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Radon Reduction
Strategies and Approaches

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RADON REDUCTION STRATEGIES AND APPROACHES

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16. ABSTRACT The chapter is for inclusion in a textbook, Environmental Radon, for graduate students. It gives a flavor of what radon mitigation entails, rather than being a detailed handbook treatment of the subject. It emphasizes the removal or reduction of soil-gas-borne radon (the major source of radon in most houses) and briefly describes the following methods of reducing/removing indoor radon: natural ventilation; forced air ventilation; forced air ventilation with heat recovery; reducing entry points (sealing); venting radon from the soil surrounding a house by drain-tile soil ventilation, sub-slab ventilation, or wall ventilation; reducing pressure differentials; removing radon from water; and air cleaning. It gives background information on house construction types, the significance of weather phenomena, and the significance of the stack effect in elevating indoor radon levels.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Soil Water	Pollution Control	13B	08H
Radon	Ventilation	Stationary Sources	07B	13A
Atmospheric Contamination Control	Sealing	Indoor Air		13H
		Soil Gas	06K	
Houses	Drain Tiles		13M	13C, 11B
Soils	Weather		08G, 08M	04B

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Chapter 8

8.1. Introduction

The application of radon reduction strategies and approaches - known as radon mitigation - is a new, specialized field within the home-building industry, as well as the subject of much ongoing research and development activity. Because it is virtually impossible to completely free the indoor environment of radon, the goal of radon mitigation is to reduce radon in the indoor environment as much as possible. Using currently developed methods, it is possible to get substantial indoor radon reductions, often to the 4 pCi L^{-1} (0.02 WL, or 148 Bq m^{-3}) level recently suggested as guidance by the U. S. Environmental Protection Agency.

The major source of radon in most structures is radon-containing soil-gas. It is believed that the basic mechanism that brings soil-gas into a house is the pressure difference between the indoor and the outdoor environment. Pressure inside closed houses is generally slightly lower than the outdoor pressure. This pressure difference is increased in winter, as a "stack effect" (as in "smoke stack") is created by the continual rising of heated air. At the lower levels of the house - including places where the house contacts the soil - pressure is lowered, creating a "sucking" action that draws the radon-containing soil-gas into the house. At the higher levels the heated air "exfiltrates" around the upper stories and the roof. In addition to the stack effect, wind effects, use of appliances that consume indoor air, and unbalanced airflow through the house contribute to house "depressurization." Because the degree of depressurization varies with weather and household activities, radon concentrations will vary within a structure over time. If indoor air cannot move freely from one area to another, there can be spatial variations in radon concentrations as well.[1]

This chapter emphasizes techniques for mitigating the naturally occurring radon that enters houses. It also emphasizes techniques for mitigating radon in existing houses as opposed to new houses. These emphases reflect the focus of research to date. The techniques have not been applied to office or other public-use buildings, because it is generally believed that public-use buildings are safer. People usually spend less time in them; they are better ventilated; and they are multi-story. Further surveys of building codes, commercial heating/ventilating/cooling systems performance, and radon levels are needed to confirm this supposition.

8.1.1. Overview of Mitigation Techniques [1]

There are four possible means of reducing radon in indoor air: The indoor concentration can be diluted by ventilation, the entry of radon can be reduced, the source of the radon can be removed, or the radon itself (and its decay products) can be removed.

8.1.1a Ventilating Indoor Concentrations. Ventilation simply means increasing the flow of outdoor air into the house which dilutes and replaces the radon-laden indoor air. Ventilation is a simple method to use, because all that is required is that windows and vents on all sides of an area be opened equally. In addition, opening windows and vents neutralizes indoor depressurization, which reduces substantially the pressure-driven flow of radon into the house. Unfortunately, ventilation isn't practical in extreme weather, or in areas where houses are susceptible to unauthorized entry.

8.1.1b. Reducing Radon Entry. Another means of reducing radon in indoor air is to reduce its entry. All cracks and openings in a house's structure are pathways for the entry of radon-containing soil-gas, so it follows that sealing them will reduce radon entry. More effective reduction of radon soil-gas entry can likely be achieved by using mechanical systems or natural phenomena to draw, or force, the soil-gas away from the house's lowest level. Radon can be removed from incoming water by using aeration or granular activated carbon. Radon removed by aeration can be vented to the outside. Carbon adsorbs radon and its decay products.

8.1.1c. Removing the Radon Source. Removing the radon source is a special case involving the waste products of uranium production, mill tailings, which were used in the construction of some houses in the past. The process of separating uranium from the waste had the effect of concentrating the radium content of the mill tailings, and they became significant sources of indoor radon in houses where they had been used as "gravel" under the slabs. In these houses, the slabs were torn out, the mill tailings excavated, and new slabs poured

8.1.1d Removing Radon and Radon Decay Products from Indoor Air. In theory, it should be possible to pass indoor air through some type of filter to which the radon and its decay products would adhere, thereby removing them from the air. There are several types of air cleaners now on the market for particle removal, and the radon decay products are in particle form. However, the issue of whether these devices can actually reduce the risk of lung cancer, as discussed in chapters 5 and 6, is complex.

8.1.2. Short-Term Mitigation Actions.

When extremly high concentrations of radon are found in houses, local radiation officials may urge temporary relocation of the occupants. In these instances, further exposure, even for another week, may be judged untenable.

