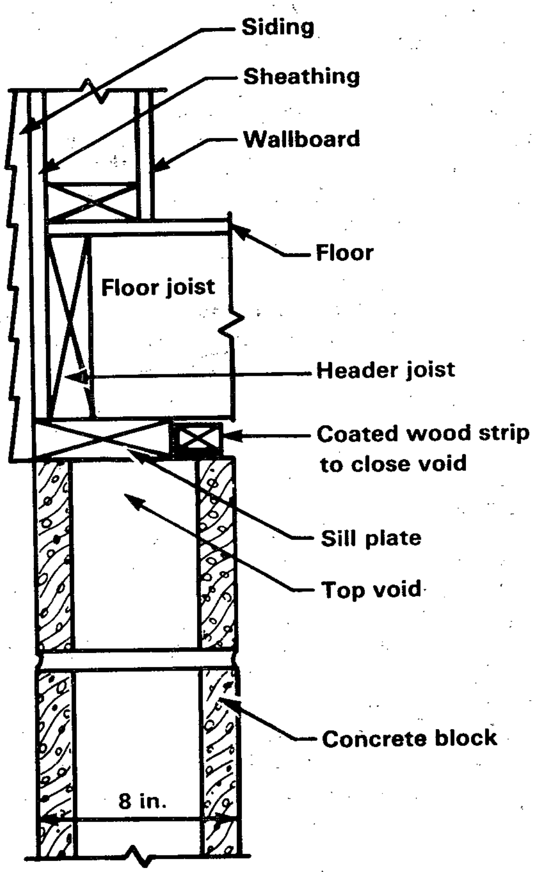
that are thus exposed on one or more of the walls can be effectively closed, and the house may be particularly suitable for wall ventilation. The best approach is to force crumpled newspaper (or some other suitable support) down into every void in the wall and then to fill the entire void carefully with mortar to a depth of at least 2 in., as shown in Figure 6. It is crucial that the mortar be forced all the way to the far face of the void under the sill plate; mortaring only the exposed part of the void would greatly reduce the effectiveness of the seal. Closing every void in the wall is a slow and difficult process, but it will pay high dividends in improved system performance.

In some houses, where the voids were fairly accessible but space was somewhat more limited, EPA used a single-component urethane foam that could be extruded through a hose-and-nozzle assembly. Some of the foams are available in aerosol cans for household use and some are available for commercial applications. Even with the use of foam, it was still necessary to force a crumpled newspaper support down into each void; however, the use of the hose and the expanding foam eliminated the need for the void opening to be large enough to accommodate part of a person's hand. Thus, where the void access is not large enough to permit mortaring but is large enough to force newspaper through, the use of a foam can be considered.

In other houses, the top voids may be entirely blocked by the sill plate. This can occur where 8-in.-wide blocks are used, and the sill plate is so large that it essentially covers the top of the block (see Figure 7). The successful application of wall ventilation is still possible in these houses. Two of the three houses where EPA had the greatest success with wall ventilation had one wall, or a portion of one wall, where the voids were inaccessible in this manner. If literally none of the void is visible under the sill plate, an attempt can be made to use the sill plate to close the void by caulking the seam between the sill plate and the top blocks with silicone caulk. When a fraction of an inch of void was exposed—too small to force crumpled newspaper and a foam nozzle through, but possibly too large to close with caulk—EPA used one approach that involved coating two sides of a strip of wood with caulk or some other suitable sealant (e.g., tar) and nailing this strip tightly in place over the void, and pressed against the sill plate and the block (Figure 7).

Figures 6 and 7 depict a house without exterior brick veneer. When walls are covered with veneer, often few or none of the top voids are exposed inside the basement because the veneer will displace the sill plate toward the inside face of the block. Thus, mortaring or foaming the block voids shut generally will not be feasible. Instead, the use of caulk (or the tar-covered wood strip approach) is required.

Figure 7. One option for closing top void when little of the void is exposed.



It is reemphasized that the *top voids must be closed in all walls— including interior block walls that rest on footings as well as exterior perimeter walls.*

Closing Major Wall Openings—Holes and Cracks in Walls

Any other visible holes or major cracks in basement walls should also be closed. Holes in the wall around utility penetrations should be closed by mortaring around the pipe or duct. Major mortar joint cracks should be sealed with caulk or some other appropriate type of sealant.

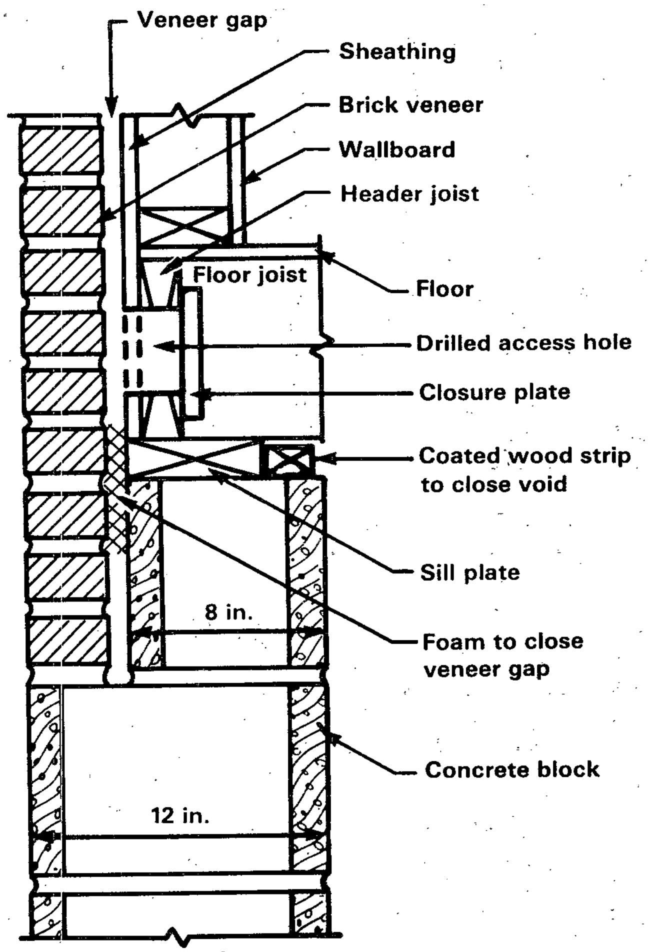
Although the pores inherently present in concrete blocks permit air leakage, they generally do not allow enough air to penetrate to overwhelm the capacity of the fan. Hence, no special effort is required to seal concrete blocks as part of a wall ventilation installation. When houses are constructed of cinder block, however, the far more porous block makes it difficult to maintain adequate suction. If wall ventilation is to be attempted in a cinder block basement, consideration probably should be given to sealing the pores in some manner. One approach that EPA has used successfully is coating the inside of the entire basement wall with a latex waterproofing paint containing Portland cement. Some other (higher-cost) options include epoxy paints and other coatings or waterproofing membranes (e.g., polymers).

Closing Major Wall Openings—Gaps Created by 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 8. 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.

EPA has not yet demonstrated very high sustained radon reductions by using wall ventilation in houses with brick veneer on more than a portion of one wall. Nor has the Agency yet confirmed that this inaccessible veneer gap is a major cause of this lack of

Figure 8. Closing top void and veneer gap when exterior brick veneer is present.



success. Measurements in some veneered houses suggest that this gap may not be a major source of air leakage and that additional fan capacity should improve radon control. EPA has attempted to close this gap by drilling through the header joist and using a hose-and-nozzle assembly to extrude urethane foam into the gap (Figure 8), but the effectiveness of this closure or the best way to accomplish it have not been confirmed. Further assessment is needed in this area.

In view of the current lack of a successful demonstration in houses with one or more complete veneer walls, such houses are currently considered less suitable for application of the wall ventilation technique. Until further testing is completed, anyone attempting to install a wall ventilation system in a veneered house should plan initially on doubling the fan capacity. If effective performance is still not achieved, attempts should be made to seal the veneer gap as illustrated in Figure 8.

Closing Major Wall Openings—Fireplace Structures

Fireplace structures incorporated into block walls offer the potential for numerous invisible, 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 draw suction on the surrounding wall may be difficult or impossible—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. Because the latter is expensive, EPA is testing an approach that involves increasing fan capacity in an effort to maintain adequate suction despite this leakage. Although its success has not yet been demonstrated suitable increases in fan capacity may solve the problem of fireplace structure leakage in many houses.

Closing Slab Openings

Although closing openings in the concrete slab is usually unnecessary for effective suction on the wall, large openings in the slab can be an important source of soil gas flow into the home, and such openings should be closed. Wall suction will not always treat all of the slab-related entry routes for soil gas; thus, it is important to address at least the major slab-related routes in conjunction with the installation of any wall suction system. Large holes and cold joints should be mortared shut or otherwise closed, as discussed in Section 2.6. In particular, for the purposes of wall ventilation, any large cracks visible in the wall/floor joint should be sealed. Such large cracks, which represent defects when the concrete slab was poured, could serve as a source of air leakage into the wall and reduce the effectiveness of maintaining the wall under suction. If the wall/floor joint consists of a French drain, this gap should *not* be mortared shut; rather, the homeowner should take advantage of the drain by selecting the baseboard duct approach for wall ventilation.

Open sumps in the basement should be covered and possibly ventilated, as discussed in Section 2.5. Floor drains that drain to a septic tank and thus contain a trap beneath the slab should be checked to ensure that the trap is full of water. Otherwise, soil gas (and odors) from the septic tank may come up the drain line and enter the home through the floor drain. If a floor drain contains a cleanout plug beyond the trap, this plug must be in place to prevent septic tank or sewer gas from entering the house even though the trap is full of water. A floor drain that connects directly to drain tiles may not be equipped with a trap. Such untrapped floor drains can be important sources of soil gas and must be plugged in some manner. Removable stoppers can be fabricated or purchased commercially. If the floor drain is ever needed (e.g., because a clothes washer or water heater in the basement overflows), the stopper can be removed temporarily. The only alternative to this stopper approach is to install a trap in the drain line, which would likely require tearing up part of the slab around the drain. With the slight depressurization of the basement that can take place when wall suction systems are in operation, failure to address these other soil gas entry routes not associated with the walls can become increasingly important.

