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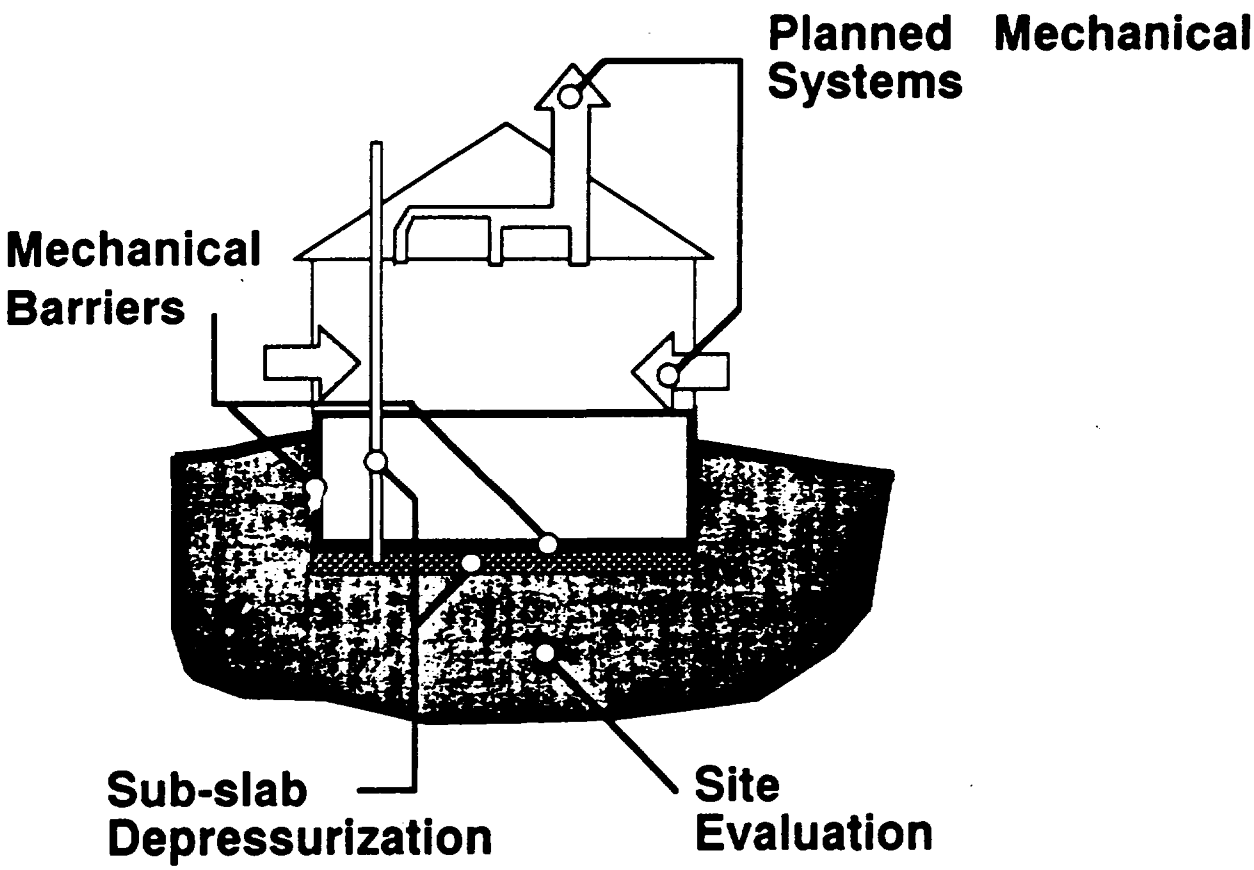
Radon-resistant Construction Techniques for New Residential Construction

Technical Guidance



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Radon-resistant Construction Techniques for New Residential Construction

Technical Guidance

By

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Metric Conversions

Readers more familiar with the metric system may use the following to convert to that system.

Nonmetric	Multiplied by	Yields Metric
cfm	0.000472	m^3s
ft	0.305	m
ft^2	0.0929	m^2
in.	0.0254	m
lb	0.454	kg
lb/ft	1.488	kg/m
mil	0.0000254	m
psi	6.895	kPa
pCi/L	37	Bq/m3

Section 1
Introduction

Growing concern about the risks posed by indoor radon, a naturally occurring radioactive gas found in varying amounts in nearly all houses, has underscored the need for dependable radon-resistant residential construction techniques. In response to this public health exposure, the U.S. Environmental Protection Agency (EPA) has developed and demonstrated a variety of methods that have been used to reduce radon levels in existing houses. *Many of these methods could be applied during construction, involve less labor and financial investments, and provide greater homeowner satisfaction and safety than would a radon-reduction technique installed after the home is built and occupied.*

This manual is designed to provide homeowners and builders with an understanding of operating principles and installation details of radon-resistant new home construction. To meet these needs, the manual is divided into four parts. The first part contains the Introduction, which you are now reading. The second part containing Section 2 is the Overview, which covers techniques being studied or used in the control of radon in new homes. Underlying operating principles, materials, and installation are discussed in Section 2. The level of detail is aimed at developing an understanding of basics, not background or details. The overview is quickly and easily read. The third part, Sections 3-6, contains technical information which takes the same material to a greater depth, and covers additional specific construction details. This part contains far more technical information than the introduction and overview, and will require more effort to read and assimilate. The fourth part, the Appendices, contains background information on the contents of the first three parts.

The intent of this manual is not to rate similar products made by different manufacturers, or to provide a stock radon-resistant package. This manual should provide a basic understanding of the types of products and systems that are available and being used. In this way, the reader will be able to select radon-resistant products and systems that will be most applicable to a particular situation.

It should be understood that some of the techniques mentioned in this manual have NOT yet been fully demonstrated in new home construction. These techniques are discussed because they have a sound theoretical potential for effectively precluding radon entry into a home. As research continues, and experience in the use of radon-resistant new construction techniques grows, it is expected that some of these theories will prove to be transferable to the homebuilder's list of radon-resistant construction options. The soil ventilation techniques described HAVE been extensively tested in existing homes and show good potential for application in new construction and are, therefore, recommended.

Section 2
Overview

Two areas are addressed in the Overview.

- Radon Entry - How radon enters a building
- Radon Control - What can be done to lower indoor radon levels.

2.1 Where Does Radon come from and Why is it a Problem?

Radon gas is the result of the radioactive decay of radium-226, an element that can be found in varying concentrations throughout many soils and bedrock. Figure 2.1 shows the series of elements that begin with uranium-238, and, after undergoing a series of radioactive decays, lead eventually to lead-210. At the time radium decays to become radon gas, energy is released. Of all the elements and isotopes illustrated in Figure 2.1, radon is the only one which behaves like a gas and can easily slip through the small spaces between bits of soil. While many of the isotopes in the uranium-238 decay series exist for a long time before they decay, radon does not remain radon for very long. It has a half-life of 3.8 days. If 1 lb* of radon were put in a jar, 3.8 days later only 1/2-lb of radon would be left; the other 1/2-lb would have decayed into the short lived decay products polonium, bismuth and lead. After another 3.8 days only 1/4-lb of radon would be left in the jar. The radon decay products shown inside the building have even shorter half lives than radon, and decay within a few hours to the relatively stable isotope lead-210. It is this rapid release of energy that causes radon and radon decay products to pose such a significant health risk.

If radon and radon decay products are present in the air, they will be inhaled. Because the decay products are not gases, they will stick to lung tissue or larger airborne particles which later lodge in the lung. The energy given off as these isotopes decay, can strike the cells in the lung, damage tissue, and may eventually develop into lung cancer. The amount of risk depends on how long a person is exposed to how high a concentration of radon and radon decay products. Estimates of the number of lung cancer deaths attributable to radon and radon decay products ranges from approximately 5,000 to 20,000 deaths per year in the United States.

For simplicity, in the remainder of this manual, radon and radon decay products will be collectively referred to as radon, except where the distinction is required.

* For the reader's convenience, nonmetric units are used in this document. Readers more familiar with the metric system may use the factors in the front matter to convert to that system.

2.2 How Radon Gets into a Home

A house will contain radon if the following four conditions exist:

1) a *source* of radium exists to produce radon
2) a *pathway* exists from the radium to the house
3) a *driving* force exists to move the radon to the house
4) an *opening* in the house exists to permit radon to enter.

If one of these conditions does not exist, then the house will not have a radon problem. An estimated 10 to 20% of the existing homes in the United States have annual average radon concentrations above 4 picocuries per liter of air (pCi/L). This may seem like a small percentage of problem homes until one considers that, of the million or so U.S. houses built each year, 100,000 to 200,000 homes will likely have radon concentrations higher than 4 pCi/L.

The *most common way radon enters a home* is when lower indoor air pressure draws air from the soil, bedrock or drainage system into the house. If there is radon in the soil gas, it will also be drawn in. Just as gravity will make water flow from a high elevation to a lower elevation, pressure differences will make radon-laden air move from an area of higher pressure to an area of lower pressure. For a variety of reasons, illustrated at length in the Technical Information section, most buildings tend to maintain an indoor air pressure lower than outdoor air pressure. If cracks and holes in the foundation are open to the soil, radon will be drawn indoors. Radon movement by pressure differences is called pressure driven transport.

Radon can also enter buildings when there are no pressure differences. Place a drop of food coloring in a glass of water and eventually the coloring will spread out (diffuse) and color the water - - even without stirring. Radon will do the same thing - - spread from an area of higher concentration to an area of lower concentration until the concentrations are equal. Radon movement in this way is called diffusion driven transport.

A less common entry mechanism is the outgassing of radon from well water. A well supplied by groundwater that is in contact with a radium-bearing formation can transport the dissolved radon into the home. At the time of this writing, it is estimated that the health risks associated with breathing radon gas released from the water are 10 times higher than the risks associated with ingesting water containing radon.

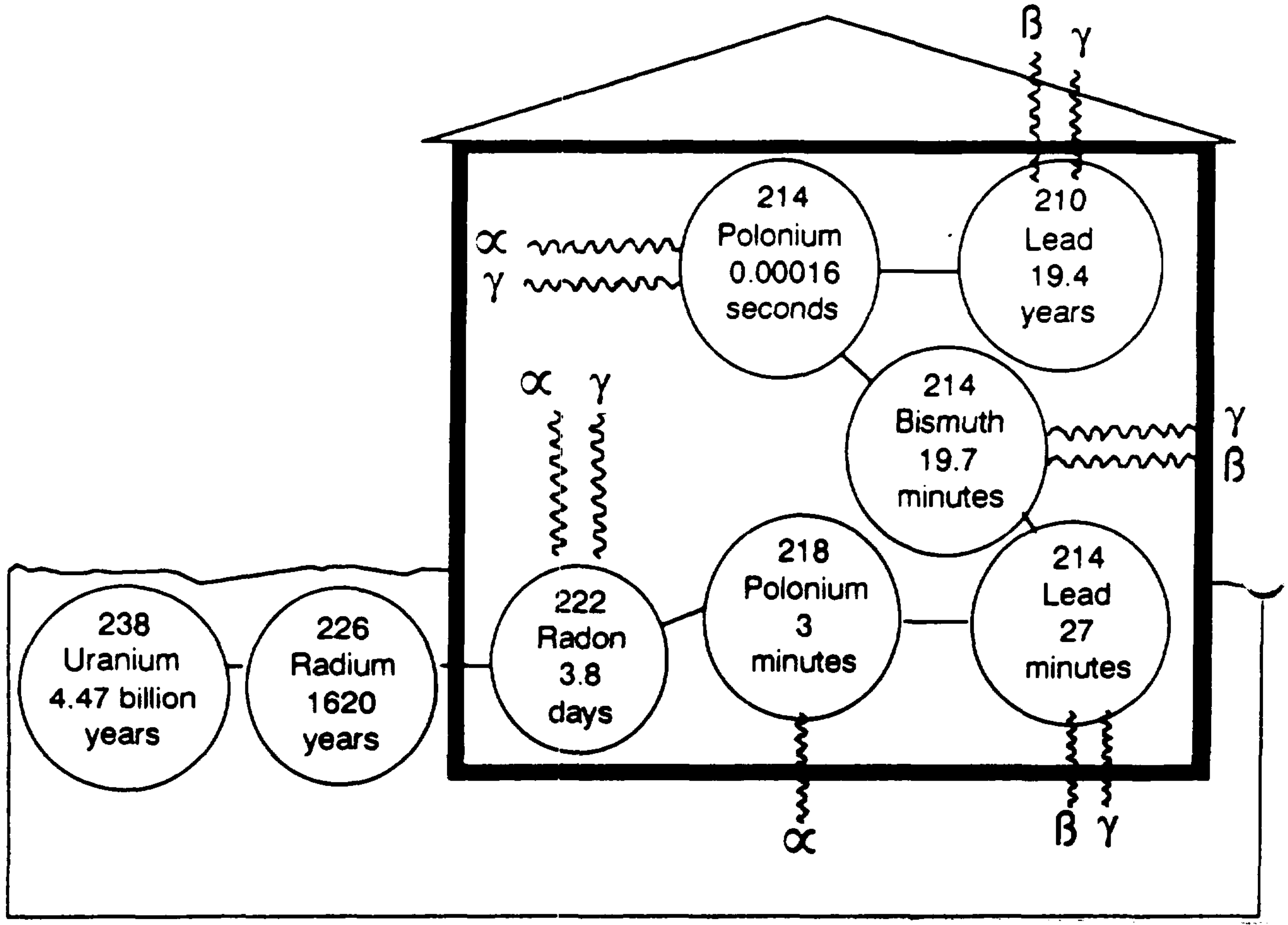

Figure 2.1. Radon Decay Chart. Radon has a long enough half-life to allow it to move from some distance away from the house through the soil into the building. Although some of the radon in the building will be removed with ventilation air, much will be trapped in the building and decay before it is removed.