Fortunately, most elevated indoor radon concentrations are not in this range, and homeowners can use a number of fairly simple interim measures to reduce their exposure, while they contemplate permanent radon mitigation measures. Occupants should stop smoking, especially in the house, and visitors should be discouraged from smoking. Occupants should reduce the amount of time they spend in parts of the house where radon concentrations are highest; for example, the basement. If possible, windows should be opened on all sides of the house to increase ventilation and reduce depressurization. Fans can be used to increase air flow through the house, especially through the basement (they should always blow <u>into</u> the house). If the house is built over a crawl space, all crawl space vents should be fully opened and remain so throughout the year.[2] Of course, exposed pipes would have to be protected from freezing. If there are obvious radon entry points that can be closed easily, these should be closed at once. For example, cover a dirt sump in a basement, and isolate from the rest of the house and discontinue use of a dirt basement. Avoid further depressurizing the house by opening windows when depressurizing appliances, such as furnaces, clothes dryers, woodstoves, and space heaters, are in use, and discontinue the use of ceiling fans.[1]

8.1.3. Limitations of Radon Mitigation [1]

Radon mitigation is a developing field and not yet as exact a science as, for instance, designing a heating system. Much has been learned recently about designing mitigation systems, but there are still a number of areas where trial and error are necessary. For instance, many design and construction characteristics of a house that influence the performance of radon mitigation systems are hidden from view. In these cases, some modifications to the mitigation systems may be necessary after they are installed and tested.

8.2. Evaluation of Sources and Entry Mechanisms

8.2.1. House Construction Types

Aside from the uranium/radium content and the permeability of the soil where the house is built, house type is one of the major parameters that influence the degree of radon entry. Most houses in this country are variations and combinations of three basic house types: Basement houses, houses on crawl space, and houses built on concrete slabs. Each presents a different mitigation problem.

Basement houses have an excavated room, or rooms, below ground level that serve the dual function of being the house's foundation and living or storage space for the occupants. The excavated space can be constructed with foundation walls of different materials; e.g., concrete- or cinder-blocks, poured-concrete, and sometimes field stone or treated wood. They can have either a concrete or dirt floor. Being below grade (below ground level), a basement offers a wide floor and wall surface area with many (sometimes concealed) cracks, gaps, and openings through which radon soil-gas can be drawn into the house. In addition, if the basement has block walls, radon soil-gas can be drawn through their porous surface into the house.

A crawl space house is built on a low foundation, partially above and partially below grade. All living areas are above grade, and the crawl space below them generally accommodates heating/air conditioning ducts and pipes in a space sufficient for a person to crawl about to service them. Crawl spaces usually offer the simplest means of radon mitigation, since they can effectively serve as a ventilated, neutral-pressure buffer between house and soil. To ventilate a crawl space year round may require that the sub-flooring and the water pipes be insulated. Crawl spaces can be less amenable to mitigation if they open into the living space of the home. That is, they are actually "mini-basements."

A slab house uses a concrete slab as the base of the house with living spaces constructed directly over it. Some houses are slab-on-grade, while others are built on slabs below grade. As with basement houses, these slabs offer a wide surface area with many (sometimes concealed) cracks, gaps, and openings through which radon soil-gas can be drawn into the house.

8.2.2. Possible Entry Points

Any opening that somehow comes in contact with the soil surrounding and below a house can be an entry point for radon. For example, radon-containing soil-gas can be drawn into a house through the sump pits that exist in many basement houses. When water rises high enough in the ground to enter the house's foundation, the sump pump in the pit automatically begins to function, pumping water out of the network of drain pipes that encircle and protect the foundation. However, when the drain pipes are dry, radon soil gas can be drawn through their tiny perforations into the drain system, and through the sump pit into the basement.[1]

Common entry points for radon, shown in Figure 5.4, are: cracks in basement walls and floors, seams where basement walls and floors meet, seams in concrete floors poured intentionally as expansion joints, floor drains connected to the soil with no trap to prevent gas entry, holes through basement walls or floors for pipes and the like, the porous surface of concrete blocks, and concealed openings in structures associated with masonry chimneys or fireplaces.[1]

Another source of radon in some houses has been water from private wells (or possibly from small municipal well systems). If the radon in the water is in sufficiently high concentrations, its release into the indoor air through showering, clothes washing, etc., can contribute to airborne indoor radon.[3] (See Chapter 5.)

8.2.3. Possible Depressurization Mechanisms [1]

Since the basic mechanism that brings radon soil-gas into a house is depressurization, activities that increase depressurization must be minimized, especially in winter. Homeowners can unwittingly increase the depressurization of the house by using appliances that "consume" indoor air. A fire in a fireplace, for instance, consumes air.

8.2.4. Water and Building Materials

Radon can enter the house in dissolved form in the water supply and be released into the indoor air by such activities as bathing and clothes washing. The concentration in water must be very high to influence the indoor air concentration. A commonly used rule of thumb is that 10,000 pCi L^{-1} (370,000 Bq m^{-3}) of radon in water will produce 1 pCi L^{-1} (37 Bq m^{-3}) when released into the air. Researchers have, however, found houses where the major cause of elevated indoor radon concentrations was radon in the drinking water supply. In these cases, systems were installed to remove the radon before it entered the house. Radon in water is a problem mainly for homeowners with private wells, and occasionally for small municipal ground water supplies. Radon that may be dissolved in larger municipal water supplies is usually released into the air before it reaches the consumer.(3)

Radon can also be introduced into the house when radium is present in building materials. The solution, of course, is to avoid the use of such materials. Granite can be a source of radon, but it is important to note that the incidence of naturally occurring radium in building materials is almost always a minor problem, compared to the incidence of radon entering a house in soil-gas. The most widely publicized example of radon contamination from building materials was in uranium mining areas where builders used the waste products of uranium mining, mill tailings, as a substitute for gravel under the concrete slabs of some houses.