Piping Network Design

Pipes must be mounted and sealed into each wall suction point and connected to one or more fans. This can be designed in several ways, the most satisfactory method determined largely by the preference of the individual homeowner.

EPA used Schedule 40 plastic sewer pipe in the test houses because this pipe seemed to be the easiest for a homeowner to work with. Other piping could be chosen for some parts of the piping network; e.g., metal air ducting. In general, 4-in. plastic sewer pipe should be used. Smaller pipe could be considered and may be more aesthetic in some installations. In general, however, the larger diameter piping is better. Since significant pressure drops can occur through the piping, the larger the diameter of the pipe, the lower the flow velocity, and thus the lower the pressure drop. A high pressure drop can cause the fan(s) to consume much of their suction capability in moving the gas through the pipes; therefore, less capacity will be available for drawing suction on the walls. Also, numerous bends in the piping increase the pressure drop. Therefore, the use of larger diameter pipe with as few bends as possible will increase the effectiveness with which a given fan ventilates the walls.

At the selected suction points in each wall, a hole should be drilled or chiseled through the near face of the block wall to expose the interior voids, but it should not penetrate all the way through the far face of the block. Logically the hole would be drilled into a void in one of the blocks (i.e., at a point midway between the end and the middle of the block). The hole dimensions should be as close as possible to those of the piping being used; e.g., a circle roughly 4 in. in diameter if 4-in. sewer pipe is being used. After the piping is mounted in this hole, any gap between the block and pipe must be sealed tightly so that air cannot leak into the block through the space around the pipe. Such leakage could reduce the effectiveness of the ventilation system in the same manner as that from other major unclosed openings in the wall. In the EPA testing, an asphaltic caulk was generally used to seal the gap between the pipe and the block.

If the penetration into the block is from the outside of the house, the fan can be mounted directly on the short, straight section of pipe that is embedded in the wall. In this design, a fan would be mounted onto the outside foundation wall at each suction point. If the wall is below grade at a given suction point, the fan would have to be mounted in a small well (similar to a window well) dug for this purpose or an elbow could be installed to bring the pipe above grade before mounting the fan. Although this design would ensure the least pressure loss through the piping network, it would probably result in more fans than would really be necessary (one per suction point, at least four per house). Another possibility might be to mount one fan at the rear of the house or perhaps one fan near each of the two rear corners and to tee the piping from each exterior suction point into a central collection pipe that runs around the perimeter of the house and back to the fans. If there are two fans, logically there would be two collector pipes, one around each side of the house. One configuration for such a system could include 6-in. pipe to serve as the central collector, with 4-in. diameter legs tapping off from the collector to penetrate the walls at the selected suction points. These pipe sizes should reduce the pressure loss in the pipe. For aesthetic purposes, some of this piping could be buried, especially in front of the house.

If the penetration into the block is from inside the basement, it would be generally reasonable to use elbows to bring the pipe legs from each suction point up to the floor joists, where they could be tapped into a central collection pipe. This central collector could conveniently run near the ceiling, up between the floor joists, and penetrate the wall at a convenient point to connect to a fan mounted on the collector pipe just outside the house. An alternative would be to have the collector exit the house through a window. Penetrating the wall would be a more permanent installation, however, and would facilitate mounting of the fan (as the fan could then be attached directly to the plastic pipe on the exterior wall). If more than one fan were used, it would be logical to have an additional collector for each fan. In this design, a fan would be attached to the side of the house at each point where a collector penetrates a wall. Again, a reasonable choice (to reduce pressure drops in the pipe) would include 4-in.-diameter legs from each suction point that tap into 6-in. collectors.

The preceding discussion assumes that the fan is mounted outside the house; however, the fan could be mounted inside the house with the fan exhaust pipe penetrating the wall so that the soil gas is exhausted outdoors. This design would avoid problems with freeze-up during the winter, but it results in fan noise indoors. Also, any leaks in the exhaust system would allow soil gas to be released inside the house.

Logistic considerations for each house probably will play some role in determining where the fans are located; however, locating them away from windows and bedroom walls would be generally desirable to reduce the inconvenience of fan noise. Positioning them away from windows also will reduce the risk of prevailing winds carrying fan exhaust with an elevated radon-level into open windows. As mentioned earlier, some homeowners may wish to locate the fans remote from the house by running a length of pipe some distance into the back yard. This would reduce fan noise and the risk of backwash, but the resulting increase in pressure drop could necessitate additional fan capacity to maintain effective suction on the walls.

Selection and Mounting of Fans

The fans used most commonly in the EPA testing of wall ventilation were 250 cfm centrifugal fans capable of drawing about 1/4-in. of water suction. In some cases, 160 cfm centrifugal fans (capable of 1 in. of water suction) were used. In the three houses where radon reduction was deemed successful, a single fan was sufficient. In two of these houses, a single 250-cfm fan was used; in the third, a single 160-cfm fan was used.

In houses where the closing of potentially major wall openings is difficult, more fans may be necessary to accommodate the increased leakage of basement air or outside air into the walls. Testing has not yet confirmed exactly how much fan capacity is required under various circumstances where effective sealing is difficult. For houses that include a wall with exterior brick veneer or with a fireplace structure, however, the use of at least two fans is suggested.

Caution must be applied if several fans are used to try to compensate for air leakage through inaccessible openings in a wall. *Under these conditions, the fans could depressurize the basement sufficiently to cause back-drafting of combustion appliances* (furnaces, fireplaces, etc.). If this occurred, the products of combustion from these appliances could be drawn out into the room instead of being drawn naturally up the flue. Such a depressurized condition could result in carbon monoxide poisoning. Where the threat of back-drafting exists, it would be advisable to consider reversing the fans so that they pressurize the walls rather than drawing suction. This avoids the back-draft threat. Currently, however, EPA has no data on the performance of wall ventilation systems operating under pressure.

The fans should be tightly clamped to the collector pipes. Any gaps in the connection between the fan and the pipe should be caulked or otherwise sealed to ensure an airtight fitting. If the fan is mounted outdoors, some reasonable weather protection for the fan should be provided. The 250-cfm fans used in the EPA tests were intended for exterior roof or wall mounting and thus came from the supplier with a protective aluminum housing. For unprotected fans, a protective housing would have to be fabricated. If the fans are mounted at a point outside the house that is lower than the suction points in the walls, the fan and motor should be protected from condensed moisture during the winter. If the fans are mounted inside the house, extreme care should be taken to ensure that the exhaust pipe is tightly mounted onto the fan outlet and that there are no leaks between the fan and the point where the exhaust pipe ends outdoors.

Fans can be made to draw suction on the wall or to pressurize the wall, either of which would likely reduce radon levels. To date, all of EPA's testing has been with the fans in suction because of the concern that cold outside air blown into the walls during winter months could cause condensation of moisture on the wall inside the basement. As discussed earlier, operation under pressure might be advisable where major unclosed wall openings exist and pose a threat of basement depressurization and back-drafting.

Testing Wall Ventilation Effectiveness

When the fans are turned on for the first time, and periodically thereafter, the homeowner would be well advised to test how well the fans are maintaining suction on the wall. A simple way to do this is to use a smoke-generating device such as an incense stick. As the smoke generator is passed over the surface of the wall, along the top of the wall, and along the wall/floor joint, the smoke should consistently be drawn into the block pores and the cracks around the total perimeter. If the smoke is blown outward at any point, soil gas may be entering the house at that point because adequate suction is not being maintained.

Design and Installation (Baseboard Duct Approach)

Wall ventilation with baseboard ducts is illustrated in Figure 9. In this approach, hollow-wall ventilation is provided by a sheet metal duct that is sealed over the wall/floor joint around the entire perimeter of the basement and on any interior block walls that penetrate the basement slab to rest on footings under the slab. Holes are drilled into each void within the baseboard duct to permit ventilation of the void network. (In some houses, the wall/floor joint consists of a French drain.) Baseboard ducts offer more uniform distribution of the ventilation than does the individual pipe-wall method because the baseboard holes into the void network are drilled along the entire linear distance of block wall, rather than being placed all at one point. Also, because the baseboard ventilation holes are at the bottom of the wall, baseboard ventilation could provide a more effective "sweeping" of the upper courses of block. Clean air leaking in near the top of the fan offers greater potential for keeping the voids in the upper courses relatively free of soil gas.