Radon can also emanate from the building materials themselves. The extent of the use of radium contaminated building materials is unknown but is generally believed to be small.

Figure 2.2 illustrates the percentages of contribution by each type of radon entry made to a specific group of study houses in the Pacific NW (Se89). Any one house can vary significantly from these figures. However, on a national basis this is an indication of the relative importance of each of the contributors.

Figures 2.3, 2.4, and 2.5 illustrate typical radon entry routes found in basement, crawlspace, and slab-on-grade construction.

2.3 Radon Control in New Construction

Like most other indoor air contaminants, radon can be controlled by keeping it out of the house, or reducing the concentration by mixing it with fresh air after it has already entered. The following approaches have been tried or suggested:

- Prevent Entry
  - Make provisions for a sub-slab depressurization or pressurization system during construction
  - Install mechanical barriers to block soil-gas entry
  - Avoid risky sites
- Planned Mechanical Systems
  - Supply fresh air to reduce radon by dilution
  - Control pressure relationships to reduce soil-air entry.

Figure 2.6 illustrates the four major topics to be considered in this manual - Site Evaluation, Mechanical Barriers, Sub-slab Depressurization and Planned Mechanical Systems. All four of these topics are covered in the Overview and

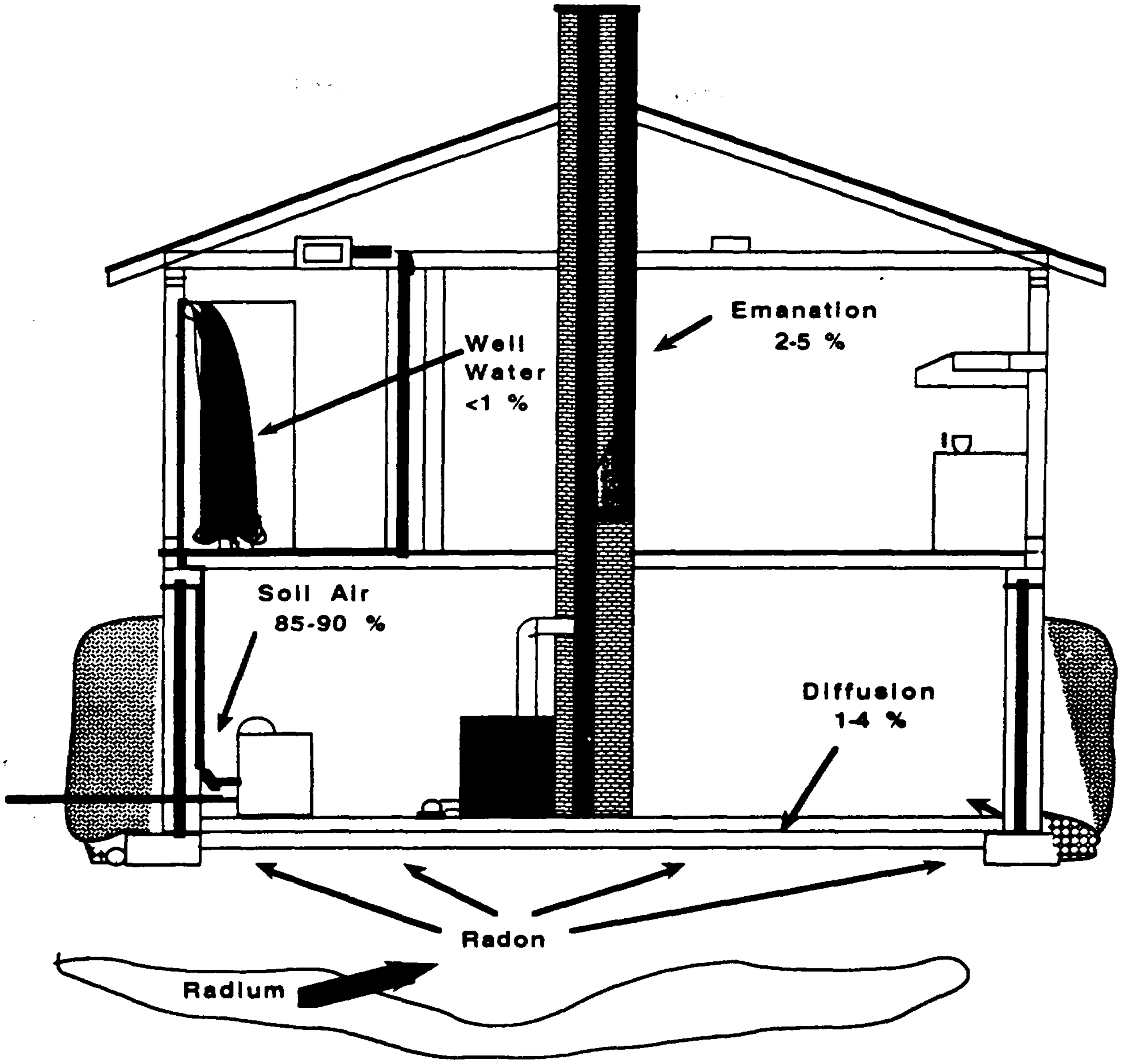

Figure 2.2. Percentage of Radon Contributions by Source from 15 Homes.

Technical Information sections. This illustration will also serve as an index to help you use this manual. The pages in the Overview and Technical Information sections where they are covered are listed beneath each topic.

2.3.1 Sub-Slab Depressurization/Pressurization Systems.

One of the most frequently used radon reduction techniques in existing homes is a sub-slab depressurization system. Typical installation costs for a system in existing homes range from $1,000 to $2,000. If the same system is installed or at least planned for, and roughed in during construction, the cost is much lower, so a prudent builder who is erecting a radon-resistant home should include features that will allow for the easy installation of such a system.

A sub-slab depressurization system creates a low pressure zone beneath the slab using a pipe system to exhaust the soil-gas from beneath the foundation. This prevents soil-gas from entering the building by reversing the airflow direction. Air will flow from the house into the soil, effectively sealing all the remaining foundation cracks and holes. For a simple view of the operating principle of a sub-slab depressurization system, refer to Figure 2.7

A sub-slab pressurization system creates a high pressure zone beneath the slab. Although this does not reverse the direction of the airflow (the air from the system will still flow into the home through cracks and holes), it does dilute the radon concentrations beneath the slab and may keep radon that is being produced in the site from getting to the foundation. In a number of existing houses it has been found that this technique performed better than sub-slab depressurization. In buildings where pressurization works best there are a few common factors. One is the presence of soil or bedrock that allows air to move very easily through it. So

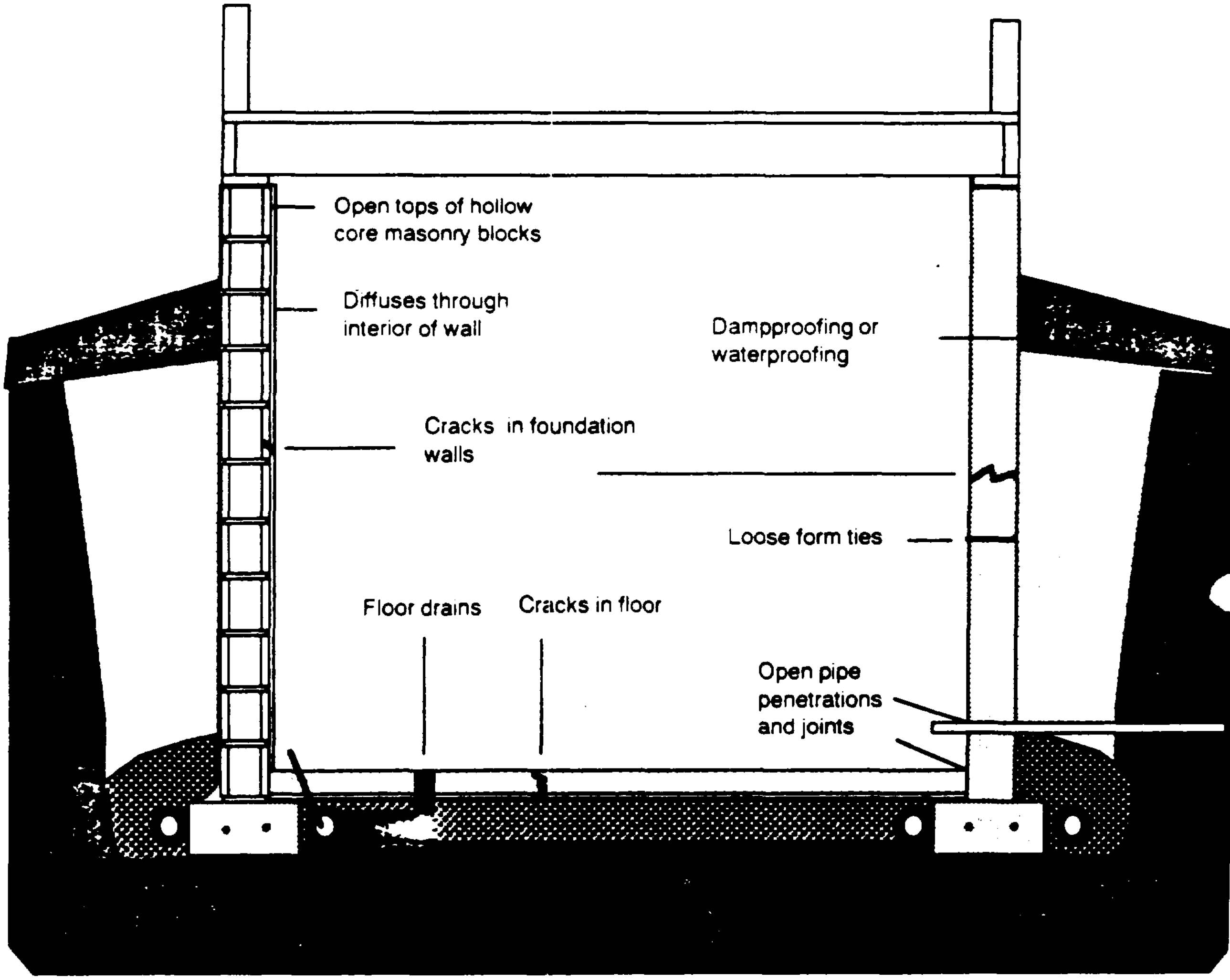

Figure 2.3. Typical Radon Entry Routes In Basement Foundations.

easily, in fact, that it is difficult to establish a low pressure field by exhausting 100 cfm or so of air from beneath the slab. It is this feature that limits the performance of soil depressurization systems. The other factors that seem important are either a relatively low concentration of radon in the soil-gas, or a remote location for the source radium, with radon transported some distance from the house through the very permeable soil. It is thought that a positive pressure created by blowing low radon concentration air under the slab dilutes the soil-gas near the foundation, and diverts soil-gas originating farther away. Pressurization has been successfully used in buildings built in coarse gravel, shattered shales, and limestones. This technique has been used in existing homes to reduce radon concentrations; however, there has been no major research effort to verify the actual effectiveness of pressurization. Other factors to consider when installing a pressurization system are the effect the introduction of, in some climates, below freezing or high humidity air will have on the concrete floor slab, and the effort that must be made to ensure that the air intake does not become blocked by foreign matter.

Sub-slab depressurization/pressurization systems are discussed in detail in Section 3.