8.3. Options for Radon Reduction

8.3.1. Ventilation - Diluting and Replacing Radon-Laden Indoor Air

Some degree of house ventilation occurs continually, even in closed houses, as the lower pressure inside draws outside air in through any available pathway. This continual replacement of indoor air with outdoor air, however small, is referred to as "air change," and the rate at which this replacement occurs is measured in "air changes per hour" (abbreviated ach).

Ach is a measure of how long it takes to completely replace all the air in a house with outside air. In the average American house, one complete air change occurs approximately every 1 to 2 hours (i.e., a rate of 1 to 0.5 ach). Newer, more energy-efficient houses could have as little as 0.1 ach. Older, draftier houses could have as much as 2 ach.[1]

One of the purposes of the ventilation techniques discussed in this section is to increase the number of air changes per hour, which increases the dilution and replacement of radon-laden indoor air. The other purpose - which may turn out to be primary with further research - is to neutralize the pressure difference between indoors and outdoors. Since the exchange rate is much less in energy-efficient houses, they are likely to benefit more from increased ventilation than are houses that already have higher exchange rates. In other words, it may be realistic to increase a ventilation rate of 0.25 ach to 0.50 ach, while it may not be realistic to increase a ventilation rate of 1.5 ach to 3 ach (the house could be uncomfortably cold), although each of these increases would give the same percent reduction in radon concentration. Based on dilution considerations and excluding the effects of pressure neutralization, each doubling of the ventilation rate would reduce radon concentrations by a factor of two. For example, an initial indoor radon concentration of 20 pCi L^{-1} (0.1 WL, or 740 Bq m^{-3}) in a house with a ventilation rate of 0.25 ach can be reduced to about 2.5 pCi L^{-1} (0.01 WL, or 92.5 Bq m^{-3}) by increasing the ventilation rate to 2 ach. Actual reductions would probably be even higher as a result of the pressure neutralizing effect of opening windows and vents.[1]

Clearly, the limiting factors in increasing ventilation rates are human comfort and energy expense. Generally, temperatures between 68° and 78° F (20° and 25° C) and relative humidities between 30% and 70% are comfortable to most people.[4] National data on temperatures [5] indicate that, on the average, there are up to four months each year when ventilation can be used without discomfort to the occupants of the house and without increasing heating or cooling costs. Beyond these four months, occupants may have to live with some discomfort and some increased heating/cooling expense.[1]

Since the most important area to ventilate is the area nearest the soil - where the radon-containing soil-gas is entering the house - one option for applying ventilation, if it is feasible, is to close-off and not use a basement that is being ventilated during extreme weather. The human comfort problem is thereby avoided, as is the energy increase in some measure, although leakage from the basement into the living areas will still increase energy costs by about 20%. The only requirements in this instance are that pipes in the basement be protected from freezing, and that the basement be abandoned[1] - not always an attractive option.

Three ventilation alternatives are discussed in the following sections, with information on their expense and their ability to reduce radon levels.

<u>8.3.1a. Natural Ventilation</u>. The easiest form of ventilation to use is natural ventilation. All that is required is that windows, or doors, and crawlspace vents be opened equally on all sides of an area. Opening windows and vents on more than one side of the house is important in order

to ensure that the pressure indoors and out remains neutral. If, for example, windows were opened only on the downwind side of a house, it would depressurize further, increasing the flow of soil-gas-borne radon into the house.[1]

Because natural ventilation is driven by winds, and pressure and temperature differences between the indoor and outdoor environments, it cannot be well controlled. Therefore, one can have only moderate confidence that natural ventilation will constantly keep radon concentrations in an acceptable range.[1] Natural ventilation would not be effective for radon concentrations above about 40 pCi L^{-1} (0.2 WL, or 1480 Bq m^{-3}) [3] if dilution were the only mechanism at work. However, the pressure neutralizing effect of opening windows and vents (mentioned in section 8.3.1) could likely make natural ventilation effective on even higher concentrations.[1] If natural ventilation is used year-round in most of the country, it will increase heating/cooling costs up to three times normal in a house with an initial exchange rate of 0.25 ach.[1]

8.3.1b. Forced Air Ventilation. Forced air ventilation, too, is relatively simple in that fans are used to force air through an area, rather than relying on prevailing winds to do this.[1] The advantage of forced air ventilation is that it enables the control of airflow through an area. Thus, one can have increased confidence that it will keep radon concentrations in an acceptable range.[1] Forced air ventilation would not be effective for radon concentrations above 40 pCi L^{-1} (0.2 WL, or 1480 Bq m^{-3}),[3] if dilution were the only mechanism at work. However, the pressure neutralizing effect of opening windows and vents (mentioned in section

8.3.1) could likely make forced air ventilation effective on even higher radon concentrations.(1)

If forced air ventilation is used year-round in most of the country, it will increase heating/cooling costs up to three times normal in a house with an initial exchange rate of 0.25 ach. In addition, operating fans year-round would cost about $100. This estimate does not include more elaborate installations with new wiring, duct work, dampers, filters, and the like.(1)

For both natural and forced air ventilation, balanced airflow is of utmost importance. Mistakes can mean the difference between reduced radon concentrations, no reduction at all, or - in some cases - increased entry of radon soil-gas into the house. Opening only upstairs windows, or using an attic exhaust fan could create negative pressure on the basement. Hence, the primary area to ventilate is always the basement, or lowest level, and fans are always placed so that they blow <u>into</u> an area.(1)

<u>8.3.1c. Forced Air Ventilation with Heat Recovery</u>. The use of heat recovery ventilators enables the use of forced air ventilation without the complete loss of all heated, or cooled, air as the air exchange rate is increased. Heat recovery ventilators, also called air-to-air heat exchangers, use a heat transfer surface to warm - or cool - incoming air. The heat transfer surface is heated or cooled by the air being exhausted from the house.(1)