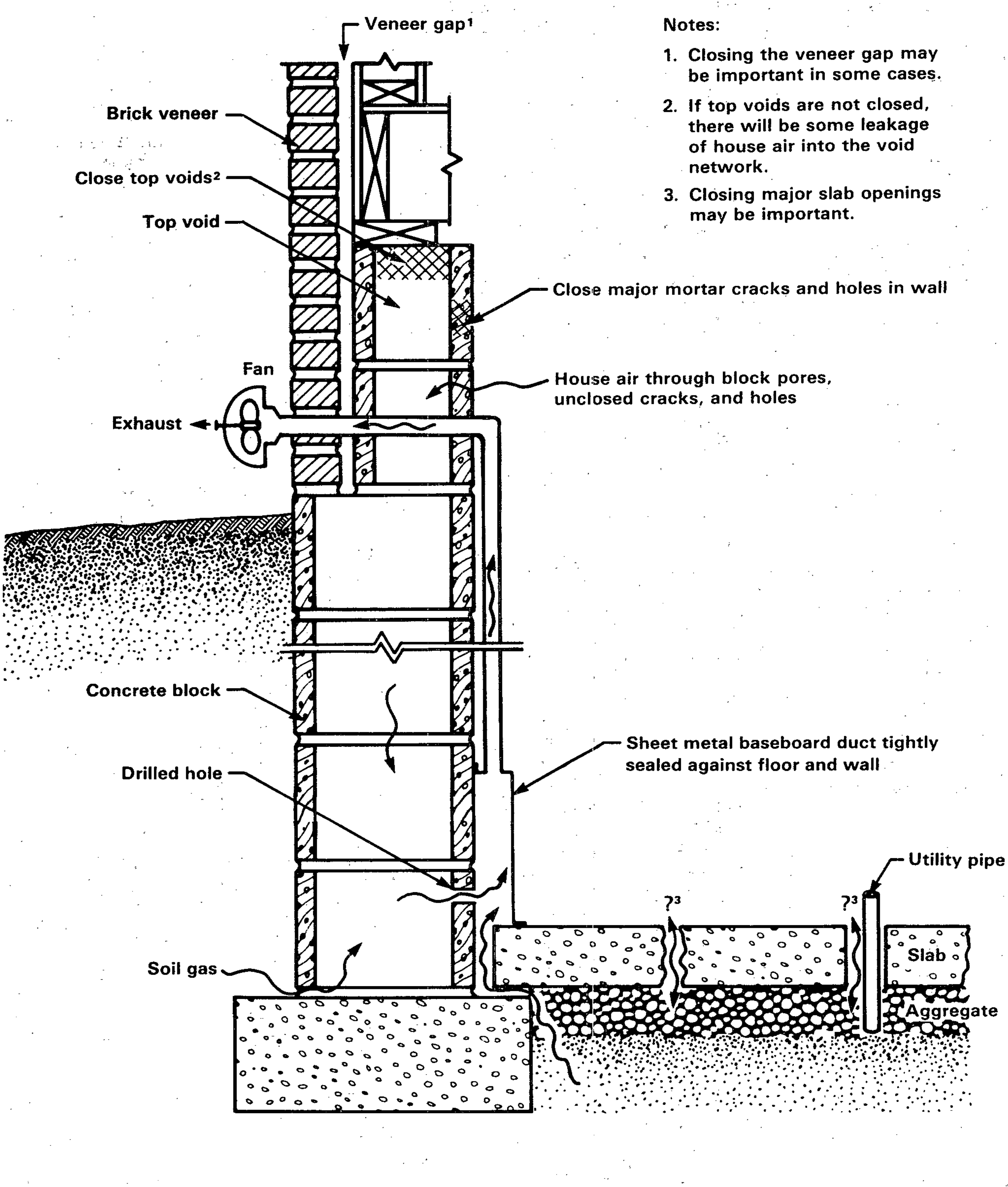
Selection of Walls To Be Ventilated

A baseboard duct must be installed on every block wall in the basement that rests on footings, including both interior and exterior walls. For an interior wall on which both faces of the wall are accessible, installing the baseboard duct on just one face might be sufficient. 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. The baseboard duct should be installed on the entire linear distance of the wall/floor joint around the total basement perimeter. Some interruptions in the duct could be considered at particularly inaccessible locations (e.g., behind a furnace or stairwell that is essentially against the wall). *All* segments of a French drain must be covered or mortared shut if really inaccessible for the duct. If a significant crack is evident along the wall/floor joint on the untreated face of the interior wall, this crack should be closed.

Closing Major Wall Openings

All major wall openings—the top voids, large holes and cracks, the brick veneer gap, and openings associated with fireplace structures—must be closed. Any major openings in the concrete slab should also be closed, as discussed previously, *except* cracks associated with the wall/floor joint. These do not have to be sealed because the baseboard duct treats this

Figure 9. Wall ventilation with baseboard duct.



joint. Such cracks actually may be helpful, as they can improve communication between the duct and the wall voids or sub-slab aggregate.

Design of Baseboard Duct System

As indicated previously, the duct should cover the wall/floor joint everywhere around the entire basement perimeter, and on at least one face of every interior wall. If the duct must be interrupted at any point because the joint becomes inaccessible, the end of the duct must be capped off so that proper suction is maintained. All lengths of French drain must be covered by the duct. Any inaccessible segment of the drain should be mortared shut, not only because it would be an untreated source of soil gas into the house, but because it could serve as a source of basement air leakage into the adjacent 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.

The baseboard ducts can be fabricated out of sheet metal, or they can be created with internal channel drains that are sold commercially. EPA has tested both materials and found that sheet metal offers greater flexibility for selecting duct size and fitting to the contours of the basement perimeter. 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, the duct was anchored to the wall and floor with masonry screws and sealed against the wall and the slab by a continuous bead of asphaltic caulk. It is *crucial* that the connection against the wall and the slab be airtight; otherwise, basement air will leak into the duct and prevent the system from being effective. Masonry screws alone will not ensure an adequate seal.

Wherever the duct must be interrupted, the open end of the duct must be sealed, preferably with sheet metal, and a sealant must be applied over residual seams. Particular care must be made where the duct "turns corners." The seam between the legs joined at the corner must be carefully sealed. When the slab is not perfectly flat, special care is required and additional caulking is needed to ensure that a good seal is maintained.

Figure 9 illustrates a duct with a rectangular cross section; triangular cross sections also were used in the EPA testing. 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 *size* of the duct is important. Of course it would be large enough to cover the holes drilled in the wall and any French drain that exists. Beyond that, it also must 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 (e.g., due to a brick veneer gap or to a fireplace structure), a larger duct will be required.

In recent testing in one house with such potential sources of air leakage through unsealed wall openings, EPA used a triangular sheet metal duct configuration that covered (in cross section) an area of the wall from the floor to 8 in. above the floor and extended up to 3 in. away from the wall. In a second house where even larger leakage was expected a rectangular duct was used covering an area of the wall to 12 in. above the floor, and extending 3 in. away from the wall (Figure 9). Smaller ducts might be considered in houses that have no major inaccessible wall openings, or when the homeowner wants to use a larger number of fans.

Unlike the pipe-wall ventilation method, the baseboard approach requires that ventilation points be installed inside the basement. In finished basements, this entails extra effort to install the duct behind the wallboard or panelling, or to cut off the bottom of the wall finishing to accommodate the duct.

The installed duct must be connected to one or more fans. This can be done in a number of ways, but the method typically used in the EPA testing was to tap plastic sewer pipe (typically 2 in. diameter) or metal ducting into the baseboard duct at one or more locations and then to lead each pipe through a window or through the wall to connect to a fan outside. As an alternative, the fan could be mounted inside the house with the exhaust pipe leading outdoors. If more than one segment of duct has been used (i.e., if the duct has had to be interrupted and does not form a continuous loop), each segment must have a tap that connects to a fan. Places where the plastic pipe taps into the sheet metal baseboard duct must be effectively sealed with caulk or an asphaltic sealant. The same considerations apply to positioning the fans as those discussed for the pipe-wall ventilation method. In general, if more than one fan is used, it seems reasonable to locate them at opposite ends of the house to help ensure effective suction around the total perimeter.

Selection and Mounting of Fans

In the baseboard duct installations tested to date by EPA either 250-cfm centrifugal fans (1/4-in. of water suction) or 160-cfm centrifugal fans (1 in. of water suction) were used. In one house, only one fan was used; however, more commonly, two fans were used, typically mounted at the two rear corners of the house. In houses with inaccessible openings in the wall, such as a brick veneer gap or a fireplace, more than one fan should be used. Testing has not yet confirmed exactly how much fan capacity is required under various circumstances where effective sealing is difficult. As discussed previously, the ventilation system can be operated to pressurize the walls rather than to draw suction if back-drafting is a threat. Fan-mounting considerations are the same as those discussed previously for the pipe-wall ventilation approach.

Testing Wall Ventilation Effectiveness

Periodic testing is suggested to determine how well the fans are maintaining suction on the wall by using the smoke technique described previously. With the pipe-wall ventilation approach, smoke tracer results suggest that there is sufficient communication in some houses between the bottom course of blocks and the aggregate underneath the slab to achieve ventilation of the wall/floor joint and thus prevent soil gas from entering via that joint. (Baseboard ducts enclose and ventilate the joints directly.)

Operation and Maintenance

The operation and maintenance requirements for either wall ventilation system include regular inspections by the homeowner to ensure that the fan(s) are operating properly (e.g., are not iced up or broken); all seals are still intact (e.g., where the top voids and other wall openings have been sealed, where the pipes penetrate the wall, where the baseboard duct attaches to the wall and the slab, where sections of pipe join together, and where the fan is mounted onto the pipe); and adequate suction is being drawn on the walls (e.g., by use of smoke testing). If the fan is mounted indoors, the exhaust system should be inspected regularly for leaks.

Fan maintenance should be performed routinely, and fans should be replaced as needed. Any seals showing signs of cracking should be repaired with asphaltic sealant or silicone caulk. *The integrity of these seals must be maintained* to permit the system to provide proper wall ventilation. If smoke testing indicates that the system is no longer properly maintaining suction on some portion of the wall, seals should be checked for failure and the duct/piping leading to the fan should be checked for blockage. If the inadequate suction persists, consideration should be given to adding a suction point and/or a fan to improve the ventilation of that portion of wall.

The homeowner should be alert to any signs of back-drafting of fireplaces and combustion appliances in the basement. Odors and smoke inside the basement are signs of back-drafting when a fireplace is operating in the house. Oil-fired burners also may produce such telltale signs.

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 *pipe-wall ventilation method* is installed in a house that lends itself well to effective closure of major wall openings—i.e., top voids are reasonably accessible, has no exterior veneer, contains no fireplace structure—EPA's experience suggests that a private homeowner may have to pay about $2500 to have such a system installed by a contractor. This estimate assumes that the house does not have a finished basement and that the job is completed without the added expense of a "radon mitigation expert" to oversee the contractor's work. The cost estimate includes both materials and labor.

In a house where effective wall closure is more difficult to achieve—possibly one requiring additional effort to close the top voids, having a veneer gap, built with porous cinder block, etc.—the costs could be significantly higher. Also, if the house has a completely finished basement, additional cost (associated with partial dismantling of the paneling, etc.) would be encountered in gaining access to the top voids and other major openings requiring closure. If the pipes are to be installed inside a finished basement, some additional cost would be associated with the modification of the paneling/wallboard, etc., to accommodate the pipes when paneling is replaced.

With the *baseboard duct ventilation method*, costs for installation by a contractor would be higher than for the pipe-wall ventilation approach because more labor is required to attach the duct to the wall and floor. Based on EPA's experience in two houses, the installed cost in a suitable house could run $5000, based on using the same assumptions as those for the pipe-wall ventilation estimate. Again, a less suitable house or a house with a finished basement could significantly increase costs.