2.3.2 Mechanical Barriers

Knowing that the greatest contributor to indoor radon concentrations is air from the soil entering the building through the foundation, it was thought that a good place to begin building a radon-resistant home is to make the foundation as radon-resistant as possible. Figure 2.8 illustrates the principle of a radon barrier. Many materials (concrete, polymeric coatings and plastic films) are outstanding air barriers and retard the transfer of radon gas by a large factor. In practice, the difficulties that arise when using barrier techniques are numerous. Failure to seal a single opening may negate the entire effort. Barriers may degrade with time or may be damaged during installation. The use of barrier techniques as a stand-alone system is not recommended, but it *is* recommended that some amount of effort be made to limit the entry of radon through the foundation. This can be done by using :

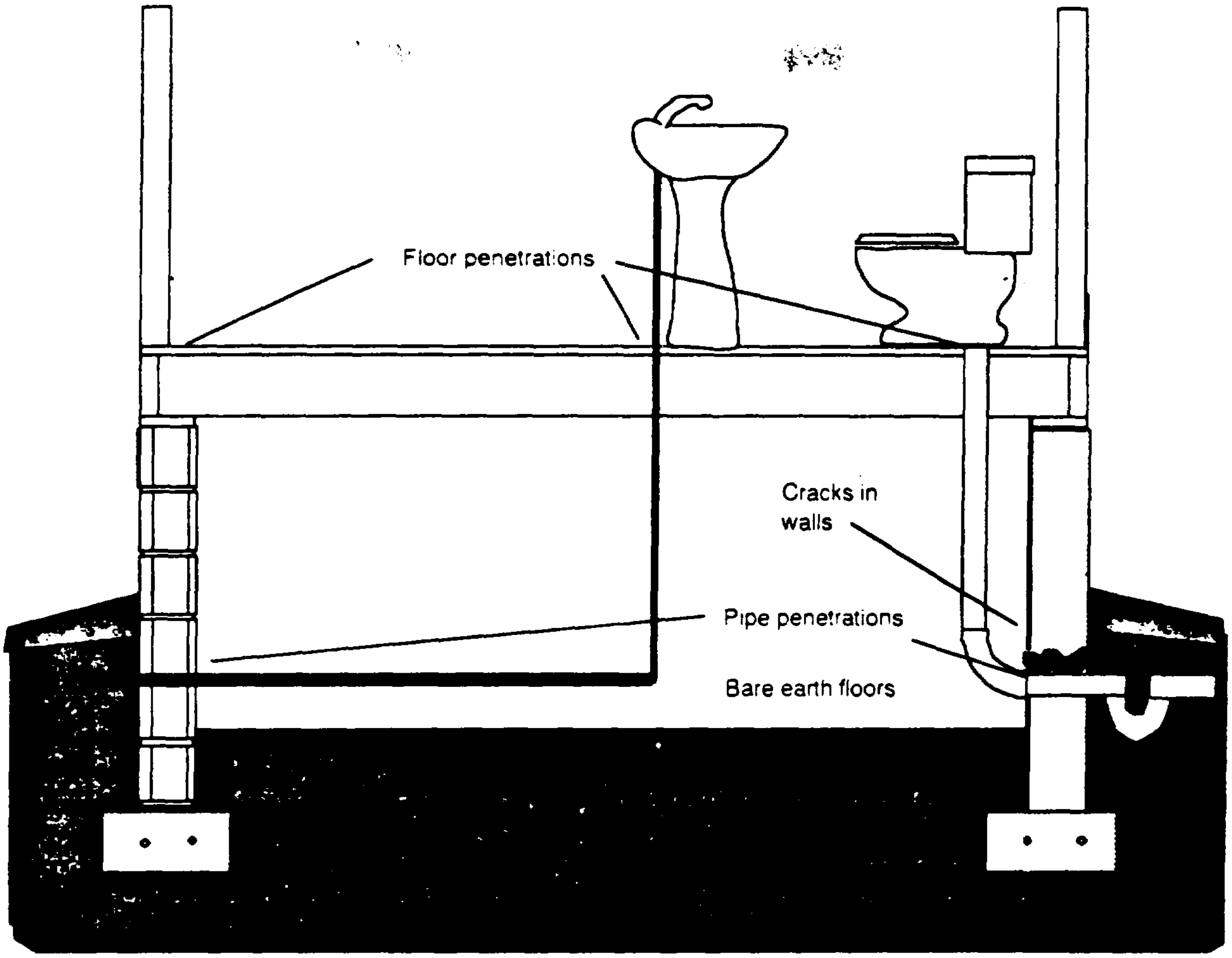

Figure 2.4 Typical Crawlspace Foundation Entry Routes.

- foundation materials themselves, sealing cracks, joints and penetrations
- foundation coatings, normally used for dampproofing
- membranes surrounding the foundation.

This section will briefly discuss foundation design and materials. Methods used to control cracking, treating the cracks that do form, and ways to seal planned foundation penetrations will be reviewed. The material presented in this manual can be easily adapted to buildings with basements, crawlspaces, or slab-on-grade foundations.

It should be pointed out that attempts to control radon by making a gastight barrier around the foundation have not been completely effective. It is likely they have done some good, but many newly constructed buildings that relied on barrier's as the only radon reduction technique have elevated levels of indoor radon. It is not known, however, what the indoor radon concentrations would have been if the barriers had not been installed. This is covered in more detail later in the manual.

2.3.3 The Site

The question most often asked by homebuilders is can one determine if radon-resistant construction techniques should be applied to a given site?

A simple test that could identify problem sites would be very helpful. At present, there are no simple, reliable methods for doing this. The reasons for this are covered in the Technical Information section. In the absence of a simple site screening test, guidance can be sought in the growing body of information developed at regional, state and local levels. Many researchers, public agencies and private homeowners are making soil, bedrock and indoor radon measurements. From these data a picture of the extent of the problem is emerging. While not yet possible to be certain about a given site, some idea of where the problem areas are has been developed. At a recent meeting of several leading mitigation contractors, the general consensus was to install radon-resistant techniques rather than spend extra time and money performing the number of pre-construction tests it would take to confidently evaluate the site. However, a

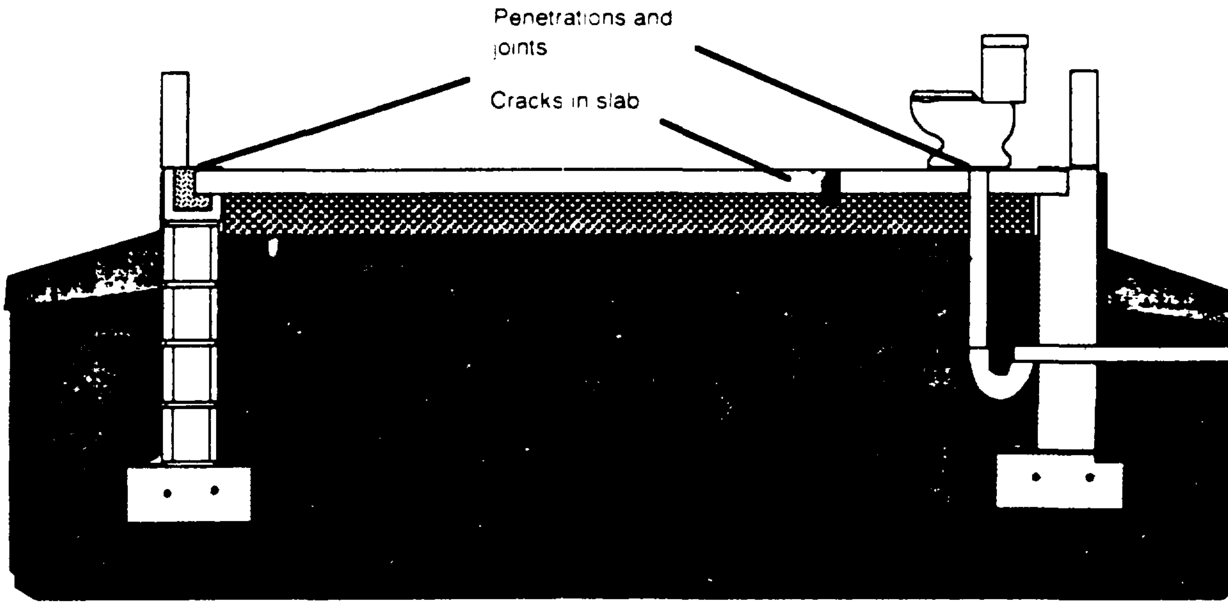

Figure 2.5. Typical Radon Entry Routes in Slab-on-grade Construction

group of testing contractors may decide just the opposite. Although no definitive methods for predicting possible indoor radon concentrations based upon pre-construction soil measurements exist, it is clear that a building being erected on a site that is known to contain high concentrations of radon should have radon-resistant construction techniques applied. Another concern when evaluating the site potential for supplying radon to the soon-to-be-constructed home is the permeability of the soil. A highly permeable soil allows easy movement of soil gases; therefore, radon can move a greater distance from the source to the building than in a tighter, less permeable soil. This can also allow soil-gases that contain lower concentrations of radon to enter the home in greater quantities, which can produce elevated indoor concentrations. Swedish Authorities suggest that a building site with soil radon concentrations greater than 1350 pCi/L or with a highly permeable soil should use radon resistant construction techniques (Ak86).

We do not recommend the avoidance of building sites that are suspected to contain strong radon sources. We do, however, strongly recommend that the homes built on those sites be designed and built with radon-resistant construction techniques.

Water from wells has been found to be a major source of radon in some homes in the United States. Radon will outgas from the rocks into the groundwater. When the water is exposed to the atmosphere, some of the radon is released.

Builders should be aware that wells can be a potential problem. The only way to ensure that a well is not a potential radon source is to have the water tested after the well is drilled. It is not adequate to make a decision based upon tests made in wells in the same area or even on adjoining building sites. A recent research project disclosed two homes with water radon concentrations of over 400,000 pCi/L, while the well used at a house between the two had waterborne radon concentrations of less than 1000 pCi/L (Ni89). It should be understood that, when considering waterborne radon, the concentrations that concern us are much higher than when we are considering radon in the air. As a rule of thumb, between 8,000 and 10,000 pCi/L of radon in the water will contribute 1 pCi/L of radon into the air. There is no standard or guideline for the amount of radon allowable in the water as yet, but a guideline is expected to be set soon. Contact your regional EPA office for more information on pending guidelines.

If radon is present in the water, the current state of technology offers two possible solutions. Water that is aerated will release the radon it carries. Several manufacturers have systems designed to aerate the water and vent the radon outdoors. An alternative system filters the water through granulated activated carbon which removes the radon from the water. There are several manufacturers of granulated activated carbon water filters. It should be noted here that at high radon levels (greater than 5,000 pCi/L) the buildup of radon decay products in the charcoal can produce a significant level of gamma radiation. Although this can be alleviated by proper shielding, disposal of the charcoal filter media can be a problem.

A site suspected to contain a waterborne source of radon should not be avoided solely on the basis of the existence of radon. Methods can be utilized to alleviate any problem that may arise from waterborne radon.