The heat recovery ventilator offers reasonable potential for treating houses with radon concentrations up to about 40 pCi L^{-1} (0.2 WL, or 1480 Bq m^{-3}).(3) By making use of the heat or cooling in the outgoing air, heat recovery ventilators reduce considerably the amount of extra energy needed to heat or cool a ventilated area. Typically, whole-house heating/cooling costs are only about 1.5 times normal, or less. These devices range in cost from $400 to $1500, and are capable of energy recoveries up to 70%.(1)

8.3.2. Reducing Radon Entry

8.3.2a. Reducing Entry Points.(1) It is possible to reduce radon entry to some degree simply by sealing all entry points that can be found. In most cases, however, sealing by itself will probably not be sufficient, because radon entry routes are too numerous and many of them are concealed. Sealing is usually recommended as a first step in any radon mitigation strategy, because it is something that most homeowners can do themselves. It can't hurt, and might help, especially if there are some big holes. It may ultimately be needed anyway to make other mitigation systems, like sub-slab ventilation, work effectively.

The first sealing step would be to seal the largest and most obvious radon entry routes, including dirt basements, sump pits, and floor drains connecting to the soil without traps. The best solution for dirt basements is to excavate the fill dirt in the area and replace it with concrete. Sump pits can be capped with an impermeable covering, like sheet metal, sealed at all joints, and a fan used to draw radon-laden air from under the cap and exhaust it to the outside. For floor drains to soil, traps can be added, or, if necessary, removable stoppers used to prevent radon soil-gas entry. Holes in the top row of concrete blocks and large holes in walls and floors should also be among the first openings sealed.

Concrete blocks have hollow spaces inside that connect and form a network inside block walls. Radon can be drawn in through the network of spaces and enter the house from the openings in the top row of blocks. To seal these, one may stuff crumpled newspaper into the hollow spaces and concrete over it if the top blocks are easily accessible. If they are not easily accessible, then a urethane foam can be extruded into the hollow spaces through a hose and nozzle assembly.

In addition to large, obvious openings, a conscientious homeowner could also seal smaller openings, although the impact will be much less. These include openings where pipes and ducts enter the basement, mortar joint cracks between blocks, gaps between block and brickwork surrounding basement fireplaces, and pores in the surface of concrete blocks.

Cracks and utility openings can be sealed by first enlarging them and then filling them with caulk, grout, or sealant. Joints between the wall and the slab can be enlarged, filled with sealant, and then covered with mortar.

Epoxy sealants or waterproof paints are used to reduce the flow of radon through porous walls, especially block walls. Meticulous surface preparation is required to ensure that these coatings will adhere to the surface.

The effect of sealing on the radon concentration in specific houses is unpredictable, because of wide variations in the strength of the source material in the soil, because each house is different, and because the unseen cracks and openings in a house's foundation may be letting in more radon than those that can be found and sealed. Also, houses continue to settle over time, and this settling can create new pathways for radon entry. In addition, sealing cannot be expected to provide a constant barrier over time; house settling and other wear and tear can reopen cracks and gaps. Thus, one can have only low to moderate confidence that sealing will effectively control indoor radon concentrations. Sealing major sources, like dirt basements and sump pits, will have a more marked effect on indoor concentrations than will the sealing of small cracks and openings.

Sealing major exposed radon sources within the house structure can range in cost from as low as $100 to several thousand dollars, as, for example, when concreting a dirt basement. Most cracks and small openings can be sealed for under $100.

8.3.2b. Venting Radon from Soil Surrounding the House. There are three techniques by which radon soil gas can be vented from the soil surrounding a house. The basic mechanism in all three is to draw a suction greater than the suction created by the depressurization of the house. This reverses the predominant flow of air so that it flows away from the house. To understand these techniques, it is first necessary to explain briefly a few basics of house construction.

Houses of either the basement or crawl space type begin below grade with footings of poured concrete. Trenches somewhat bigger than the planned walls are dug, and concrete is poured into them to provide a firm "footing" for the foundation walls that they will support. Block foundation walls have hollow spaces inside. Each successive course of blocks is laid so that the center of the top block covers the ends of the two blocks below. This "ties" the wall of blocks together, and also creates a network of hollow spaces inside the wall that connects both vertically and horizontally.

Foundation walls can also be made of field stone or timbers, but in all these cases the foundation walls are usually built over footings of concrete. Mortar is used to attach the bottom of the foundation walls to the footings.(1)

It is believed that a significant amount of radon soil-gas may enter the house in the area of the footings; that is, around the mortar that attaches the bottom of the foundation walls to the footings, around the mortar that holds the blocks or stones together, and through the porous exterior surface of blocks in the foundation walls.(1)

In many basement houses, construction is also characterized by a concrete slab which forms the floor of the excavated room. Basement, slab-below-grade, and slab-on-grade houses have this slab-over-soil construction in common, and in this case it is believed that radon soil gas enters through utility perforations, cracks, spaces, and joints in the floor, as well as through sumps and floor drains. Slabs are usually poured over aggregate, most often, crushed rock, to give them a firm base.(1)

The sections that follow describe drain-tile soil ventilation, sub-slab ventilation, and wall ventilation, all of which are designed around the unique construction characteristics of different types of houses to draw radon away from the house's foundation.