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 $100 to $500 for the fans, piping, sheet metal, and incidentials, depending upon the number of fans required and the size of the basement.

Operating costs would include electricity to run the fan(s) and possibly some heating penalty due to increased ventilation of the house (some of the gas drawn out of the walls by the fan includes house air that has been drawn through the block pores and cracks). Occasional replacement of the fan would also be an operational/maintenance cost. The cost of electricity to run a single 0.03-hp (25-W) fan 365 days per year would be about $15. Assuming that the system increases house ventilation by roughly 50 cfm, the cost of heating 50 cfm of outside air to house temperature throughout the winter would be about $125. Thus, the total operating cost would be about $140 per year. This would increase somewhat with each additional fan. Experience is too limited to predict how often each fan might have to be replaced, but a new fan would cost between $40 and $100.

2.9 Ventilation of Sub-Slab

Principle of Operation

Soil gas accumulates in the soil and the aggregate (the crushed rock) that underlies the concrete slab in a basement or a slab-on-grade house. The gas can then enter the house through any opening in the slab; e.g., the wall/floor joint, settling cracks and cold joints, or openings around utility penetrations. In some extreme cases in eastern Pennsylvania, sub-slab soil-gas radon concentrations as high as 10,000 pCi per liter (50 WL) have been measured. The intent of active sub-slab ventilation is to use a fan to sweep the soil gas out of the aggregate before it can enter the house. A frequently employed approach involves using the fan to draw suction on the aggregate and thereby maintaining a pressure lower than that inside the house. With this system, any gas flow consists of cleaner house air flowing outward into the aggregate through the openings in the slab rather than soil gas flowing up into the house.

Two variations of the sub-slab ventilation system have been tested by various researchers: 1) the individual pipe variation, in which two (or more) nonperforated pipes are installed vertically down through the slab and into the aggregate and all ventilation is achieved by drawing suction on (or blowing air into) these pipes; and 2) the perforated piping network variation, in which a more extensive network of horizontal perforated pipe is laid under the slab and suction is drawn on this network. The first approach relies on a good layer of aggregate (or a fairly permeable soil under the slab), so that the effects of the one or two ventilation points can radiate underneath the entire slab. The second approach is less dependent on the uniformity of the aggregate and ensures better ventilation under the total slab; however, this approach could entail considerable effort in cutting channels through an existing slab to place the perforated pipe and could be expensive. In practice this variation has most commonly been used either in new construction or in existing houses where the slab has had to be torn out to remove contaminated soil from under the house (e.g., uranium mill tailings) or when the existing slab has had to be replaced for structural reasons. In these cases, the perforated piping network is then relatively easy to install before a new slab is poured.

Some houses have perforated pipe that was laid under the slab during construction for water drainage purposes. This pipe typically drains into a sump within the house footings. By drawing suction on the sump in such houses, the sub-slab can be ventilated by using this in-place perforated piping network.

An extensive sub-slab piping network sometimes will provide adequate ventilation in a passive mode, without power-driven fans, by connection of the network to a stack which penetrates up through the roof. The suction created by this stack is low (it results from natural thermal effects in the stack and a reduced pressure at the roofline caused by wind movement). The flow resistance through the aggregate, however, sometimes may be sufficiently low so that, with an extensive piping network, this low suction might be adequate.

Applicability

Sub-slab ventilation, by itself, would be most applicable in houses where 1) the concrete slab is expected to contain the major soil gas entry routes (e.g., cracks and other openings), and 2) a reasonably uniform layer of crushed aggregate is known to underlie the entire slab or where soil permeabilities are moderate to high. The slab might be expected to contain the major radon entry routes in slab-on-grade houses and often is in houses with poured concrete basement walls. In concrete block basement houses, the wall void network probably will always contain major radon entry routes. Based on EPA's data, sub-slab ventilation by itself may not always do an adequate job in treating the wall-related entry routes unless major wall openings are effectively sealed, and unless there is good connection between the sub-slab aggregate and the wall voids, so that the sub-slab ventilation system can draw adequate suction on the wall void network. In some concrete block basement houses, effective application of sub-slab suction may require that either a number of individual suction points be installed, or that an extensive network of perforated suction pipe be laid under the existing slab to ensure good sub-slab suction near the wall/floor joint. The use of sub-slab ventilation *in conjunction with* wall ventilation can effectively treat important slab-related entry routes that may not be adequately addressed by wall ventilation (e.g., slab cracks remote from the walls).

A reasonably good, uniform layer of aggregate (or a permeable soil) is necessary to ensure that suction from the sub-slab system extends effectively underneath the total slab. If the aggregate is thin or nonexistent under sections of the slab, then these sections may not be adequately treated. If uncertain about the nature of the aggregate underneath a particular slab, a homeowner should be prepared to install a larger number of individual suction points in the event that, for example, two points per slab prove to be inadequate. An initial test of aggregate permeability discussed in the Design and Installation subsection may provide a preliminary check on the condition of the aggregate. In some houses, a more extensive (and more expensive) network of perforated pipe under the slab may ultimately have to be considered to ensure that the ventilation is adequately distributed.

The sub-slab variation involving a network of perforated pipe under the slab is most applicable in new construction or in houses where the slab must be torn out anyway to remove contaminated material from under the house (or to replace a structurally unacceptable slab). It can also be applicable in houses that already have in place sub-slab drain piping connected to a sump. The extent of the existing sub-slab network in these houses, however, is not always known, and radon reductions achievable by drawing suction on the sump may not be adequate.

Confidence

Variations of the sub-slab ventilation technique have been tested by a number of organizations in the United States, Canada, and Sweden. The performance achieved in these tests has varied, depending on the form of the technique being tested, the design of the particular installation, and the type of substructure a house has. With the individual-pipe variation in houses with poured concrete basements, investigators in all three countries have reported reductions of 80 to 90 percent in the indoor radon concentrations (Er84, Na85, Sc86). In some cases, reductions of 90 to 95 percent have been reported (Br86a). These results cover 39 houses in Sweden, several in the United States, and several in Canada.

EPA's testing of the individual-pipe variation in concrete block basement houses has shown reductions between 58 and 86 percent during summer months, based on hourly measurements of 24 to 48 hour duration before and after the fan was turned on; however, performance deteriorated substantially during cold weather (He86). Other investigators have reported higher reductions with sub-slab suction in concrete block basement houses, up to 96 to 99 percent, with the use of higher-suction fans (Br86b). The radon measurements in these houses, however, were based on several grab samples, and it is not known whether the reported high levels of reduction were sustained through the winter months. None of the individual-pipe sub-slab ventilation tests to date in block basement houses appear to have involved extensive efforts to close major openings in the walls in an effort to improve suction on the wall voids. Such closure efforts may improve performance.

Testing of the sub-slab network variation in both poured concrete basements and concrete block basements in Canada and the United States has yielded highly variable results (Ar82). The variations are caused by differences in the extent and configuration of the perforated piping network beneath the slab; whether or not a fan was utilized to draw suction on the network (in some cases, the systems were passive, and did not include a fan); and the extent of other remedial steps taken in conjunction with the sub-slab installation. Many of these network installations were part of a remedial program in existing houses built over contaminated soil (e.g., uranium mill tailings) or were incorporated into new construction in these locations. A power-driven fan often was not employed because the higher levels of reduction provided by an active fan were not required to reduce the radon levels in the houses below the target level. Thus, the optimum performance available by retrofitting one of these systems into a house having a very high natural radon level, has not been demonstrated consistently. Reductions up to 95 percent and higher were realized in existing houses where such networks have been installed even without a power-driven fan, but it is not entirely clear what fraction of the reduction can be attributed to the sub-slab system and what fraction to other remedial steps that were implemented simultaneously (e.g., removal of contaminated material from underneath the slab).

The radon levels in one concrete block basement house were reduced by greater than 99 percent on a sustained basis by use of a passive sub-slab system in combination with other mitigation steps (i.e., sealing of block walls, replacing the slab, placement of good aggregate, and placing a polymer liner under the new slab) (Ta85). In another house with a piping network (of unknown extent) already in place underneath the slab, suction on the sump into which the pipe drained produced radon reductions in excess of 90 percent (Sa84).