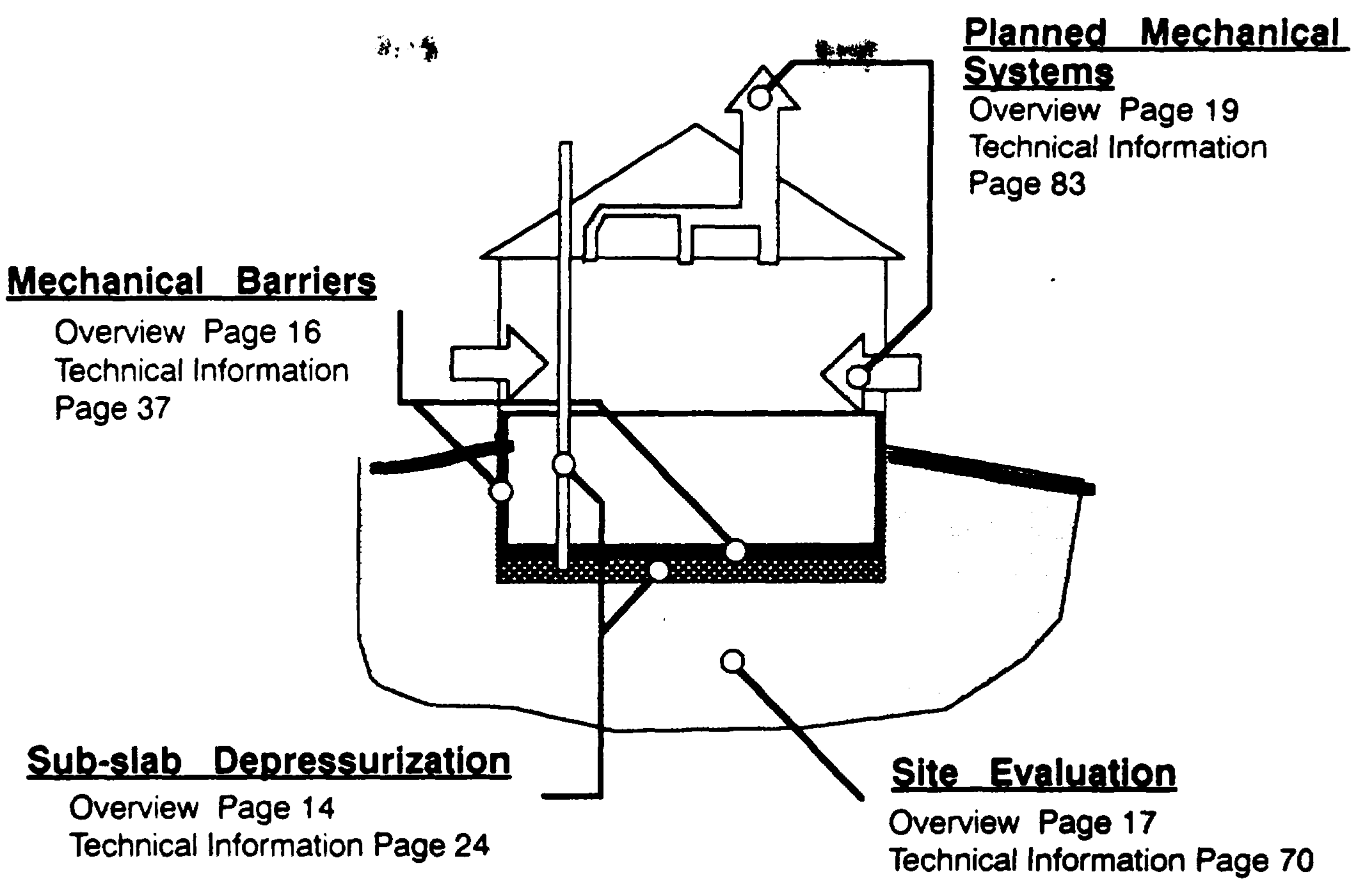

Figure 2.6. Major Radon-resistant New Construction Topics.

2.3.4 Planned Mechanical Systems

The entry of soil gas into buildings is the result of a complex interaction between the building shell, the mechanical system, and the climate. Important climatic variables are the wind velocity, indoor/outdoor temperature differences, rainfall, and atmospheric pressure changes. Indoor radon concentrations can be reduced by planning the mechanical system so that fresh air dilutes the radon that has entered the building, and by controlling interior air pressures to reduce soil gas entry. *This approach has not been extensively tested in the EPA Demonstration Projects in existing homes.* It also requires a great deal of insight into the dynamics of building operation for a given climate. These issues are discussed at more length in the Technical Information section. If this method is considered, the following guidance can be used:

- Be sure that combustion appliance performance is not impacted.
- Supply fresh air in accordance with ASHRAE requirements.

Consult ASHRAE (ASHRAE85) ventilation requirements and the National Fire Protection Association (NFPA1). As a system is designed, consider the use of :

- Power vented combustion devices or combustion devices that use outside air.
- Fresh air supply ventilation systems (heat recovery or non-heat recovery).

2.4 Recommendations

The following sections contain recommended radon-resistant construction techniques that a builder may wish to incorporate into the home. It should be understood that these are recommendations only and should not be construed as guidelines or regulations. The recommendations are based upon the best available information gathered from numerous research projects.

2.4.1 Sub-Slab Depressurization Systems

To facilitate the use of soil depressurization, it is suggested that a permeable layer of material be placed beneath the slab, all the major foundation penetrations be sealed and a passive stack be run from the permeable layer up through the roof like a plumbing vent. Appropriate materials for the permeable layer are 3/8 to 1-1/2 in. diameter stone pebbles, or manufactured drainage products (perforated plastic pipe or drain boards). A passive stack is much easier to add while

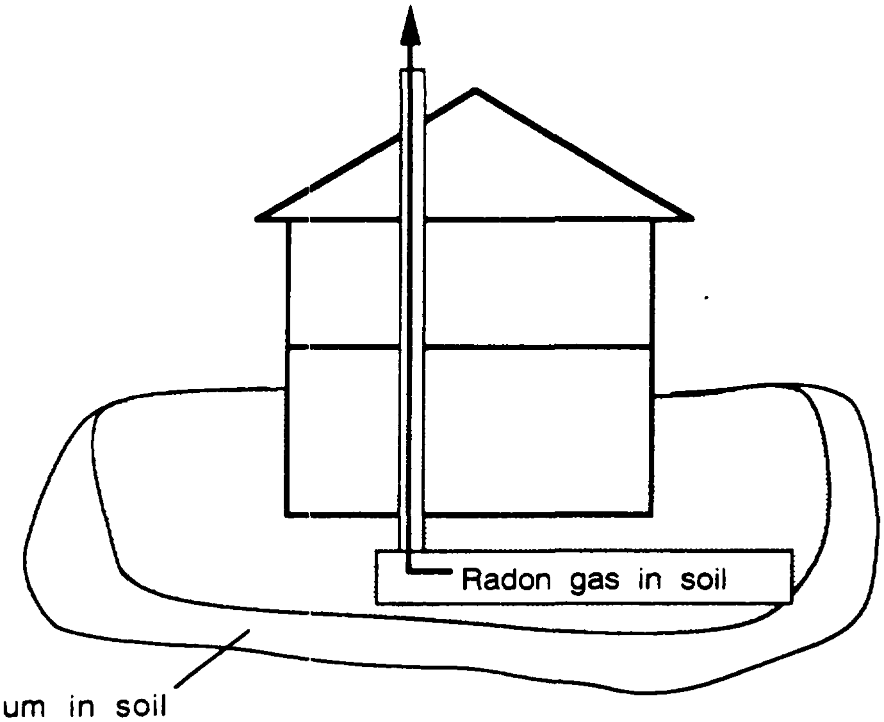

Figure 2.7. Sub-slab Depressurization Theory.

building the house, and is easily power vented later if required. There is evidence that, while not foolproof, a properly designed passive venting system can sometimes have some impact on indoor radon levels.

2.4.2 Mechanical Barriers

Below-grade walls may be constructed of poured concrete, masonry blocks, or other materials such as all-weather wood or stone. This manual discusses details for use in poured concrete and masonry foundations because these are the most common materials used for new construction. Recently, trade associations such as the American Plywood Association and the National Forest Products Association have issued publications on designing radon-resistant permanent wood foundations. Information on these types of foundations can be found by contacting the appropriate trade association (NFoPA88).

The following is a list of recommendations that builders can use to utilize the foundation as a mechanical barrier to radon entry.

Foundation walls and floor slabs are often constructed of poured concrete. Plastic shrinkage, and therefore cracking, is a natural function of the drying process of concrete. Many factors, such as the water/cement/aggregate ratio, humidity, and temperature, influence the amount of cracking that occurs in a poured concrete foundation. Cracking may be minimized by :

- Proper preparation, mixture, and curing of concrete

  (ACI302.1R-80, ACI332R-84)
- Ferrous reinforcing (rebar rods and woven wire meshes)
- Use of concrete additives to change the characteristics of concrete
- Water reducing plasticizers, fiber-reinforced cements (ACI212.1R-81).

To help prevent cracking in masonry walls, or minimize the effects of cracks that do develop:

- Using correct thickness of unit for depth of soil (NCMA71)
- Using ferrous reinforcing (corners, joints, top course) (NCMA68)
- Coating interior and exterior of wall with dampproofing.

Cracks and joints in concrete and concrete block can be sealed using caulks. Polyurethane caulks have many of the properties required for durable closure of cracks in concrete. These features are :

- Durability
- Abrasion resistance
- Flexibility
- Adhesion
- Simple surface preparation
- Acceptable health and safety impacts.

Typical points that should be sealed with caulks are :

- Plumbing penetrations (soil pipes and water lines as minimum)

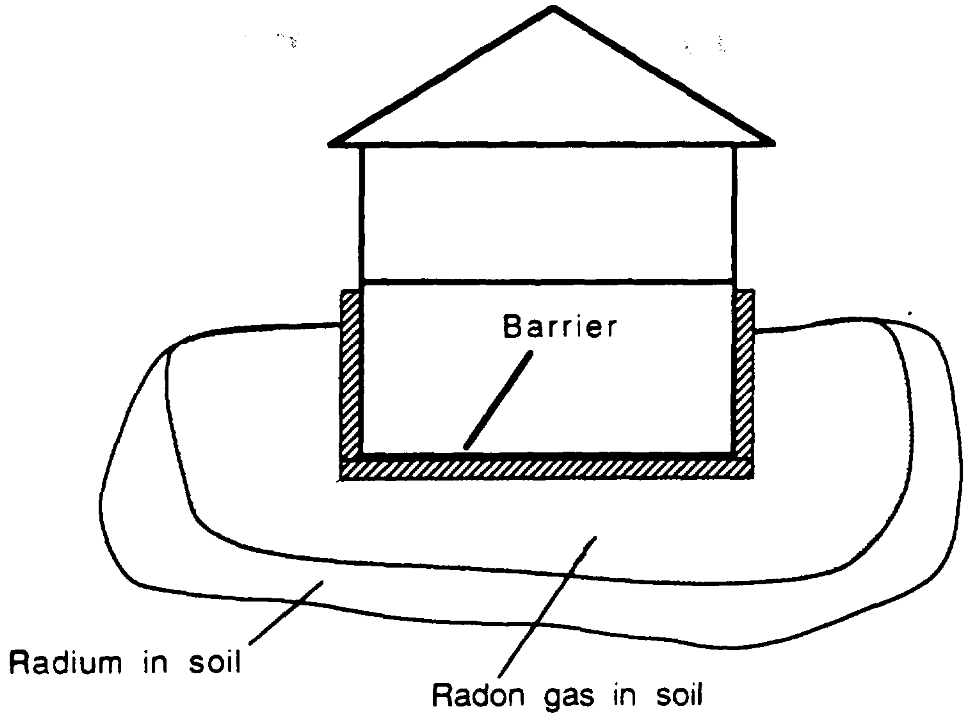

Figure 2.8. Radon-resistant Barrier Theory.

- Perimeter slab/wall crack and expansion joints (tool crack or use "zip" off expansion joint material.

The open tops of concrete block walls are openings that should be sealed. This can be done by installing a row of solid blocks, lintel blocks or termite cap blocks at the top of the wall.

Drainage details that leave openings through the foundation should be avoided or modified. Sump holes and french drains are widely used examples of this type of detailing. It is best to avoid them if possible, by using alternate drainage systems. When these design details are unavoidable, a little thought can allow the use of these details and still keep radon from entering the home. The Technical Information section will discuss these designs in greater detail.

In many areas of the country, some type of dampproofing or waterproofing treatment is required by code.

The application of dampproofing and waterproofing materials on the exterior, interior, or both sides of the foundation that can serve as a radon resistant barrier is *recommended* to help control radon entry. It must be understood that a coating applied to a foundation intended to resist the flow of radon into the building is in addition to the normal waterproofing/dampproofing requirements.

Coatings are applied to the outside or inside of the foundation, creating a radon- resistant barrier between the source and the inside of the home. They come in a wide variety of materials including paint-like products that can be brushed on the interior of the foundation, tar-like materials that are applied to the outside, and cementitious materials that can be brushed or troweled on. They cannot be applied to the underside of the concrete floor slab for obvious reasons, so must be applied to the inside surface of the slab. The effective life of an interior coating can be greatly diminished by damage; therefore, care must be taken to provide protection to the material used.

Membrane barriers are applied to the exterior of the foundation and also beneath the floor slab during construction. Materials used for the membrane barriers range from co-extruded poly olefin to polyvinyl chloride to foil sheets with many other materials in between. All membrane barriers must have the edges sealed to prevent radon from migrating around the edges and back into the building.

It is recommended that, as a minimum, a membrane be placed beneath the slab, and all foundation penetrations to the soil be sealed or otherwise dealt with in a manner which will prevent the entry of radon into the home.

Section 3
Soil Depressurization

Introduction

The next four sections contain details and references for those wishing a deeper understanding of radon-resistant construction issues. The four major topics:

- Sub-slab Depressurization
- Mechanical Barriers
- Site Evaluation
- Planned Mechanical Systems

are used to organize this portion of the manual.