Drain-Tile Soil Ventilation. Drain-tile soil ventilation is a good radon reduction option for a house with a drain-tile system completely encircling it. As described in section 8.2.2, drain-tile systems encircle the foundations of many houses to protect them from water. If such a system loops the entire house, is completely intact with no tiles crushed, silted in, or missing, and attached to each other, rather than simply touching each other, it offers a relatively simple and cheap ready-made means of drawing suction on the soil surrounding the house's foundation. This option is the most esthetically pleasing of the soil ventilation alternatives, and can be very effective if the full loop gives good distribution of the suction.[1] Of course, the only way one can be sure if a drain-tile system meets the above criteria is to have a completely new system installed, and this would be quite expensive. Adding drain-tile soil ventilation to an existing drain tile system is fairly inexpensive, however, so it is generally cost-effective to try this method.[1]

Drain-tile soil ventilation uses a fan to draw suction on the network of drain tiles. This suction draws radon soil-gas into the tile network, thereby preventing it from entering the house in the vicinity of the footings. Since the drain-tile network encircles the house at the base of the foundation, the suction in the system can also draw soil-gas from under the house's slab (if it has one) as well.[1] Adding such a system to an existing drain-tile network is fairly simple. In the case of a drain-tile system that connects to a sump pump in the basement, the entire sump pit area is capped with an impermeable material, sealed, and a fan is used to draw suction on the sump pit and the drain-tile system attached to it.[1]

In the case of a drain-tile system that drains to a location remote from the house - to an above-grade discharge or a dry well - the drain line is located and cut, and a fan, trap, and riser assembly is added (see Figure

8.1). Thus, water can still drain from the drain tiles, and the fan can draw suction on the drain tiles without drawing in air from the discharge area.[1]

In both of the above methods, the fan is located outside and must be enclosed to protect it from weather and debris and to protect animals and children. Since the radon concentration in the air exiting the fan can be very high, homeowners are cautioned to locate it either in an area remote from the house, or at a safe height. The fan should also be inaccessible to children.[1]

Drain-tile soil ventilation can be used for reducing any radon concentration; although for concentrations above 200 pCi L^{-1} (1.0 WL, or 7400 Bq m^{-3}),[3] it may not be able get below 4 pCi L^{-1} (148 Bq m^{-3}). Since drain-tile soil ventilation functions by drawing soil gas away from the house's footings, it might not work as effectively if there are interior walls in the basement sitting on footings of their own. In this latter case, the fan might not always draw sufficient suction to keep soil-gas from entering around the footings of these walls. It would be extremely unusual for such interior walls to have drain tiles of their own. Even in this latter case, drain-tile soil ventilation may be made to work adequately by using a higher powered fan.[1]

If a homeowner were to have a contractor install a new drain-tile system and include in the installation the fan, trap, and riser, the entire system would cost about $1200, assuming that no unusual problems were encountered. A do-it-yourself installation would probably require about $300 in materials.[1] Power to operate the fan in the drain-tile system year-round would cost about $25. Since the suction would draw some warmed or cooled air out of the house, heating or cooling costs could be expected to increase by about $125 per year.[1]

Sub-Slab Ventilation.[1] For basement houses and slab-on-grade houses, ventilation of the area below the slab may be used to draw accumulated radon soil-gas out of the aggregate, or soil, beneath the slab.

Suction on the sub-slab area can be drawn in several ways: (1) individual pipes can be inserted into the slab and a fan used to draw suction (see Figure 8.2); (2) if drain pipes exist below the slab, these can be used with a fan to draw suction on the sub-slab area; (3) a network of perforated pipes can be laid, the slab poured over them, and a fan used to draw suction; or (4) an extensive network of perforated pipes can be laid, attached to a stack, and natural phenomena possibly used to draw radon out of the sub-slab area.

For existing houses, the most practical solutions are the individual pipe method and the drain-pipe method. In the individual pipe method, several pipes are inserted vertically into the aggregate through holes drilled in the slab. The number of pipes needed is dictated by the permeability under the slab and the size of the slab. The inserted pipes are connected to each other by horizontal pipes, usually running around the ceiling and connected to a fan. The fan draws suction on the entire sub-slab area through the inserted pipes, and exhausts the radon soil-gas outside the house, usually at roof level. Another possibility for existing houses is a variation on drain-tile soil ventilation. The perforated drain pipes that were laid for water drainage under some slabs during construction usually drain into a sump within the house's footings. By using a fan to draw suction on the sump and the drain pipes, the sub-slab area is ventilated.

Both these methods rely on a good layer of aggregate or a permeable soil below the slab to allow the effects of a few suction points or the drain pipes' to radiate to the entire slab. Permeability can be tested fairly easily before installation is begun by drilling a hole into the slab, inserting a pipe into it, and attaching a fan to it temporarily. With the fan operating, smoke tracer tests at joints and cracks remote from the fan (see section 8.4) will give a good indication of how much air can move through the aggregate or soil. If permeability is poor, more suction points may be needed, or a network of perforated pipes will have to be laid.

In the perforated pipe network method, an extensive layer of perforated pipes is laid horizontally, a fan attached to it, and the slab poured over the pipes. Because of the expense of tearing out an existing slab and replacing it, this method is best suited to new construction. It has also been used in existing houses when the slab had to be torn out anyway, because there was contaminated material under it (e.g., uranium mill tailings), or because there were structural problems.

In some houses, an extensive sub-slab piping network may provide adequate ventilation in a passive mode, without a fan. By connecting the piping network to a stack that exhausts at roof level, suction is created through natural thermal effects inside the stack and a reduced pressure at the roofline caused by wind movement. If the flow resistance through the aggregate is low, the weak suction created by this stack effect may be sufficient to ventilate the sub-slab. Passive ventilation appears to work only in cold weather.