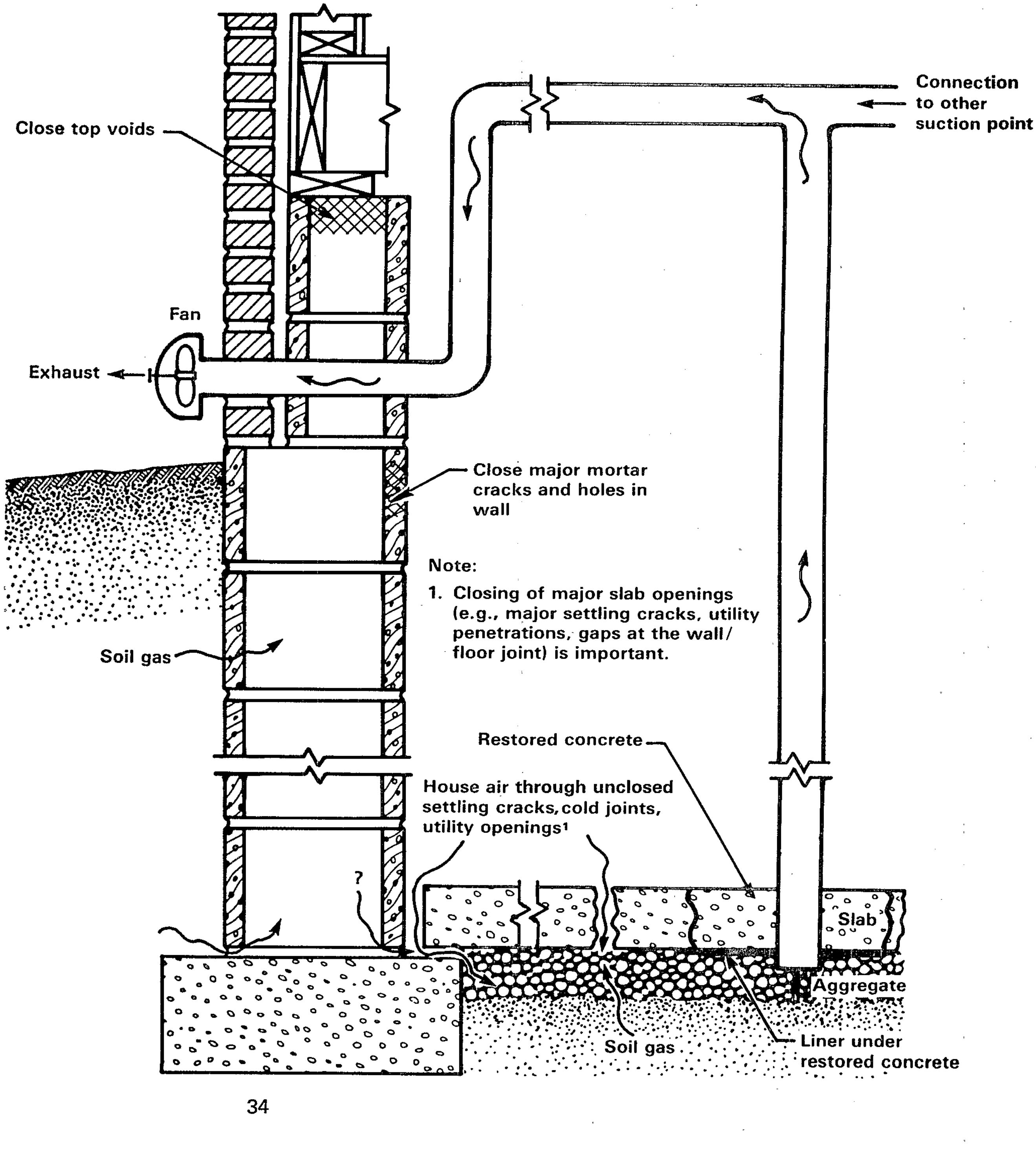
The confidence level of the sub-slab ventilation system is believed to be as follows:

- Individual-pipe variation in houses with poured concrete basement walls and in slab-on-grade houses—moderate. The major uncertainties are the nature of the aggregate (and/or the permeability of the soil) beneath the slab, and the effectiveness with which separate radon reduction steps are implemented to address soil gas entry routes associated with the concrete basement walls (e.g., closing of cracks and holes).
- Individual-pipe variation in concrete block basement houses—low. This rating is based on EPA's experience to date and the limited nature of the data from other sources. This confidence level might be increased through the use of

1) higher-suction fans, 2) more effective wall closure in conjunction with sub-slab ventilation, 3) an increased number of sub-slab suction points near the walls, or 4) the perforated pipe network variation.

- The perforated pipe network variation in poured concrete basement and slab-on-grade houses—moderate to high. The nature of the aggregate under the slab becomes less of an uncertainty, and good distribution of suction underneath the slab is more ensured.
- The network variation in concrete block basement houses—low to moderate. The potential for effective treatment of the wall voids is im-

Figure 10. Sub-slab ventilation using individual suction point approach.



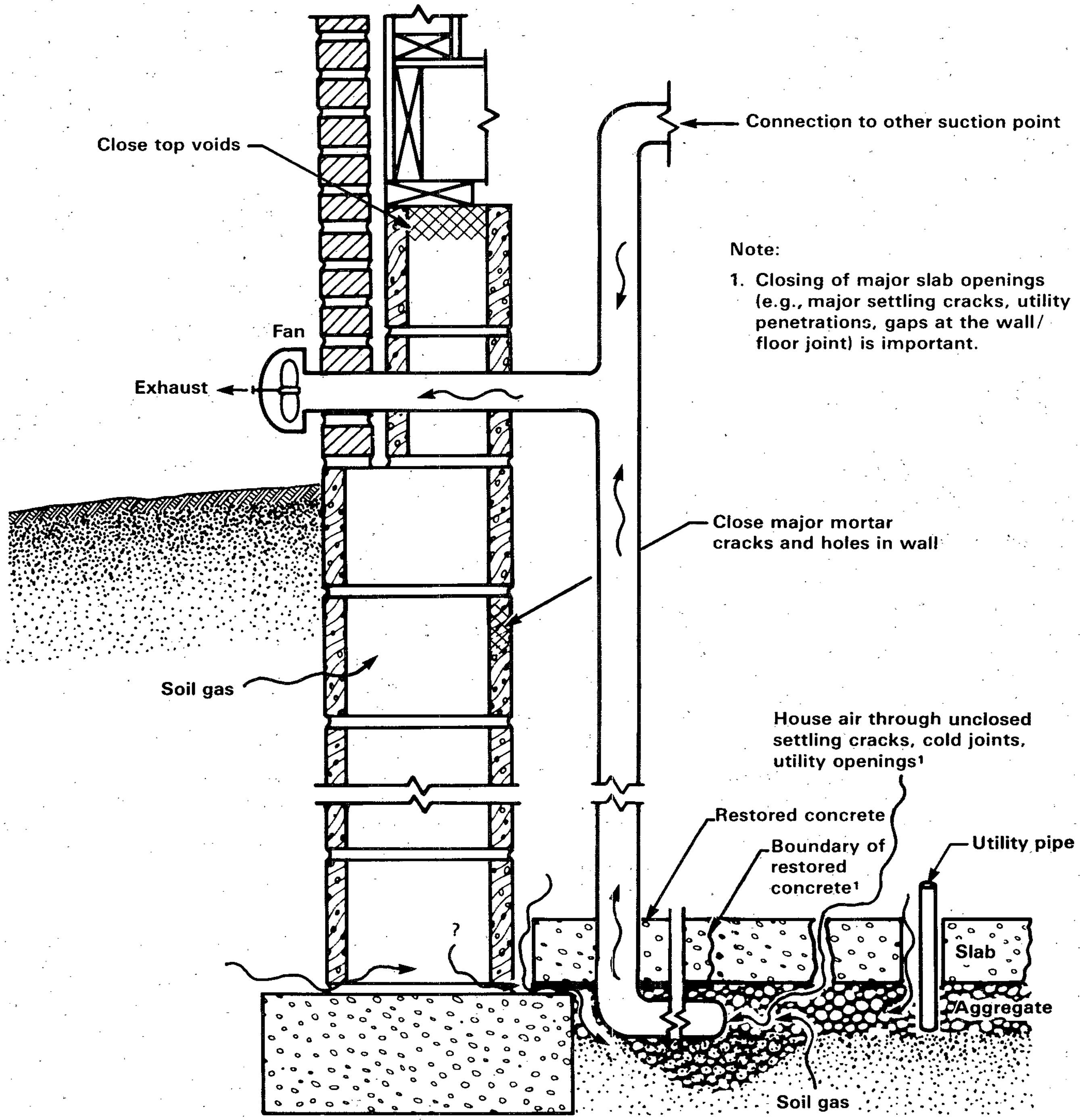
proved by the network design. For an improved confidence level, major wall openings must be closed.

Design and Installation (Individual-pipe Variation)

The schematic diagram of a potential individual-pipe sub-slab ventilation system, where the suction pipe terminates just below the slab (Figure 10), shows the system as having two ventilation points in the slab both connected to a single fan operated to draw suction. Figure 10 represents a typical installation; variations are possible.

In a variation, such as Figure 11, the suction pipe has a horizontal run underneath the slab so that the

Figure 11. Sub-slab ventilation using individual suction point approach (option with horizontal run under slab).



vertical riser can be at a remote location in the room, out of the traffic pattern. The steps involved in the design and installation of this type of sub-slab ventilation system are described below.

Closing Major Openings in Slab

The sub-slab suction system will not be able to maintain adequate suction underneath the total slab if there are major openings in the slab; e.g., holes, large cold joints, openings around utility penetrations, significant settling cracks, or large openings at the wall/floor joint. House air drawn into these large openings can prevent adequate suction at points beyond the opening. Soil gas also could enter the house via these openings, depending on the pressures in the house and the soil. Such major openings should be sealed with mortar or, if sufficiently small, asphaltic sealant, caulk, or other suitable material.

If the major opening is a French drain, it would be advisable not to close this opening, but rather to utilize a baseboard duct approach (similar to that described in Section 2.8) to draw suction on this gap (and potentially on the sub-slab). This approach is discussed further later.

Other slab-related entry routes (specifically, sumps and untrapped floor drains which connect to the soil) also should be addressed, as discussed in earlier sections, as they can be major sources of soil gas entering the house. This soil gas can be generated by soil outside the zone being treated by soil ventilation systems. Sumps and floor drains should be addressed as part of any radon reduction strategy.

Closing Major Openings in Basement Walls

If sub-slab suction is being installed in a block wall basement house, major openings in the block wall should be closed. Not only would this aid the sub-slab system in maintaining suction on the void network, but also would increase the possibility that the sub-slab systems can address the wall-related entry routes. Such wall openings can be a major route for soil gas entry, and their closure should be part of any radon reduction strategy in any event.

If the sub-slab suction system is being installed in a house with poured concrete basement walls, any significant openings in the concrete walls should be sealed in order to reduce or eliminate wall-related soil gas entry routes. Such openings may include significant settling cracks and the seam where the basement wall joins the slab of an adjoining slab-on-grade.

Selection of Number and Location of Suction Points in Slab

The number and location of suction points is designed to ensure effective treatment of the total slab. If a reasonably uniform crushed aggregate (or reasonably permeable soil) underlies the slab, two suction points should be sufficient for a typical slab. A guideline used by one Swedish firm is to place one suction point for every 300 to 500 ft^2 of slab floor area. EPA's test results have been mostly at the upper end of the range. Houses where the nature of the aggregate is unknown may require additional suction points to control the entire area under the slab.