In theory, the application of radon barriers should be adequate to avoid elevated radon levels in houses. In practice, however, a backup radon mitigation system has been found essential for maintaining indoor radon concentrations below 4 pCi/L in most homes studied. In recent radon-resistant residential construction projects conducted by EPA and/or private builders, several of the homes designed to be radon-resistant have contained radon concentrations above 4 pCi/L. In each of those houses a backup system consisting of an active (fan assisted), or passive (wind and stack effect assisted), sub-slab depressurization system was installed at the time of construction. When mechanical barriers failed to adequately control radon, the soil depressurization methods were made operational.

3.1 Sub-Slab Depressurization Overview

Of the study homes mentioned in the previous section, some passive systems seemed sufficient to lower the radon concentrations, while in all cases, active systems resulted in significantly lower concentrations. However, some of those projects are on-going and longer term testing may show that some of the active systems will fail to maintain concentrations below the guideline for the long term. Table 3.1 summarizes the findings of these particular projects. See Appendix A for more information on the data contained in this table.

Table 3.1 Summary of Radon Concentrations in EPA New Construction Projects.

Project	# Houses	Barrier Only pCi/L	Soil Depressurization Passive pCi/L	Soil Depressurization Active pCi/L
EPA-VA1	10	14.5	6.0	<1
EPA-NY1	15	15.8	13.9	2.8
EPA-VA2	2	1.3	<1	<1
EPA-PA1	1	13.4	7.0	1.1

The most common way radon enters a home is when air pressure differences move soil gases containing radon through the spaces between soil particles to the foundation of the home. Just as gravity will make water flow from a higher area to a lower area, pressure differences will make radon laden soil gases move from an area of higher pressure to an area of lower pressure. Most buildings tend to maintain themselves at an air pressure lower than the surrounding soil. This characteristic is due to weather driven parameters such as indoor/outdoor temperature differences and wind. The use of exhaust fans and combustion devices in a home will also create a negative pressure in the home. If cracks and holes in the foundation are open to the surrounding soil, radon will be drawn into the building. Figure 3.1 illustrates the principle of pressure transported radon and also shows some of the things that produce the differences in pressure. Refer to the section on planned ventilation for more information on pressure differences.

3. 2 Sub-Slab Depressurization Systems

As previously mentioned, the air pressure in most homes is less than the air pressure in the surrounding soil. The difference in air pressures is what draws radon into the home. A sub-slab depressurization system alters the pressure beneath the concrete slab, making the sub-slab pressure less than the indoor pressure. It is the altered air pressures that keep radon from entering the home.

Figure 3.2 shows the theory of operation, a simple system layout, and the components of a sub-slab depressurization system.

Careful attention to detail when in the design stage of a sub-slab depressurization system will help ensure the easy installation of a system if it is found to be required. The proper details are given in the following sub-sections, beginning at the sub-slab area and progressing upward to the exhaust.

3.2.1 Overall Design Considerations— Active and Passive Systems

When designing an active or passive system, many design considerations are common to the two systems. For example, some provision for removal of condensation that forms in the exhaust pipe will be required. Routing of the pipes from the basement to the roof must be considered when the house is being designed. Placement of the exhaust is extremely important.

Removal of condensation is an important consideration. Water collecting in an elbow or other low point of the system can effectively block the pipe, and reduce or disable the system. Builders should strive to design a pipe system that will allow condensation to run back through the pipe to the sub-slab aggregate. This can be accomplished by ensuring

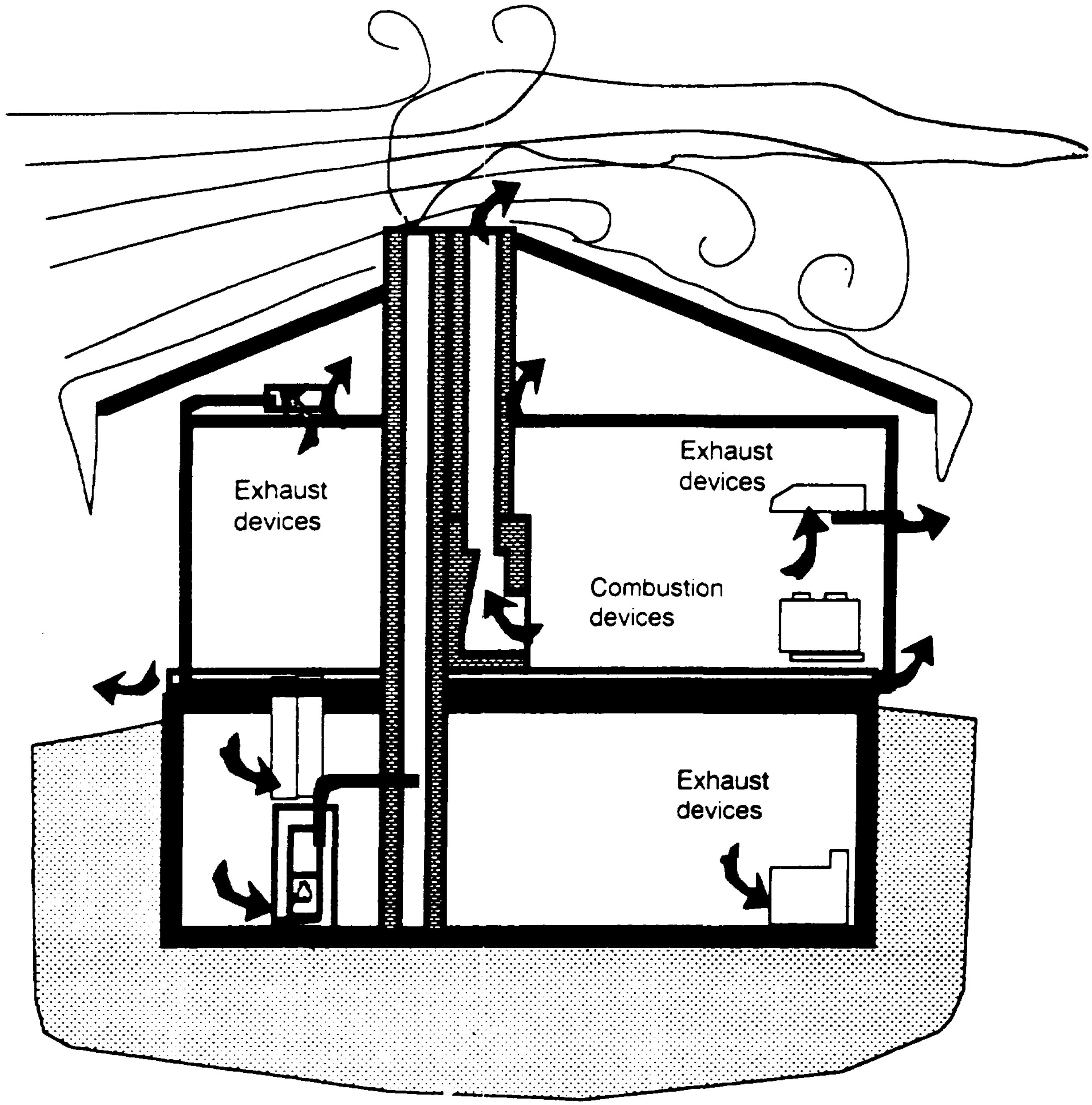

Figure 3.1. Negative Pressure Sources In a Typical Home.

that the pipe run is vertical the entire distance from the basement to the exhaust. A completely vertical pipe run with no bends or elbows will also provide a pipe system with lower static pressure losses which enhances the effectiveness of both active and passive systems. If elbows or a low point is incorporated in the design, a condensate pump can be used to drain the water away. The use of condensate pumps will increase the cost of the system both in materials and labor, so the ideal situation is to design a system that does not require pumps.

Pipe routing should be considered when the home is being designed. This will ensure that there is an area reserved for the exhaust pipe and preclude any possibility of having to build the system with numerous elbows and long horizontal pipe runs. Ideally, the pipes should be run through an interior wall of the home or up through closets.

The exhaust should be located above the highest ridge line. Some builders prefer to exhaust their systems out an attached garage roof, rather than through the main roof. This type design does require at least one short horizontal run, and will not seriously impact the effectiveness of an active system. When choosing the exhaust point, avoid the reentry of radon-laden soil-gas into the home through open windows and doors. Do not exhaust the soil-gas in an outdoor occupied area such as a porch or patio. Locating the exhaust close to a chimney that could backdraft and draw the exhausted soil-gas back into the home should also be avoided. For a good discussion on the theory of exhaust design, see the 1985

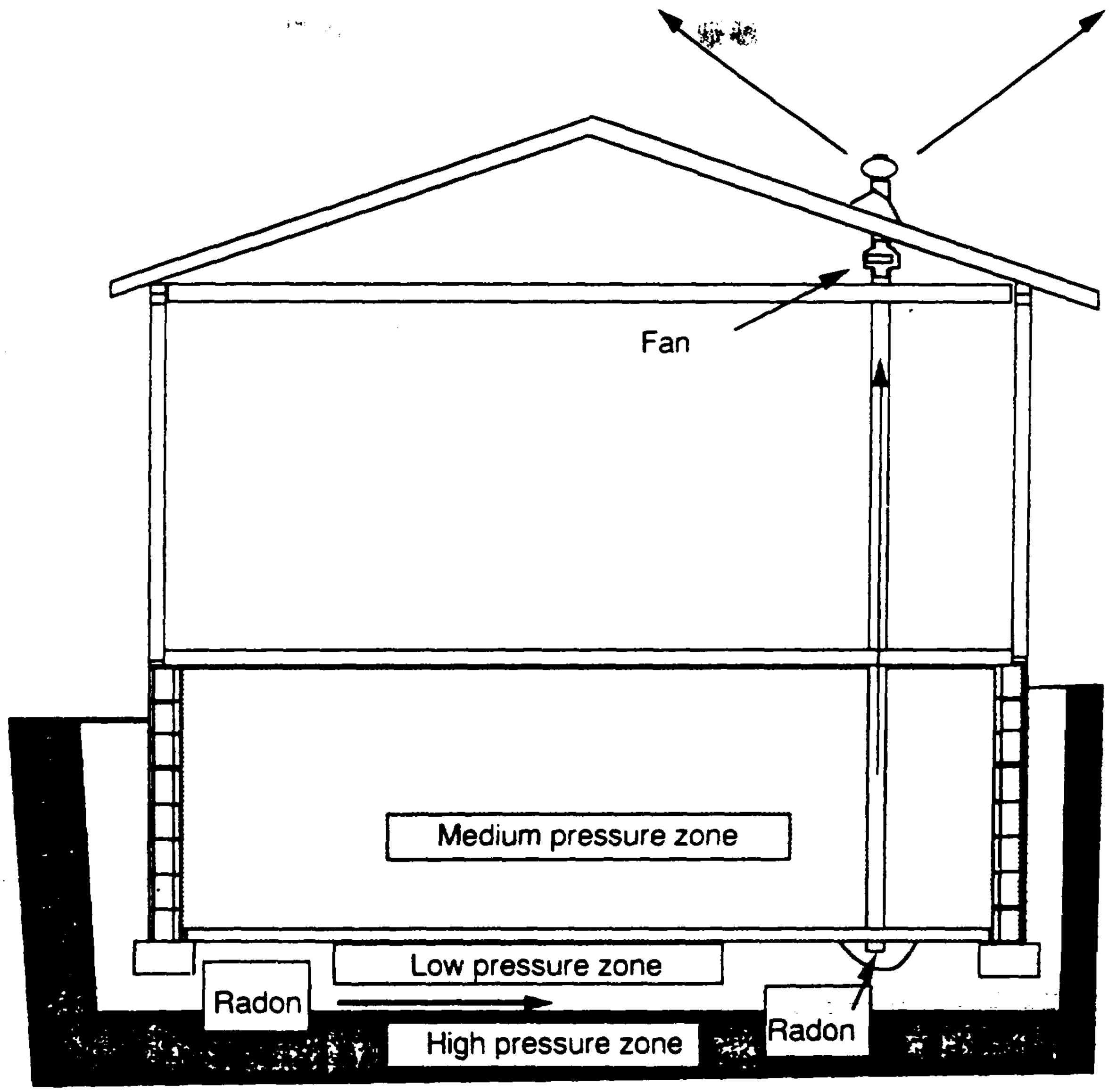

Figure 3.2. Theory of Operation of a Sub-Slab Depressurization System.

edition of the ASHRAE Fundamentals Handbook, Chapter 14 (ASHRAE85).