Another variation of sub-slab ventilation that is being tested is forcing air into the sub-slab area, rather than drawing suction on it; that is, pressurizing, rather than depressurizing. This would have the effect of pushing radon soil-gas away from the slab and foundation.

None of the methods described above will function effectively without sealing openings in the slab. Without sealing, house air could be drawn into the system, overwhelming its suction power. Holes in the slab, large seams (cold joints), openings around utility penetrations, large settling cracks, and large joints where the wall and floor meet must be sealed with mortar. Small openings can be sealed with asphalt, caulk, or similar sealants.

Sub-slab ventilation is one of the most effective radon reduction methods known at the present time and can be used for any radon concentration. Because of the cost, however, homeowners might elect to use less expensive methods for radon concentrations below 40 pCi L^{-1} (0.2 WL, or 1480 Bq m^{-3}). The effectiveness of sub-slab ventilation may be reduced by the existence of block walls in a basement, because it is difficult to draw enough suction to keep radon soil-gas from entering through the walls. Closing the hollow spaces in the top course of blocks, as well as other gaps and openings in the walls, will improve sub-slab ventilation of block-wall houses considerably, and using higher powered fans can overcome much of the leakage into a system.

Having a contractor install an uncomplicated individual pipe sub-slab system could cost between $1000 and $2500. A similar installation of a piping network, including the labor to cut channels into an existing slab to lay the pipe, could cost between $2000 and $7500. A sub-slab ventilation system would place about the same annual energy load on a house as wall ventilation and drain-tile soil ventilation: power to operate a fan year-round could be about $25 and, assuming the fan draws some house air into the system, heating/cooling costs could increase about $125.

Wall Ventilation.[1] If a basement has block walls, another option for reducing radon soil-gas entry is to draw suction on the walls themselves. The same network of hollow spaces that enables radon to enter the house can be used to draw radon away from the house.

The basic approach in wall ventilation is to attach a fan to the network of spaces inside each wall, draw radon soil-gas out of the walls, and exhaust it to the outside. There are two variations of wall ventilation: (1) the single-point pipe method, and (2) the baseboard method (see Figure 8.3). For either of these methods to work effectively, all walls must be treated, including any interior walls that penetrate the concrete floor. Both methods also require that all large openings in the walls be closed. Otherwise, the house air being drawn in through these openings will simply overwhelm the system, and it will have very little suction power left for radon soil-gas control.

Closing all large openings in the walls means the same sealing of the hollow spaces in the top row of blocks as was described in Section 8.3.2a.

Other large openings must be closed. These include space around pipes where they enter the basement, and any other visible holes and gaps.

With large openings effectively closed, the wall ventilation system can be installed. Usually, the choice between the single-point pipe method and the baseboard method is dictated by the conditions in the basement, by the expense involved, and by the relative importance of the usability and appearance of the area.

The single-point pipe method is the cheaper. It involves drilling one hole into a hollow space in each wall and inserting a pipe into each drilled hole. The pipes usually lead up to connecting pipes encircling the entire perimeter of the inside of the basement. At the end of the pipe network is a fan that draws suction on the walls. Many variations of this method are possible, depending on the unique requirements of the basement. For instance, the pipes could be inserted into the network of hollow spaces from outside the house, and the fan could be inside, or outside, the house.

In the more expensive baseboard method, holes are drilled into the hollow spaces around the entire perimeter of the walls near the floor. Then a two-sided baseboard "duct" is constructed of sheet metal, or some other suitable material, and attached with sealant and screws to the wall above the drilled holes and to the floor in front of them. In this way, all holes - and the joint where the wall meets the floor - are completely covered by the baseboard duct, and the duct system is attached to a fan. Because there are holes all along the perimeter of the basement, a more uniform suction is drawn on the walls than with the single-point pipe method.

If wall openings are not sufficiently closed, the fan used to draw suction or to pressurize the walls cannot work effectively. Among possible openings that may require closing are the hollow spaces in the top row of blocks, the space between brick veneer and the exterior wall, and spaces between fireplace structures and the walls of the basement. A higher powered fan may help to increase the efficiency of a wall ventilation system. In some cases, wall ventilation may simply not be adequate to keep radon-containing soil-gas from entering through openings in the slab.

Wall ventilation is usually added as a supplement to sub-slab ventilation if sub-slab ventilation does not function effectively alone. To have a contractor install an uncomplicated single-point pipe system in an unfinished basement would probably cost about $2500. A similarly uncomplicated contractor installation of a baseboard system in an unfinished basement would probably cost about $5000. An uncomplicated installation would be one in which the hollow spaces in the top course of blocks are easy to access and close, and in which there are few appliances or other obstacles around which the pipes must be installed.

The cost of a do-it-yourself installation, although not generally recommended, could be as little as $100 to $500 for pipes, sheet metal, fans, and miscellaneous supplies, depending on the number of fans required and the size of the basement.

A wall ventilation system would place about the same annual energy load on a house as drain-tile soil ventilation. Operating a fan year-round could cost about $25 and, assuming the fan draws some house air into the system, heating/cooling costs could increase about $125.