The suction points generally should be placed at approximately equal distances from each other and from the end walls. Ideally (in an effort to achieve adequate suction on the walls and the wall/floor joint) no point in the perimeter wall/floor joint should be much more than about 15 ft from a suction point. Often the suction point will involve a plastic pipe embedded straight down through the slab, terminating just below the slab. With this design a vertical pipe will protrude up through the slab at each suction point (Figure 10). In practice, the suction points would likely be positioned so that the vertical pipe is located in a central location yet out of the traffic pattern in the room; e.g., near an existing vertical load-bearing post. Another possibility (shown in Figure 11) is to locate the vertical pipe penetration into the slab at a point near a perimeter wall so that it is out of the way and then to run the pipe horizontally under the slab so that suction is drawn at a more central location. The disadvantage of this approach is that it requires cutting a channel (up to 15 ft long) in the slab, thus increasing the installation cost. A third possibility is to install four (or more) suction points of the type shown in Figure 10. At least one suction point should be near each of the walls. This arrangement supports adequate suction at each wall/floor joint while the risers are placed away from the traffic flow. Generally, each of the four suction points should be placed midway along the wall with each far enough away from the wall so as not to be over the footings.

If the house has a French drain, the logical approach would be to use the existing French drain opening to gain access to the sub-slab. In this situation a baseboard duct system (Figure 9) should achieve reasonable suction on the sub-slab through communication between the drain and the aggregate under the slab. In houses with block basement walls, the baseboard duct approach has the added advantage of facilitating simultaneous suction on the wall void network (Section 2.8).

Testing Permeability of Sub-slab Aggregate

A preliminary check of the condition of the aggregate beneath the slab is advisable before final system design and installation is begun. One approach for doing this is cutting or core drilling a hole (perhaps 4 in. in diameter) in the slab at one of the points where a suction pipe is to be installed. This will reveal the aggregate at that point under the slab and give the first visual clue regarding its condition. Ideally, the aggregate should be coarse crushed stone or clean washed gravel, preferably at least 2 in. deep. If the aggregate looks reasonably good at that point, the condition of the surrounding aggregate can be tested by mounting a temporary fan inside the house over the hole in the slab to draw suction. The fan can be mounted either on a length of 4-in. pipe which would fit into the hole or on a sheet of plywood that covers the hole and temporarily sealed by caulking around the edges resting on the slab. With the fan in operation, smoke tracer tests can be conducted at cracks and joints remote from the fan to determine to what distance the suction is extending under the slab. If smoke is drawn down into the remote cracks with the fan operating, the suction is extending to that point. As an alternative test, small holes can be drilled in the slab at several remote points and smoke tracer testing conducted. If the equipment is available, pressure probes can be inserted into the small holes to measure sub-slab pressures with the fan on and off. If results indicate that the fan is clearly depressurizing the slab, there is reason to believe that the aggregate is a reasonable approach for radon control.

Installation of Suction Pipes into Slab

Holes must be made in the slab at the points where the suction pipes are to be installed. This usually requires the use of 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, operated by experienced operators, may be needed.

If the pipes are to be embedded straight down into the aggregate (Figure 10) the hole will typically be about 1.5 ft square at each suction point. Soil should be dug out of the hole and the bedrock should be hammered out (if necessary) to create an excavation perhaps 1 to 2 ft deep and, if possible, its horizontal dimension should be larger than the hole through the slab. After being filled with crushed rock **up to the level of the underside of the slab**, the excavation will serve as a collector for soil gas. The vertical plastic suction pipe should be embedded in this gravel base, extending at least 6 in. down into the gravel. The open end of the pipe should be covered with a hardware cloth screen. To prevent plugging the aggregate with cement or sealant when the slab hole is repaired, some material (e.g., building felt) should be placed over the top of the gravel before cementing the hole. All seams should be coated liberally with an appropriate sealant (e.g., asphaltic sealant), so that house air will not be drawn down through cracks, decreasing the system's effectiveness. Seams to be sealed include the circular seam between the PVC pipe and the building felt and the square seam between the felt and the side of the hole in the concrete. Some investigators further propose that the surface of the broken concrete be cleaned and coated with an epoxy adhesive. Before the adhesive has dried, the hole is then filled with concrete and leveled to match the existing floor.

Some investigators have reported success without the large hole and the excavation described in the previous paragraphs. In this simpler case, a hole is drilled through the slab just large enough to accommodate a riser (typically 4 in. in diameter) that is embedded and sealed directly in the smaller hole.

If the pipes are to have a horizontal run under the slab (Figure 11), it will be necessary to cut a trench through the slab to permit the horizontal section to be laid. The initial cut in the concrete slab, outlining the dimensions of the trench, can be made with a concrete saw. The bulk of the concrete demolition and removal will still be done by using a jackhammer. The exposed trench should be partially excavated and filled to the underside of the slab with gravel; the region around the end of the pipe should be excavated to a greater depth as described previously for the vertical-pipe approach. The suction pipe is buried in the gravel. In this design, the gravel-filled trench serves as an enlarged soil gas collector. The exposed area in the trench should be covered (e.g., with building felt), sealed, and recemented.

Design of Piping Network

The vertical piping coming up out of the slab must be connected to one or more fans. This can be done by various methods. The piping used in the EPA sub-slab testing has been 4-in.-diameter plastic sewer pipe. Other investigators have used pipe of similar size. In view of the relatively low gas flows achieved by using sub-slab suction, this diameter ensures a relatively low pressure drop through the pipe; i.e., the suction capacity of a given fan will be utilized primarily in drawing suction on the sub-slab, rather than moving gas through the pipe. Where gas flows are sufficiently low, smaller pipe diameters can be considered (e.g., 2 in.). Workers in Sweden have used 2-in. pipes. The larger the pipe that can be tolerated aesthetically, however, the more effective a given fan will be in ventilating the sub-slab.

Perhaps the most common piping design configuration for sub-slab systems with two suction points in basements is to extend the vertical pipes protruding from the slab up to the level of the floor joists at the basement ceiling, and then running the piping laterally between the joists from one of the points to a location where it can be teed into the pipe from the other suction point. The single horizontal pipe leaving this T then penetrates the basement wall at some convenient location to connect to a fan outdoors. (As an alternative, the fan could be placed indoors with the exhaust pipe penetrating the wall.) Thus, a single fan would draw suction on the two sub-slab suction points. Each pipe also could penetrate the wall separately and connect with a separate fan. Workers in houses with poured concrete basements report good results with just a single fan, even when more than two suction points are connected to it. However, in cases where the permeability under the slab is not good (and in block wall houses, where the sub-slab system is designed to treat the wall voids as well) multiple fans may be required. In any piping system an effort should be made to reduce the number of bends in the piping. Each elbow creates a pressure drop and reduces the effectiveness of the fan's suction.

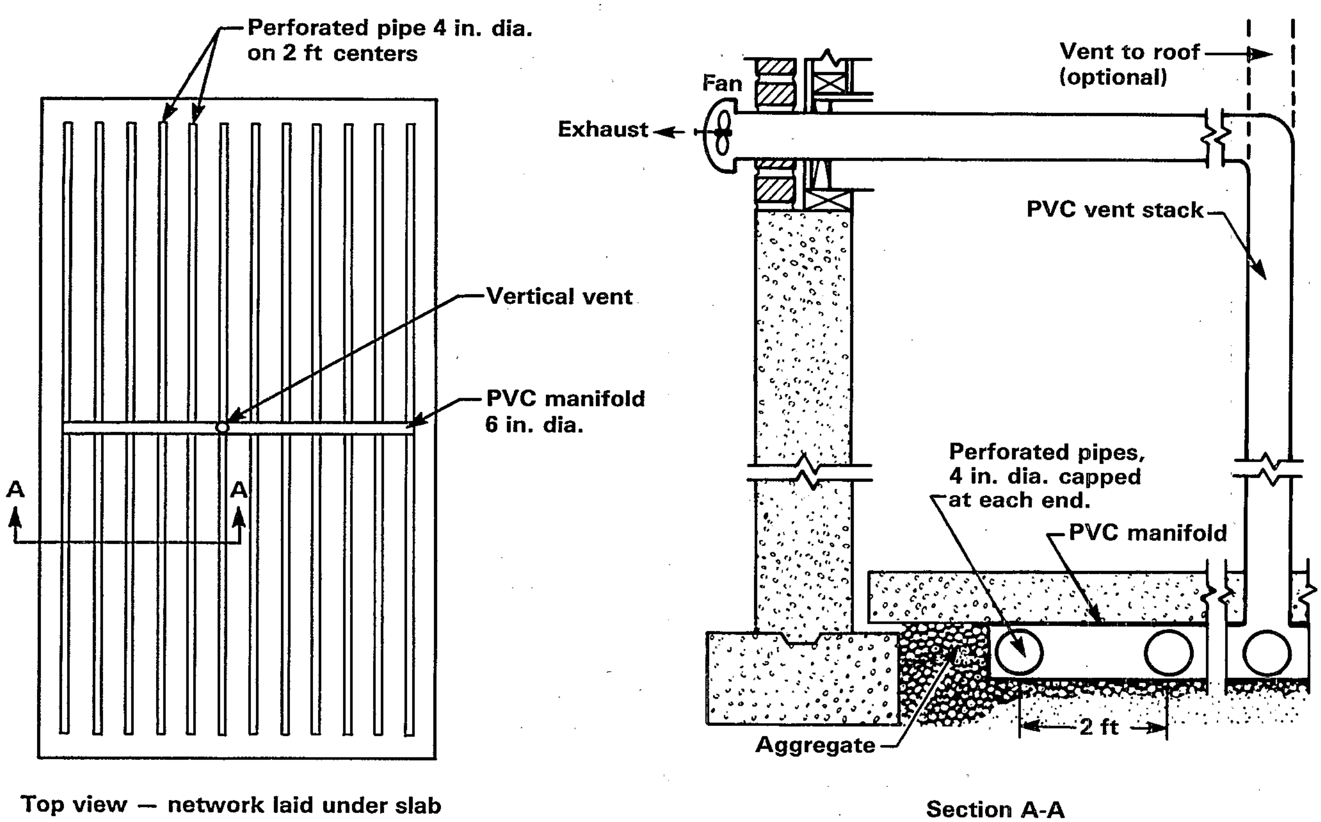
In slab-on-grade houses with a finished ceiling rather than exposed floor joists overhead, running the lateral pipe across or above the ceiling could be desirable, but it could also be run at floor level. Another option is to run the pipe up through the ceiling and the attic, mounting the fan on the roof. In order to reduce fan noise and back-wash it is advisable to penetrate the exterior house wall and to place the fan(s) away from windows and bedroom walls. Placing the fan exhaust above head level will prevent inadvertent exposure of individuals to high radon levels in the exhaust.