3.2.2 Sub-Slab Preparation

Figure 3.2 illustrated that a low pressure area being developed beneath the slab will draw the radon out of the soil, up the pipe, and exhaust the gas outdoors. If the sub-slab material consists of tightly packed soil or contains large rocks, the pressure field may not extend to all areas of the soil surrounding the foundation, and allow radon to enter the home where the pressure field does not exist. One way of ensuring the proper extension of the pressure field is to install media beneath the slab prior to the pour that will allow the easy movement of the air, thus helping to extend the pressure field.

In areas where it is available, crushed gravel is an inexpensive material to use. Sub-slab gravel provides a drainage bed for moisture and a stable, level surface for pouring the slab. The material preferred for radon reduction is crushed aggregate with a minimum of 80% of the aggregate at least 3/4 in. in diameter. This stone should have a free void space above 40 %. One standard specification of this type of gravel is D.O.T. # 2 gravel. A minimum of 4 in. of aggregate should be placed under the entire slab. Care must be taken to avoid introducing fine dirt particles during and after placement of the aggregate.

In areas where gravel is not readily available, drainage mats designed for soil stabilization may be used. The use of these drainage mats may not be cost effective in areas where gravel is available, but where gravel must be shipped in from long distances, drainage mats can be cost effective.

Some builders prefer laying perforated PVC piping in the gravel before the slab is poured, and connecting the perforated pipe to the exhaust pipe of the system. The use of perforated pipe may not be necessary in active systems but probably will assist a passive system.

Membranes beneath the slab help to keep a continuous radon barrier in the event of slab cracking. For more information on this detail see the discussion on membrane barriers.

The use of footing drains for water control can affect the distribution of the pressure field. Interior footing drains sometimes terminate in a sump hole. If this is the case and the sump hole is not sealed airtight, the possibility exists for air to be drawn into the sump by the sub-slab system and weaken the pressure field. Make sure all sumps are sealed airtight. Sometimes interior footing drains extend out beneath the footing and run to daylight, as shown in the section on mechanical barriers. If this is the case, provision must be made to make the ends of the drain airtight while still allowing water to drain. Reverse-flow valves are ideal for this application.

To summarize, any opening or connection that allows the depressurization system to draw air from anywhere but beneath the slab is detrimental to its effectiveness and must be avoided.

3.2.3 Preparation of the Slab

A thorough discussion of slabs is included in the section on foundation materials as mechanical barriers and should be referred to. However, when installing a soil depressurization system, it is more important to seal the large openings that would defeat extension of a low pressure field than it is to seal every small crack. This is because the airflow through small cracks from the building into the soil will effectively seal them against soil gas entry.

3.2.4 Active Sub-Slab Depressurization System Materials and Installation Details

As can be seen on Figure 3.3, active sub-slab depressurization systems consist chiefly of a pipe system and a fan. There are several other components that should be included in a good system, but are not necessary to make the system reduce radon concentrations.

Most builders use 4 in. schedule 20 PVC pipe. Other sizes can be used but 4 in. PVC is readily available and is commonly used by builders for other purposes. Fans made for use in sub-slab systems are available in a variety of sizes from many vendors. The fans normally used are rated in a range of 90 to 150 cfm at no static pressure. Manufacturers of fans used for radon reduction are fairly quick to improve their products on advice from the people who are using their products. When the radon industry first started, many of the fans leaked at seams and joints, and required disassembly of the fan to seal those openings. Most manufacturers now supply fans that do not leak, but builders should be aware that this problem did exist and may still exist in some fans.

Additional materials and components that are normally included in a system satisfy safety needs, system performance indications, and common sense.

Service switches should be placed within view of the fan to ensure that the system will not be activated while maintenance is in progress.

Systems should be clearly marked as a radon reduction device to ensure that future owners of the building do not remove or defeat the system. An operation manual describing the system and its purpose should be made available.

Some type of device should be included in the system to advise the owners on system performance. These devices may be simple pressure gauges that tap into the pipe and measure and display the pressure in the exhaust pipe. A visual check of the gauge will alert the homeowner to possible system malfunctions. Electronic pressure sensing devices that illuminate a warning light or sound an audible alarm when a pressure drop occurs are also used but cost more than a simple gauge indicator. It is advisable to use a device that warns of a pressure change rather than something that warns that the fan is not running because there are several things that can stop a system from operating effectively that do not effect the fan.

Rain caps at the end of the pipe are intended to keep rain from entering the system. Builders use various cap designs for this purpose. The use of rain caps can cause a loss of air flow in a system, which may lessen the effectiveness of the system. It is advisable to use a rain cap that is designed in such a way as to not seriously impede airflow. For more information on rain caps and stack design, see the ASHRAE 1985 Fundamentals Handbook, Chapter 14 (ASHRAE85).

Attention to detail during the installation process will help ensure the proper operation and long life of the system. Starting at the floor slab, seal the void between the pipe and the floor slab with a non-shrink grout or a flexible, highly adhesive sealant. Place a sticker or other labeling device on the pipe identifying the pipe as belonging to a radon reduction system. Ideally a label should be placed at regular intervals along the entire pipe run. A visual system performance monitoring device should be placed in an area that is often visited and in plain view of the homeowner. Audible alarms can be placed in any area, as long as the homeowner can hear them. It is a good idea to place alarm sensors in easily accessible areas because they sometimes need adjusting. Run the pipe as straight as possible to the attic to ensure proper draining of condensation. *The fan should always be located in a non-living area as close to the exhaust as possible. [illegible] is extremely important because a leak in the fan or in the piping above the fan will blow the radon back out of the pipe.* If the fan is placed in the basement, and a pipe leak occurs above the fan, radon laden air will be introduced into the living area, and can cause radon levels to build to very high concentrations. Most builders connect the fans to the pipe system with rubber sewage pipe connectors. This allows for the easy removal and replacement of the fan if that should become necessary. Always install a service switch in sight of the fan. Run the pipe through the roof and flash well. If desired, cap the pipe with a rain cap.

3.2.5 Passive Sub-Slab Depressurization System Components and Installation Details

A passive system is much the same as an active system with the exception of the fan. A passive system relies only on stack and wind effects to produce the pressure field. As can be seen on Table 3.1, passive systems do not always reduce radon concentrations to acceptable levels, but careful design and installation may improve the effectiveness of a passive system.

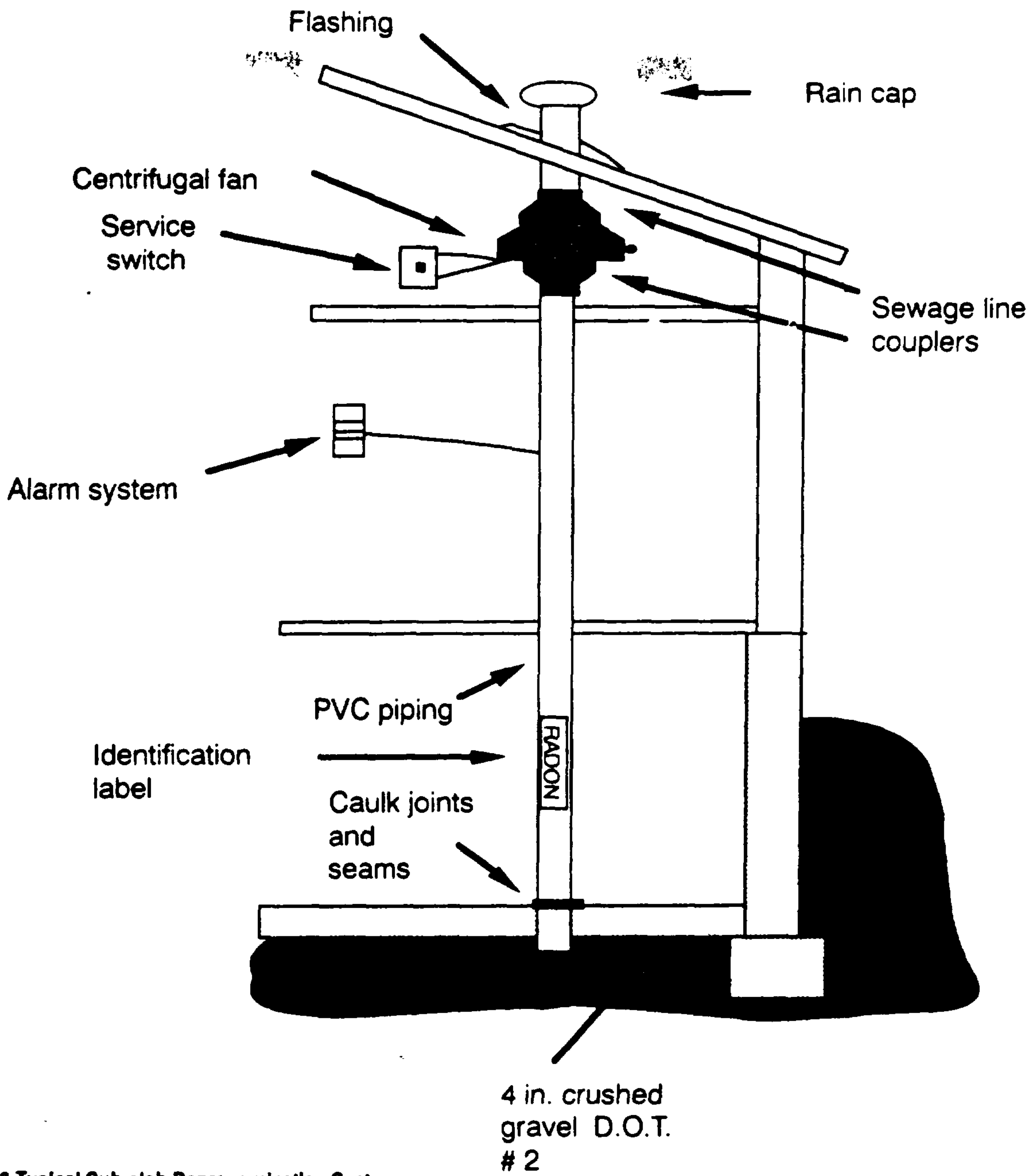

Figure 3.3 Typical Sub-slab Depressurization System.

It is probably beneficial to a passive system to lay a network of perforated drainage pipes in the gravel bed beneath the slab prior to the pour. The use of horizontal pipe runs and elbows in a passive system may greatly lessen the effectiveness to the system and should be avoided. Some builders use 6 in. PVC in a passive system to help lessen the pressure drop.

3.3 A Crawlspace Post-construction Alternative

Due to difficulties often encountered in sealing subfloors and insulating pipes in crawlspace houses, which rarely have a poured floor slab, another radon-resistant alternative that can be applied after construction should be considered. This mitigation technique is a variation of the successful sub-slab depressurization methods used in basements. Polyethylene sheeting is often used as a moisture barrier applied directly over the soil in crawlspaces. The polyethylene sheeting can be used as a gastight barrier that forms a small-volume plenum above the soil where radon collects. A fan can be installed to pull the collected soil gas from under the sheeting and exhaust it outside the house.

The wide-width polyethylene sheets should be set directly on the earth in a way that produces at least 1-ft overlaps. Some field applications have included a bead of caulking to seal between sheets of polyethylene. A better seal has been achieved by using an aerosol spray. A good seal is obtained by spraying both surfaces of the polyethylene, allowing time for them to get tacky, and pushing the two pieces of polyethylene together. In locations where the soil surface is exceptionally hard and smooth or the crawlspace is very large, a drainage material can be placed under the sheeting to improve airflow. If a large number of support piers exist or if the suction point is located close to support piers, the polyethylene sheeting should be sealed to the piers with caulking and wood strips. The plastic sheeting may also be sealed to the foundation walls to reduce air leaks. Some retrofit applications of this crawlspace radon mitigation technique have worked well without attempting to seal the sheets of polyethylene together or sealing the polyethylene to piers or walls. Many others have not been successful without sealing. When this technique is used, a complete sealing job is recommended for greatest protection. Application of this technique may not be appropriate in crawlspaces that receive heavy traffic.

Some builders prefer to concrete the floor of crawlspaces when site and design conditions permit getting the mix into the crawlspace. If a crawlspace has a concrete slab, for radon-resistant construction the crawlspace should be treated similar to a basement with the advantage of greater ventilation potential.

Section 4
Mechanical Barriers

Introduction

This manual has presented four topics concerning radon-resistant construction issues. Discussed in this manual are techniques to:

1) prevent radon entry by using a sub-slab depressurization system
2) prevent radon entry by using mechanical barriers
3) reduce radon and radon entry with planned mechanical systems
4) determine the potential for a radon problem by evaluating the site.

This section addresses the mechanical barrier approach, Section 3 addresses building in a sub-slab depressurization system. Section 5 discusses site evaluation. Section 6 addresses a ventilation system planned to supply outdoor air to the house, and reduce the pressure differentials that drive soil-gas into the building.