8.3.2c. Reducing Pressure Differentials. Because pressure-driven flows are believed to be the basic mechanism by which radon soil-gas enters a structure, it is important to minimize any additional depressurization of the house, especially in winter and in the areas where radon soil-gas enters - basements, or rooms directly over the soil.(1) It appears that the major sources of depressurization inside the house are combustion appliances which consume indoor air, further lowering indoor air pressure, and thermal bypasses which facilitate the stack effect. Among these are furnaces, water heaters, clothes dryers, woodstoves, fireplaces, and space heaters. Of these, furnaces and water heaters probably depressurize the house the most, because they generally operate a much greater percentage of the time than do any of the others.(1) The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has recommended since 1981 that direct outside supplies of "makeup" air be provided for combustion appliances, because they believe this is necessary for effective and controlled ventilation and acceptable indoor air quality (6). By supplying each air-consuming appliance with its own air supply through separate ductwork to the outside, further depressurization of the house is prevented, and increased flow of radon soil-gas into the house is prevented. In the case of a fireplace, depressurization can be prevented simply by cracking a window while the fireplace is in use.(1)

Another possible source of depressurization inside the house is local exhaust fans; e.g., ceiling fans that are used intermittently. They are not as important as combustion appliances, but they do draw suction on the interior of the house when they are operating. Thus, it would be advisable to keep use of such fans to a minimum, especially in winter. Also, if portable fans are used to ventilate the house, always ensure that fans blow into, not out of, the house.[1]

It is difficult to generalize about the impact on indoor radon concentrations of preventing appliance depressurization. There are too many variables. Among these variables are the number and operating conditions of the appliances, the type of house in which they are installed, and the strength of the radon source material. Best estimates are that the average annual radon reduction benefit may be between 0% and 50%. It is impossible to estimate the cost of installing separate ductwork to an unknown array of appliances.[1]

8.3.2d. Removing Radon from Water. The two methods available for removing radon from drinking water involve the use of aeration and granular activated carbon (GAC). Both methods can be used in the house, or at the source of the water.

When water containing radon is exposed to air, some of the radon escapes. Thus, aeration is a viable means of removing radon from water. A diffused aeration tank typically can remove more than 95% of the radon, and spray aeration has achieved efficiencies of 93%.[7] Packed tower aeration, which has been shown to be effective in removing volatile compounds from water, also appears to have potential for removing radon from water, although it has yet to be tested at pilot- or full-scale.

Granular activated carbon has been used to adsorb noble gases such as radon. Efficiencies as high as 96% have been reported.[7] Because of its short half-life (3.8 days), much of the radon decays on the GAC bed before breakthrough.

An aeration system for an average house would cost about $1000. Annual operating costs would be about $80. A GAC system for an average house would cost between $500 and $1500 with annual operating costs of about $20 to $40. The disadvantage of the GAC system is that the occupants are exposed to the radioactive material adsorbed on the GAC.

8.3.3. Air Cleaning - Removing Radon and Radon Decay Products from Indoor Air

Another approach to reducing the risks of radon is to remove radon and its decay products from the indoor air. There are various types of devices on the market that can remove particulates from the air, and these devices can remove radon decay products that have attached to these particulates. However, it is unclear whether these air cleaners can effectively remove radon itself from the air.

This uncertainty exists because there is insufficient data to enable precise description of the ways in which radon and its decay products may cause lung cancer. It is generally believed that the most dangerous situation involves inhaling decay products attached to relatively small particulates that are more likely to deposit in the deepest, most sensitive parts of the lung. Air cleaners are thought to be more efficient at removing larger particulates than smaller ones. If this is so, then the radon still in the air after it has passed through an air cleaner will generate decay products that will attach to smaller particulates than would have been the case without air cleaning. Thus, although the risks may have been somewhat reduced by removing larger particulates and the decay products attached to them, the risks may also have been somewhat increased because the remaining decay products can become attached to particulates that will make them more dangerous.

The same issue arises even if the air cleaner is very effective at removing particulates of all sizes, because the remaining radon can then generate decay products that will not attach to any particulates, becoming "unattached decay products." Although data are inconclusive, some scientists believe that such unattached decay products may be even more effective at causing lung cancer than decay products attached to particulates. (See Chapter 7.)

Thus, while air cleaners that are now available are likely to be effective at reducing the overall concentration of radon decay products in indoor air by reducing particulate concentrations, it appears that they may not be as effective in reducing the corresponding health risks. Additional research is needed to resolve these uncertainties, although the necessary scientific studies may be analytically complex. On the other hand, development of air cleaning systems that simultaneously remove radon itself, if this can be accomplished in a practical fashion, would offer significant benefits.

8.4. Evaluation and Maintenance of Radon Mitigation Systems (1)

None of the methods described above can be installed and forgotten. They all must be evaluated periodically to ensure that they are still working, and they all require maintenance.

Evaluation of the radon mitigation methods described in Section 8.3.2b. after they are installed is usually done by smoke tracer tests. The goal is to determine if the system is drawing sufficient suction to keep radon soil-gas out of the house. With the mitigation system operating, a smoke generator (e.g., a smoke tube) is passed over the surface of walls, along the wall-to-floor joint, and any other likely entry points. Smoke should be consistently drawn into the area being tested. In those places where it is not, there is reason to suspect that radon is still entering the house because of insufficient suction. Other diagnostics that would be conducted by the system's installer include flow and pressure measurements in vent pipes, and pressure measurements under the slab and in block wall cores.

Maintenance of radon mitigation methods involves inspecting outside fans for damage or icing, periodic oiling of fans, checking seals where fans are attached to pipes, checking seals over basement cracks, gaps, and openings, and checking traps to be sure they are still filled with water. In the case of natural and forced-air ventilation, maintenance would also involve periodic checking to ensure that all windows and vents remain uniformly open on all four sides of the area being ventilated. For heat recovery ventilation, it would be necessary to check periodically to ensure that there is a balanced flow of air into and out of the system.