The sub-slab variation just discussed is the configuration most commonly tested; however, some limited testing has also been conducted on the following configurations: 1) one point operating to pressurize the sub-slab by blowing air under the slab, with a second point serving simply as a vent; and 2) all points operating to pressurize beneath the slab. Insufficient data have been collected on the performance of these configurations to warrant comment. One concern with pressurization is possible freezing around the footings in cold climates. In addition, in low permeability soils, pressurization could force soil gas from the sub-slab into the house through unsealed cracks and openings in the slab.

Selection and Mounting of Fans

The fans used in the EPA testing of sub-slab suction were single 250 cfm fans (maximum capacity) capable of drawing about 1/4-in. of water suction at low flows. Other researchers have typically used smaller, higher-suction fans ranging in maximum capacity from 60 to 150 cfm and capable of suctions between 3/8-in. and 1.2 in. of water. In view of the relatively low flows typical in sub-slab suction systems, a lower-capacity fan capable of drawing greater suction appears to be a reasonable choice. The fan selected should be as quiet as possible.

Figure 12. Sub-slab piping network suggested for new houses (Central Mortgage and Housing Corp. of Canada).



The considerations in mounting the fan(s) on the pipe(s) outside the house or in mounting the fan(s) inside the house are the same as those discussed previously in connection with wall ventilation (Section 2.8).

Testing of Sub-slab Suction Effectiveness
After the fan has been turned on for the first time, and periodically thereafter, the homeowner would be well advised to test how well the fan is maintaining suction underneath the slab. The testing method was described in Section 2.8.

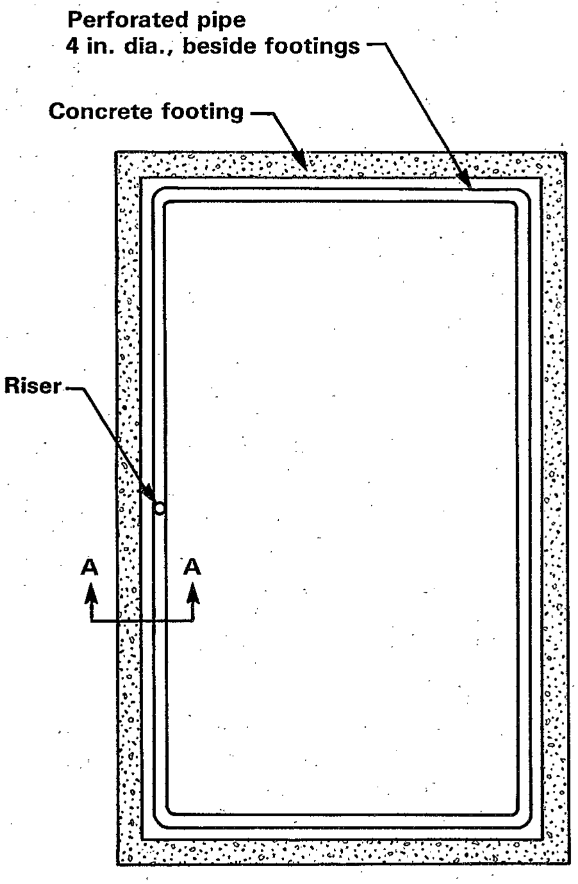
Design and Installation (Perforated Pipe Network Variation)
The primary question in the design of this sub-slab ventilation variation is the extent and configuration of the perforated piping network to be installed under the slab.

Closing Major Openings in Slab and Walls
Major openings in the slab and walls should be closed as discussed in connection with the individual-pipe sub-slab suction approach.

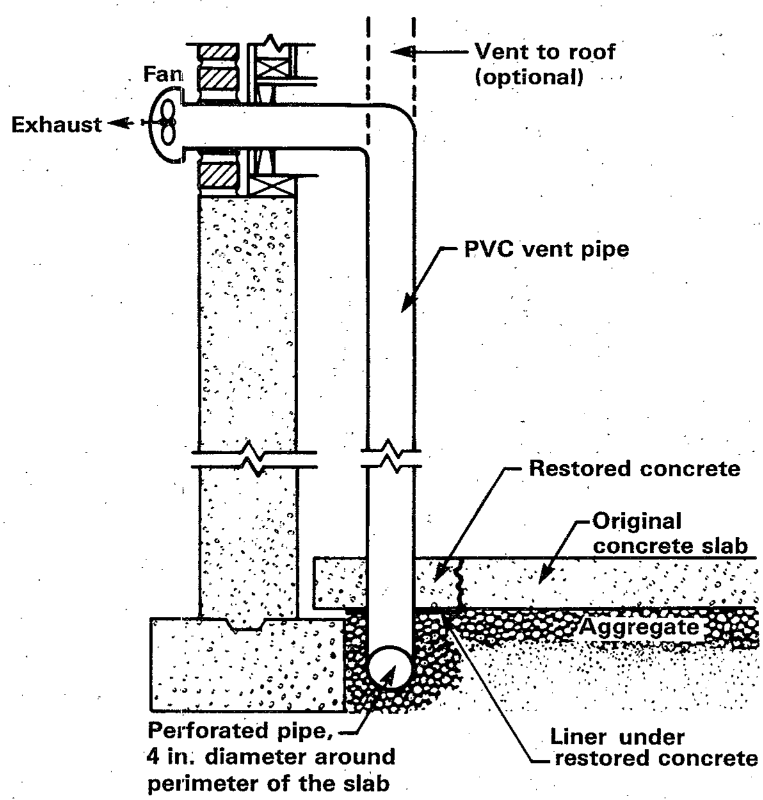
Design of the Sub-slab Perforated Piping Network
Several configurations have been considered for the perforated piping network. One configuration specified in guidelines for new houses is illustrated in Figure 12 (Ch79). In this configuration, a single 6-in.-diameter PVC pipe is laid horizontally underneath the slab in the middle of the house, from front to back. This PVC pipe would serve as a manifold for 4-in.-diameter perforated pipes, which would be laid at right angles to the manifold pipe on 2-ft centers, from one side of the house to the other, and capped at both ends. A vertical pipe, tapped into the manifold pipe, comes up through the slab in the center of the house. This design would ensure effective venting of the sub-slab, but could not be installed without totally removing the original slab. Thus, a network this comprehensive should be considered only for new construction (or for existing houses where the original slab must be torn out for removal of contaminated material underneath).

Another possible configuration for a subfloor network is illustrated in Figure 13 (PDER85, Ta83). In this case, the 4-in. perforated pipe is laid underneath

Figure 13. Sub-slab piping network around perimeter of slab.



Top view — network around perimeter of slab



Section A-A

the slab around the entire interior perimeter of the footing about 18 in. in from the wall. Other configurations are also possible.

Because of the difficulties involved in installing a system such as this in existing houses, only a partial system (or maybe a couple of partial systems) could realistically be considered for an existing house. For example, one segment of perforated pipe can be placed around one part of the perimeter, and a second segment around another part, to keep interior walls or other obstructions from preventing clear access to the slab (Figure 13).

Installation of Perforated Pipe Under Slab
The channels in the slab where the pipe is to be laid would initially be outlined with cuts about 2 in. deep into the slab with a concrete saw. The remainder of the concrete demolition would be completed with a jackhammer. The exposed channel would be excavated to a depth of about 1 to 2 ft and filled to the underside of the slab with crushed aggregate. The 4-in.-diameter perforated pipe would be laid in the middle of this gravel bed, and each end would be capped to ensure effective collection. Each segment of perforated pipe must be connected to a vertical plastic pipe through which the suction on the system will be drawn. As described in the previous section on the individual-pipe sub-slab suction approach, the aggregate in the entire trench must be covered with some suitable material (so that the new concrete does not plug the aggregate). All seams between the cover, the sides of the trench, and the vertical riser should be coated with asphaltic sealant, and the rough sides of the trench may require coating with epoxy adhesive. Fresh cement is then poured to restore the slab.

Design of Piping Network
The PVC pipe risers coming up through the slab from each of the perforated piping segments can be connected in the manner described for the individual-pipe variation. The riser from one segment should be extended by using additional PVC pipe up to the overhead floor joists and then running the pipe horizontally between the joists to the point where it can be teed into the riser(s) from the other segment(s). The resulting single pipe would penetrate the exterior wall at a convenient point, and a fan would be mounted outside. Alternatively, the risers from each segment could penetrate the wall separately and be provided with separate fans, or the fan(s) could be mounted inside the house with the fan exhaust pipe penetrating the wall to the outdoors.

PVC pipe (4-in. diameter) would be a reasonable selection for this piping network, as long as a power-driven fan is used to draw suction on the perforated pipe. Smaller pipe can be used if a low pressure drop can be maintained.

If the perforated piping network is extensive enough, a passive system (with no power-driven fan) may provide adequate radon reductions. In this case, the PVC risers coming up through the slab would be connected to 6-in.-diameter piping that would be brought up vertically through the living area and the attic of the house and terminated 1.5 to 4 ft above the roof. The 6-in. pipe is needed to reduce the pressure drop through the piping, as the suction drawn by the natural stack effect in the pipe and by the wind movement over the roof will be low. A power-driven fan may be required in this stack if the passive ventilation proves insufficient. Maintenance of the natural thermal stack effect may require insulation of the riser through an unheated attic. Unless the installed perforated piping network is substantial, houses with high initial radon levels would best be served by going directly to the power-driven fan.

Selection and Mounting of Fans
As discussed previously for the individual-pipe approach, one or more fans (possibly 60 to 100 cfm) capable of reasonably high suction (0.3 to 1 in. of water) with low noise would appear to be a reasonable choice.

Operation and Maintenance
The operation and maintenance requirements for the sub-slab system consist of regular inspections by the homeowner to ensure that the fan is operating properly (e.g., is not iced up or broken); the seals where the suction pipes penetrate the floor and the new cement remain intact; and adequate suction is being drawn on the sub-slab (determined by smoke testing). If the fan is mounted inside the house, the exhaust system should be inspected for leaks.