Theoretically, a gastight barrier could be placed between the soil and foundation to eliminate radon entry from the soil. Like many other building details, it is much easier to draw such a detail than to actually install it. Many materials form effective retarders to gas transport. The problem is effectively sealing cracks, joints and penetrations. As anyone who has tried to build an airtight house can tell you, it is not as easy as it seems.

The types of mechanical barriers that have been tried or suggested for radon control, fit into one of the following categories :

- foundation materials themselves
- coatings
- membranes
- possibility of a "site" barrier.

Ongoing EPA research on radon-resistant new construction has encountered numerous difficulties in making a gastight mechanical barrier effective enough to confidently keep indoor radon levels below 4 pCi/L. The types of problems encountered included quality control on the job; incomplete communication between researchers, contractors and subcontractors; reluctance of builders to change drainage detailing; and the smallness of the radon atoms.

The first problems on the list are not specific to radon control but are encountered on nearly every construction job. In spite of quality control and communication problems, and the understandable wariness builders show when asked to build something in a different way, the residential construction industry has responded to new techniques, materials and public demands. The average house being built today is very different than a home built 10 years ago. If a product or method can be demonstrated to reliably keep radon out without presenting significant problems with cost, scheduling or installation, many builders would learn to use it. The major difficulty faced by mechanical barrier approaches is the thoroughness that seems to be required to ensure that no radon problem will occur.

In 1988 and 1989, EPA projects studied newly constructed houses which incorporated mechanical barriers and provisions for active and passive sub-slab depressurization to determine the effectiveness of each approach. Preliminary results from these five studies found that, when there was a source of radon beneath the houses, the mechanical barriers were *not adequate* to ensure basement levels below 4 pCi/L. *However, there is no way to judge how high the radon concentrations in these buildings would have been had the mechanical barriers not been employed.* These data should not be used as evidence that the barriers used (or that mechanical barriers in general) do not reduce radon levels indoors. In fact there are good reasons to employ barriers to enhance the performance and reduce the energy penalty of soil depressurization techniques.

When trying to make a barrier to soil gas entry, the routes of concern in new construction are the same as those that have previously been identified for existing houses. These entry routes are covered in Part 2, the Overview. Houses that are combinations of the above substructures often provide additional entry routes at the interface between the two substructures. The following subsections address the types of mechanical barriers (foundation materials, coatings and membranes), the potential radon entry routes associated with common foundation detailing, and suggestions for details that reduce the risk of elevated indoor radon. When possible, these alternatives include barriers that can be used to block radon entry while continuing to use traditional construction methods. Depending on current local or regional building practices, some of the suggestions may require significantly different construction methods.

4.2 Foundation Materials

The materials used to construct a foundation can often be used as an effective barrier to the entry of radon laden soil gas. Below-grade walls may be constructed of poured concrete, masonry, or other materials such as pressure treated wood or stone. The materials covered in this section, poured concrete and masonry block, are the most common for new construction. Details for radon protection in permanent wood foundations can be found in a National Forest Products Association publication entitled "Radon Reduction in Wood Floor and Wood Foundation Systems" (NFoPA88).

In residential buildings, foundation walls made of poured concrete are generally constructed to a compressive strength of 2,500 to 3,000 psi. The forms are held together with metal ties that penetrate the wall. A poured concrete wall is a good barrier to radon transport. The major weaknesses in this regard are cracks, joints and penetrations. It is these openings in the walls that allow soil gas to enter the building without actually having to diffuse through the concrete. It is recommended that concrete walls be built in compliance with guidelines established by the American Concrete Institute (ACI332R-84). Such concepts as cover mix, reinforcing, slump, temperature, vibration and a variety of other factors help to keep the foundation from cracking.

Residential foundation walls built of concrete masonry units may have open cores, filled cores or cores closed at the top course. Masonry walls are frequently coated with an exterior layer of cementitious material, referred to as "parging," for water control. This coating is usually coved at the bottom of the wall to make a good exterior seal at the joint between the footing and the block wall. Uncoated block walls can range in porosity depending on the type of aggregate used. Uncoated blocks are neither an effective water nor radon barrier. It is recommended that concrete block walls be built according to guidelines issued by the National Concrete Masonry Association (NCMA72). Their publications cover thickness of block, reinforcing, pilaster location, control joints, sequencing and other issues that prevent cracking or foundation failure.

There are geographic areas throughout the U.S. in which the majority of foundation walls are poured concrete and other areas where masonry walls predominate. Poured concrete walls are generally available only in areas where contractors have the in-house expertise to build them and either rent or have invested in reusable forms. In areas where both types of construction are found, the costs of each seem competitive.

There are building codes that dictate dampproofing or waterproofing treatment for both type foundations. The treatments can also inhibit gas movement through the wall. Concrete blocks are much more porous than poured concrete, although the parge or waterproofing coats moderate the difference. Recent laboratory tests have confirmed that uncoated concrete masonry walls allow substantial airflow, but that there is a great deal of variation in the porosity of blocks, due mainly to the use of different aggregates by the block manufacturer. Block walls can allow substantial soil gas circulation in the cores of unfilled blocks, providing an area source of radon. Various measures are available to alleviate this problem, including exterior (or interior) gas barrier membranes and solid or filled block tops.

Although it is clear that concrete blocks are more porous than poured concrete, some studies reveal no strong correlations concluding that a home built with a concrete block foundation is more likely to have a radon problem than one built with a poured concrete foundation. A New Jersey study (Ru88) found mean radon concentrations in 581 basements with poured concrete walls of 6.3 pCi/L ± 14.1% and that the mean concentration in 3408 basements built with concrete block walls was 5.7 pCi/L ±11.1%. There is no statistical difference between the two means. A survey conducted in Connecticut (Si90) in a smaller sample population revealed a geometric mean radon concentration of approximately 1.7 pCi/L in 755 homes with poured concrete foundations. The same study revealed a mean concentration of approximately 2.0 pCi/L in 129 homes with block foundations. The amount of error in the two means is not known at the time of this writing; however, it is suspected to be significantly high enough to show no statistical significance between the two means. It is one more example of a variable that would seem to have an effect on indoor radon concentrations not meeting those expectations. The expected effect is lost in the complex interaction of the far more important factors that affect radon source strength and transport. It is interesting to note that the 639 stone foundations tested had mean basement radon concentrations of 6.2 pCi/L ± 10.1%, virtually identical to the other two types of foundation walls.

4.3 *Common Masonry Wall Details and Their Impact on Radon Resistance*

4.3.1 *Masonry Walls with Termite Caps, Solid Blocks, and Filled Block Tops*

Builders may construct a foundation wall with solid, filled, or sealed block tops for several reasons including termite-proofing, energy conservation, distribution of weight of the structure and radon-resistance. The National Concrete Masonry Association (NCMA72) recommends that a solid or grouted top course be installed to distribute the loads of joists and beams. Some building codes require solid tops to block hidden termite entry. In spite of this, the block tops in many residences are left open except at anchor points. Houses have been observed in which block tops were generally sealed, but cores were left unsealed at access doors to crawlspaces, around ash pit doors and other openings. Sealing hollow cores at or near their tops can prevent soil from entering the basement, but more importantly might make the building easier to mitigate in the event that it has elevated radon. Sealing the bottom course might prevent air beneath the slab from entering the block wall, but if the wall cores are used as part of a water control method it may not be possible.

It is recommended for potential radon control to seal open blocks at the time of construction.

Block tops have been successfully sealed using :

- mortar mixed with plastic binder to fill the top cores (quality control and shrinkage can be problems)
- "Termite caps" - cored blocks with a 2-in. thick solid cap as the top course
- solid or lintel blocks to seal one of the top courses.

When solid blocks or termite caps are used, anchor bolts must be placed in the joints between the blocks. Lintel blocks and grouted top courses allow for more flexible placement.

4.3.2 *Masonry Walls with Weep Holes*

Weep holes are used to drain water from the block cores into the sub-slab area when surface waterproofing barriers fail. Such a connection between the exterior and interior sub-slab area is an obvious channel for radon entry, allowing soil gas to pass from the sub-slab to the interior of the block wall. Openings from the sub-slab into the block wall would also make it more difficult to apply active sub-slab depressurization at a later date. If the block tops are sealed and the interior of the block wall is sealed, then weep holes would be much less of a problem as radon entry points or as barriers to sub-slab depressurization.

The National Concrete Masonry Association (NCMA) issues technical notes to provide contractors with guidance in construction practice. The NCMA-TEK 43, Concrete Masonry Foundation Walls (NCMA72), provides illustrated cross-sections of foundation walls showing weep holes through the footing. These run from the exterior of the wall to the sub-slab area, connecting an exterior drainage system to an interior drainage system. This system does not directly drain the block wall, but the combination of dampproofing and exterior drainage should make it unnecessary.

Contractors often create weep holes in the bottom course of block rather than buying prefabricated weep block. Some masons open holes in both shells of the block; others open the block cores to the interior but leave the exterior shell intact. Some builders prefer weep holes as an alternative to exterior drainage, while other builders reportedly use weep blocks in lieu of backfilling with granular material, although such backfilling is recommended or required in most areas. The actual need for weep holes in properly designed and constructed masonry walls is questionable. Moreover, a solid block installed as the bottom course of a foundation wall is recommended to keep radon from seeping into block cores around the footing. The NCMA-TEK 160A, Radon Safe Basement Construction (NCMA87), shows no weep holes in walls or footings but offers no prediction of the consequences of eliminating them. A potential concern is that even properly applied waterproofing materials may fail over time.

It has been suggested that it might be possible to retain the weep hole while venting the upper blocks above grade to allow soil gas to escape. This idea has not yet been tested, and would need to be combined with an interior barrier such as paint. In general, weep holes should be avoided and, if drainage problems are expected, an exterior drainage system should be installed.

It is recommended that, if weep holes are used, care be taken that they do not present a radon entry path or a barrier to later sub-slab depressurization. At this time the best approaches appear to be either avoiding weep holes by carefully planning and installing a drainage system that would prevent water from entering the block walls or sealing the block tops and interior of the block wall.

4.3.3 *Stemwalls in Slab-on-Grade Houses*

Stemwalls, also called frost walls, are below grade foundations that support the load of the above grade walls and thereby the roof. There is usually a footing beneath them at some depth below the frost line. The major radon related issue for these walls is the geometry of the slab/stemwall joint. This will be covered in the section on floors. If stemwalls are constructed of concrete blocks then the block tops should be sealed. See Sections 5.3.1 and 5.3.2.

4.3.4 *Foundation Walls in Crawlspace Houses*

Foundation walls in ventilated crawlspaces are substantially different than walls in basements and unventilated crawlspaces. In basements and slab-on-grade buildings it is clear that barriers should be applied between the soil and the foundation or be the foundation itself. With ventilated crawlspaces there are two locations that present themselves for the application of barriers. First, as in the other, barriers can be placed between the soil and foundation. Secondly, a barrier effort can be made between the crawlspace and the upstairs living area at the floor deck. The second option will be treated in Section 4.5. If the first option, making a barrier between the soil and the crawlspace, is selected, then the basement wall details that apply to sealing open blocktops and preventing the foundation from cracking also apply to the crawlspace walls.

4.4 *Floors in Basements, Slabs on Grade, and Crawlspaces*

Concrete slabs are the only floors considered for this sub-section. As already pointed out in the beginning of Section 3.2, poured concrete is a good retarder for radon gas and soil gas. The major problems will be cracks, joints and penetrations. The focus of this sub-section will be on crack prevention and sealing joints and penetrations. A good deal of this material applies to both poured concrete and masonry walls.

4.4.1 *Crack Prevention*

Plastic shrinkage cracking of concrete is a natural function of the drying process. Many factors come into play as concrete cures, including water content, cement content, atmospheric humidity, temperature, humidity, air movement over the slab surface and aggregate content. The preparation of the sub-slab area is also important. Reinforcement can be used to reduce shrinkage cracking. It has not been traditionally mandatory in residential floor slabs. Residential builders typically become concerned about shrinkage cracking and/or slab reinforcement when they are working in areas with unstable soils or when they need to ensure slab integrity under specific finished floor systems (ceramic tile, for example).

There are many ways to minimize slab cracking, although it probably cannot be eliminated entirely. The American Concrete Institute (ACI) publishes a number of documents outlining standard practice for building concrete and concrete masonry structures. A number of these apply to crack prevention. Specifically the reader is referred to

ACI302.1R-80 Guide for Concrete Floor and Slab Construction, and ACI332R-84 Guide to Residential Cast in Place Concrete. The following discussion describes a number of treatments, some of which are familiar to the commercial/institutional/industrial construction area but uncommon to the residential marketplace.