8.5. Developing a Mitigation Strategy

In the previous sections an array of mitigation methods together with their relative effectiveness and costs have been presented. These are only the raw material with which a homeowner would develop a mitigation strategy. A complete strategy would likely include the following steps:

1. Screening measurement to determine if radon levels are elevated;
2. Follow-up measurements to determine the extent of the problem;
3. Taking short-term measures to protect occupants while long-term mitigation measures are being decided upon;
4. Contacting local radiological health officials, environmental health officials, or an experienced radon mitigation contractor to seek guidance;
5. Contractor conducting house diagnostics to determine where radon is entering;
6. Contractor installing radon mitigation system;
7. Contractor conducting post-mitigation measurements to evaluate the effectiveness of the installed system;
8. Contractor making any necessary modifications to the system;
9. Contractor again conducting post-mitigation measurements;
10. Homeowner conducting periodic checks of system to ensure that it continues to function effectively.

As outlined above, many homeowners will understandably need the assistance of radiation and radon mitigation experts in dealing with a suspected indoor radon problem. Assistance with radon measurements can be obtained from laboratories and businesses who routinely conduct radon measurements. The U. S. EPA conducts a voluntary Radon Measurement Proficiency Program which allows firms to demonstrate their capabilities in measuring indoor radon. Lists of participating firms in various areas are available from EPA regional offices.[2]

Assistance in making important decisions about how to proceed is available from the radiation health officials in most states. In some states this assistance is available from the state's environmental protection agency.

Some states are also conducting training courses for building contractors who wish to become proficient in radon mitigation. Information on which contractors have taken such training are also available from the state's radiological health office or environmental protection agency.

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Figure 8.1. Drain-tile soil ventilation system, draining to remote discharge area.[3]

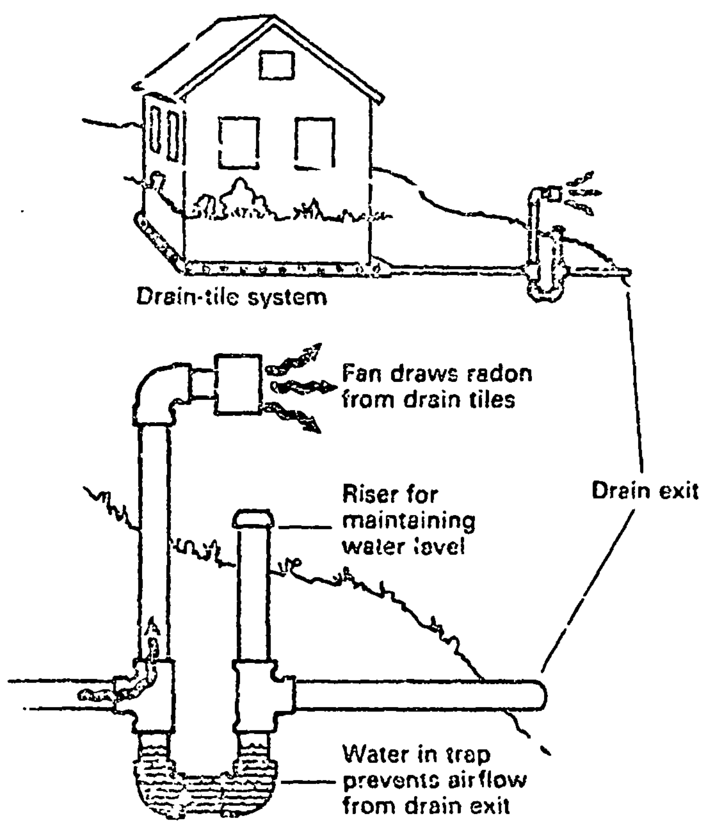

Figure 8.2. Individual pipe variation of sub-slab ventilation.(3)

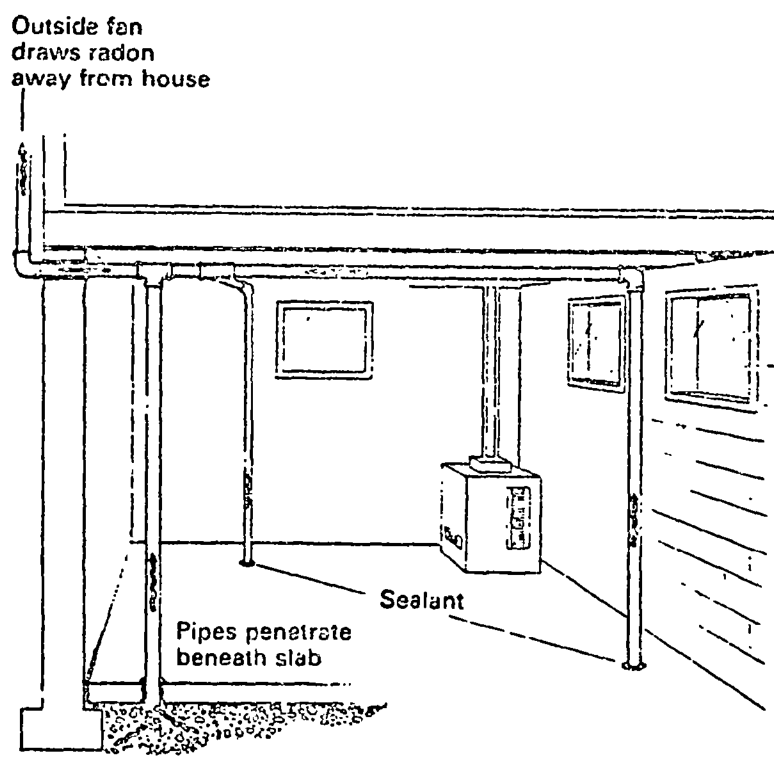

Figure 8.3. Two variations of wall ventilation: left - the baseboard method, and right - the single-point pipe method.(3)