Routine fan maintenance should be performed as necessary. The fan should be replaced as needed. If the new concrete develops cracks where it contacts the pipe or the original slab, these cracks should be sealed (e.g., with asphaltic sealant, caulk, or some more extensive procedures). Any new cracks/openings that appear in the slab or wall should be sealed. If smoke testing indicates that the system is no longer properly maintaining suction on some portion of the slab, the fan and the piping leading to the fan should be checked to ensure that the piping is not blocked. If inadequate suction persists, consideration should be given to adding a suction point to improve the ventilation of that portion of the slab.

Estimate of Costs
If the individual suction point variation of sub-slab suction is installed in a house where no special effort is required to close major openings in the walls, a homeowner might have to pay approximately $1000 to $2500 to have such a system installed by a construction contractor based on EPA's experience. This estimate assumes that the house presents no un-

usual difficulties and that the job is completed without the added expense of a "radon mitigation expert" to oversee the contractor's work. The cost estimate includes both materials and labor. If significant labor time must be spent in closing major wall openings (so that the sub-slab system will adequately treat the walls), costs would be significantly higher.

For the piping network approach, costs will increase as a result of the labor required to make the channels in the slab. Costs would vary depending upon the extent of the network installed. A rough estimate for installation by a contractor is $2000 to $7500.

Installation of a sub-slab suction system is not an easy "do-it-yourself" job, but parts of the installation may be completed by some homeowners. In that case, the installation cost would be limited to the cost of materials (about $100 to $500) and the cost of hiring a jackhammer operator or renting an electric hammer.

Operating costs would include electricity to run the fan(s) and possibly some heating penalty due to increased ventilation of the house. Occasional replacement of the fan would also be an operational/maintenance cost. The cost of electricity to run a single 0.03-hp (25-W) fan for a year would be about $15. Assuming that the system increases house ventilation by about 50 cfm, the cost of additional heating would be approximately $125 per year (in houses with basements, this estimate assumes that the basement is heated to the same temperature as the remainder of the house). Thus, the total operating cost would be approximately $140 per year, which increases somewhat with each additional fan. A new fan would likely cost between $40 and $100 when replacement is needed.

Section 3

Available Technical Assistance

Government at all levels recognizes the need to provide points of contact within their organizations where the concerned public can obtain the most recent technical information with regard to indoor radon. The following lists of State (Section 3.1) and U.S. Environmental Protection Agency (Section 3.2) offices were compiled to address this need.

3.1 State Radiological Health Program Office Contacts (RAD85)

Homeowners and contractors should first contact their State official, listed below, if they require assistance in interpreting the material in this manual or for further support in resolving indoor radon problems.

Alabama	Godwin, Aubrey V., Director Division of Radiological Health State Department of Public Health State Office Building Montgomery, Alabama 36130 Business: 205/261-5315
Alaska	Heidersdorf, Sidney D., Chief Radiological Health Program Department of Health & Social Service Pouch H-06F Juneau, Alaska 99811-9976 Business: 907/465-3019
Arizona	Tedford, Charles F., Director Arizona Radiation Regulatory Agency 925 South 52nd Street, Suite 2 Tempe, Arizona 85281 Business: 602/255-4845
Arkansas	Wilson, E. Frank, Director Division of Radiation Control & Emergency Management Department of Health 4815 West Markham Street Little Rock, Arkansas 72201 Business: 501/661-2301
California	Ward, Joseph O., Chief Radiological Health Branch State Department of Health Services 714 P Street, Office Bldg. 8 Sacramento, California 95814 Business: 916/322-2073
Colorado	Hazle, A. J., Director Radiation Control Division Department of Health 4210 East 11th Avenue Denver, Colorado 80220 Business: 303/320-8333, Ext. 6246
Connecticut	McCarthy, Kevin T.A., Director Radiation Control Unit Department of Environmental Protection State Office Building 165 Capital Avenue Hartford, Connecticut 06106 Business: 203/566-5668
Delaware	Tapert, Allan C., Program Administrator Office of Radiation Control Division of Public Health Department of Health & Social Services Cooper Building, Cooper Square Post Office Box 637 Dover, Delaware 19901 Business: 302/736-4731
District of Columbia	Bowie, Frances A., Administrator Department of Consumer & Regulatory Affairs Service Facility Regulation Administration 614 H Street, N.W., Room 1014 Washington, D. C. 20004 Business: 202/727-7190
Florida	Jerrett, Lyle E., Director Office of Radiation Control Department of Health & Rehabilitative Services 1317 Winewood Boulevard Tallahassee, Florida 32301 Business: 904/487-1004

Georgia	Rutledge, Bobby G., Director Radiological Health Section Department of Human Resources 878 Peachtree Street, Room 600 Atlanta, Georgia 30309 Business: 404/894-5795
Hawaii	Anamizu, Thomas, Chief Noise and Radiation Branch Environmental Protection and Health Services Division Department of Health 591 Ala Moana Boulevard Honolulu, Hawaii 96813 Business: 808/547-4383
Idaho	Funderburg, Robert, Program Manager Radiation Control Section Department of Health and Welfare Statehouse Mail Boise, Idaho 83720 Business: 208/334-4107
Illinois	Cooper, John, Manager Office of Environmental Safety Department of Nuclear Safety 1035 Outer Park Drive Springfield, Illinois 62704 Business: 217/546-8100 800/672-3380 (Toll Free In State)
Indiana	Stocks, Hal S., Chief Radiological Health Section State Board of Health 1330 West Michigan Street Post Office Box 1964 Indianapolis, Indiana 46206 Business: 317/633-0152
Iowa	Eure, John A., Director Environmental Health Section Iowa Department of Health Lucas State Office Building Des Moines, Iowa 50319 Business: 515/281-4928
Kansas	Romano, David J., Manager Bureau of Air Quality and Radiation Control Department of Health and Environment Forbes Field, Building 740 Topeka, Kansas 66620 Business: 913/862-9360
Kentucky	Hughes, Donald R., Manager Radiation Control Branch Cabinet for Human Resources 275 East Main Street Frankfort, Kentucky 40621 Business: 502/564-3700
Louisiana	Spell, William H., Administrator Nuclear Energy Division Office of Air Quality and Nuclear Energy Department of Environmental Quality Post Office Box 14690 Baton Rouge, Louisiana 70898-4690 Business: 504/925-4518
Maine	Hinckley, Wallace, Assistant Director Division of Health Engineering 157 Capitol Street Augusta, Maine 04333 Mailing Address: State House, Station 10 Augusta, Maine 04333 Business: 207/289-3826
Maryland	Resh, David L., Administrator Community Health Management Program Department of Health and Mental Hygiene O'Conor Office Building 201 West Preston Street Baltimore, Maryland 21201 Business: 301/225-6031
Massachusetts	Hallisey, Robert M., Director Radiation Control Program Department of Public Health 150 Tremont Street, 7th Floor Boston, Massachusetts 02111 Business: 617/727-6214
Michigan	Bruchmann, George W., Chief Division of Radiological Health Bureau of Environmental and Occupational Health Department of Public Health 3500 North Logan Street Post Office Box 30035 Lansing, Michigan 48909 Business: 517/373-1578
Minnesota	Hennigan, Alice T. Dolezal, Chief Section of Radiation Control Environmental Health Division Minnesota Department of Health 717 Delaware Street, S.E. Post Office Box 9441 Minneapolis, Minnesota 55440 Business: 612/623-5323
Mississippi	Fuente, Eddie S., Director Division of Radiological Health State Department of Health 3150 Lawson Street

Post Office Box 1700
Jackson, Mississippi 39215-1700
Business: 601/354-6657

Missouri
Miller, Kenneth V., Chief
Bureau of Radiological Health
1730 East Elm Plaza
Post Office Box 570
Jefferson City, Missouri 65102
Business: 314/751-8208

Montana
Lloyd, Larry L., Chief
Occupational Health Bureau
Department of Health and Environmental Sciences
Cogswell Building
Helena, Montana 59620
Business: 406/444-3671

Nebraska
Borchert, Harold R., Director
Division of Radiological Health
Department of Health
301 Centennial Mall, S.
Post Office Box 95007
Lincoln, Nebraska 68509
Business: 402/471-2168

Nevada
Vaden, John D., Supervisor
Radiological Health Section, Health Division
Department of Human Resources
505 East King Street
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3.2 U.S. Environmental Protection Agency Program Responsibilities

Guimond, Richard J., Director Criteria and Standards Division Office of Radiation Programs (ANR-460) Environmental Protection Agency 401 M Street, S.W. Washington, D. C. 20460 FTS: 557-9710 Commercial: 703/557-9710	Health effects, measurement protocols, contractor proficiency program action level guidance, quality assurance
Bliss, Wayne A., Director ORP Las Vegas Facility Environmental Protection Agency Post Office Box 18416 Las Vegas, Nevada 89114 FTS: 545-2476 Commercial: 702/798-2476	Sampling and analysis field evaluation
Porter, Charles R., Director Eastern Environmental Radiation Facility Environmental Protection Agency 1890 Federal Way Montgomery, Alabama 36109 FTS: 534-7615 Commercial: 205/272-3402	Sampling and analysis field evaluation
Craig, A. B., Deputy Director Air & Energy Engineering Research Laboratory (MD-60) Environmental Protection Agency Research Triangle Park, North Carolina 27711 FTS: 629-2821 Commercial: 919/541-2821	Radon mitigation research program (new and existing houses)
Cotruvo, Joseph A., Director Criteria and Standards Division Office of Drinking Water (WH5500) Environmental Protection Agency 401 M Street, S.W. Washington, D.C. 20460 FTS: 382-7575 Commercial: 202/382-7575	Radon and radiation in drinking water
Keene, Bryon E., Chief Radiation and Noise Branch Environmental Protection Agency, Region 1 John F. Kennedy Federal Building Boston, Massachusetts 02203 FTS: 223-4845 Commercial: 617/223-4845	EPA Regional Representative for Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont
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Section 4

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