Reinforcement with ferrous metals: The use of metal reinforcement embedded in the slab increases its strength. Woven wire mesh is the most common material for residential applications. For slabs on grade, the Council of American Building Officials (CABO86) One and Two Family Dwelling Code recommends 6 x 6 in. - W2.9 x W2.9 woven wire mesh. To help control cracking it has been suggested that this is appropriate for a basement slab as well.

Rebar (also called rerod) is most commonly used for footings or garage slabs and would not generally be used throughout a basement slab. A No. 4 rebar (1/2 in. bar) runs 0.668 lb/ft. It would probably be installed in a garage slab 12 in. on center, leaving 3 in. at each end and running in both directions.

Concrete additives: A number of additives can be used to change the characteristics of concrete. The American Concrete Institute (ACI) discusses these additives in its technical guides. A discussion of the various fibers used to reinforce concrete, is titled State of the Art Report on Fiber Reinforced Concrete (ACI544).

Water-reducing admixtures: Also known as plasticizers, these admixtures reduce the amount of water used in the concrete. This reduces shrinkage and cracking while increasing the workability of the concrete. One example of a plasticizer is WRDA-19, by Grace Construction Products, which is labeled "an aqueous solution of a modified naphthalene sulfonate, containing no added chloride." Chlorides are frequently added to concrete as antifreezes, but various codes limit the chloride content of concrete because of its corrosive effect on ferrous metals and its reducing effects on concrete strength. American ATCON's report to the Florida Phosphate Institute (Sc87) recommends the use of a plasticizer to reduce the likelihood of water being added on site to produce more workable concrete. See ACI212.1R-81, Admixtures for Concrete.

Fiber-reinforced concrete: Various fiber additives are available that can reinforce poured concrete and reduce plastic shrinkage cracking. Fiber reinforcing has the advantage over woven wire mesh in that the fibers are homogeneously distributed throughout the slab thickness. The type of fiber used is important because studies have shown that the alkaline environment of Portland cement destroys some of the fibers that are sold for this purpose. Polyester fibers and glass fibers have been noted by ACI as being vulnerable in an alkaline environment. Some companies apply a surface treatment to fibers to protect them from damage by alkalinity (glass fibers so treated are known in the trade as "AR fibers"), but the ends of the fibers are exposed when they are chopped up during the manufacturing process, and they can decay from the ends inward. The polypropylene material used in some fiber products is chemically stable in an alkaline environment. The much higher modulus of elasticity of glass fibers compared to organic fibers may be an advantage for the glass since it more nearly matches the modulus of elasticity of concrete. The comments above apply to fiber additives used in surface-bonding mortars as well as those used in poured concrete slabs. See ACI212.1R-81, Admixtures for Concrete.

Curing: Proper curing is critical to the strength and durability of poured concrete. Many avenues are available to ensure a good cure, ranging from watering the slab to covering it with wet sand, wet sawdust, or a waterproof film [e.g., waterproof paper, BurleneTM (burlap/polyethylene)] or coating it with a curing compound. Penetrating epoxy sealer applied to the slab while it is still wet can act as a curing agent and slab strengthener. Polyurethane sealants are applied after the slab is dry, because moisture would lift them off the slab. There are a number of other liquid membranes and emulsions, including a number of solvents which require substantial ventilation as they dry.

Use of higher strength concrete: Typical residential concrete slab construction requires a 28-day compressive strength of only 2,500 to 3,000 psi. Concrete can be ma stronger by reducing the water/cement ratio. If the water/cement ratio is kept at 0.5 or less, the minimum 28-day compressive strength will increase to 3800 psi. Moreover, if the ratio is reduced to 0.45, the compressive strength increases to 4300 psi. To achieve compressive strengths of above 3500 psi, the slump cannot exceed 3 in. The compressive strength and the slump of the concrete are no more important, however, than the placability of the concrete or the finishability of the surface. Unfortunately, placability and finishability are not easily measured quantities like slump and compressive strength, and often do not receive sufficient emphasis.

4.4.2 Joints

French Drains and Floor/Wall Cracks: The French drain (also called a channel drain or floating slab) is a construction feature that appears to provoke strong reaction from its defenders and detractors alike. French drains are only a co cern in basement foundations. This slab detail is a standard feature in new houses in parts of the country as varied as New York and Colorado, but in other places it is virtually unknown. French drains are used in areas with expansive soils, such as parts of Colorado, to protect the slab from damage if the wall moves. In central New York state, the main function of the French drain is to drain away water which may seep down the walls. One national builder has discontinued and now prohibits the use of French drains in houses because of the potential for radon problems. This builder states that French drains also have been found to significantly increase indoor moisture levels.

Various treatments can be used to seal French drains against gas entry. Some of those treatments have crack-spanning capability in case of structural movement. French drains can be sealed airtight and still preserve their water drainage function by caulking the channel to a level below the top of the slab and sloping the trough toward the sump. This assumes that the sump lid is inset below the surface of the slab and that a water-trapped drain in the sump lid drains

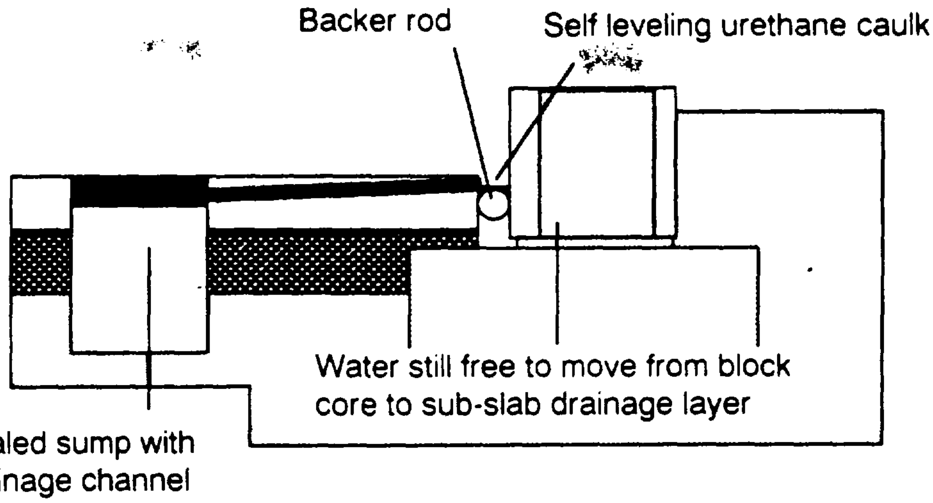

Figure 4.1 Sealing a French Drain.

water into the sump. Figure 4.1 shows a French drain treatment.

It is recommended that French drains be avoided if possible because of the difficulty in sealing them at the time of construction and the expense and difficulty of sealing them after construction.

Perimeter Crack: The perimeter crack is located between the edge of the floor slab and the foundation wall. This applies to slabs in basements, crawlspaces and slab-on-grade foundations. As a cold joint, this perimeter crack is always a potential radon entry point. Contractors building radon-resistant houses may deliberately create a significant floor/wall crack so that it will be easy to work with and seal. A perimeter expansion joint is made of a closed-cell, flexible foam strip. The expansion joint is presliced so that the top 1/2 in. can be pulled off to leave room for caulk. Another approach is to tool the floor/wall joint with an edging tool and seal it with caulk. Particular attention should be paid to sealing this crack in slab-on-grade houses because the joint is often inaccessible after the house walls are raised.

Control Joints: When large areas of slab are poured, some cracks are unavoidable. There will be cold joints because the slab was poured in small sections to avoid cracks, or the slab will crack because the pours were too large. To direct the inevitable cracking that will occur in either case, a control joint can be made by grooving the surface of the slab. The groove should be large enough to seal with caulk. Cold joints can make use of the same expansion joint materials that have a "zip off" top that was described for the slab edge crack.

4.4.3 Penetrations

Every house has some minimum of penetrations through the slab or foundation walls. The ones always present are :

- water pipe entry
- sewer pipe exit

Common additional penetrations are:

- floor drains
- sump holes
- air conditioner condensate drains.

Openings around water pipe entries and sewer exits that pass through concrete can be easily sealed using caulks. Many builders use plastic sleeves to protect metal pipes from corrosion when they pass through concrete. In this case an effort can be made to leave a space around the pipe that can be sealed with caulk or backer rod and caulk. The same techniques can be used for pipes passing through block walls.

Depending on the details of a *floor drain*, a great deal of soil gas can enter through large openings to the drainage matrix. This is true not only of slop drains that are simply holes through slabs into the sub-slab area, but also of other types of drains. Even water trapped drains with water in the traps can allow radon an entry passage where the dish shaped bottom of the drain seats into the drain pipe. It is recommended that floor drains connect to pipe that drains to daylight using solid PVC pipe glued at the joints, or that water trapped drains or mechanical traps be installed that do not have unsealed joints on the room side of the water trap.

Sump holes are usually a collection point for the drainage system. Almost by definition this is a terrifically good radon collection system. It must have access to large areas of soil beneath the foundation so it is easier for water to run into the sump than to penetrate the foundation. It is better if there is no open sump at all. A sub-slab drainage system that can drain by gravity to a daylight opening serves the same purpose as a sump hole but offers no fewer radon entry routes. If this is not possible then the sump hole must be sealed (a code item in some places to keep children from playing in them). Sumps can be sealed airtight and still function as a water collection and removal system by routing the interior and/or exterior drainage pipes or layer into the sump. The sump hole is then sealed with a corrosion resistant lid that is recessed a few inches to create a shallow sump. The lid is fitted with a water trapped drain so water that happens across the floor will end up in the sump. Lastly, a low profile sump pump is installed to eject any water collected in the sump through a check valve to approved disposal. This detail is illustrated in Figure 4.2.

Air conditioner condensate lines are sometimes installed so that they penetrate the slab to dispose of the water in the sub-slab area. Even when water is trapped, this can be a problem because the traps often dry up during the heating season. At this point they become radon entry routes. It is recommended that air conditioning condensate lines run to a drain that will not dry out or that a condensate pump be installed that collects the condensate and disposes of it through a water trap. Often a washing machine drain is located in a basement near enough to use it.

Sealants for Cracks, Joints and Penetrations: Masonry sealants for radon-resistant applications must have good adhesion and be durable and elastic. Polyurethane comes in gunnable grades, and one- and two-part self leveling types. Self-leveling urethanes can be used only on level surfaces as they are very mobile. In fact if there is even a small crack at the bottom of a joint being sealed, the self leveling caulk may drain out. The popularity of polyurethane is based on a combination of good adhesion even under difficult conditions, long service life, good elasticity and easy availability. Copolymer caulks have very similar properties to the polyurethanes. Recently some copolymer caulks have been packaged as sealants specific to radon control. Silicone caulks have also been used in radon control but require more extensive surface preparation for good adhesion. Many radon mitigators have adopted the use of silicone caulks for sealing sump lids and access ports because they make a tight-fitting gasket that can be removed more easily than polyurethane at a future date. Butyl caulk is susceptible to attack by groundwater acids. Polysulfides have been largely supplanted by polyurethanes because the former are more chemically reactive with asphalts.

Surfaces should be clean and dry when caulk is applied. Bear in mind that the idea is to get a flexible membrane to bridge between the two surfaces that the crack divides. It is a poor practice to simply fill every crack. Manufacturers usually specify appropriate dimensions for their caulks. Often this is a minimum 1/4 x 1/4 in. For small cracks, it may be necessary to grind them larger to meet the caulk manufacturers' specifications. For cracks much larger than 1/4 in., a backer rod should be used to support the caulk so that it can be applied correctly.

CAUTION: Caulks give off organic compounds. Some of these are carcinogenic. Users are reminded here that they should have the Manufacturers Data Sheets for any chemicals they use. These sheets identify hazardous aspects in the use of the products. OSHA requires that contractors have these sheets available for employees and that a safety training program be in effect for these products.

4.5 Crawlspaces

Crawlspaces are being treated here as a special case of using the foundation materials to make a mechanical barrier. In this sub-section isolating the living space from the crawlspace by sealing the floor between the two spaces will be discussed. A sheet of plywood is a relatively good barrier to radon laden crawlspace air and, as with the other material barriers, it is the joints and penetrations that are the problems. The major entry points are through numerous electrical, heating, and plumbing penetrations in the house floor and via the return air ducting often located in the crawlspace. Lower air pressure in the house and the return air duct than in the crawlspace draws radon laden crawlspace air into the living space of the house.

During construction, all possible penetrations between the crawlspace and the house should be sealed to simply prevent the passage of radon up into the living areas. Attempts to seal penetrations can be made by using expandable closed-cell foam sealants and urethane caulk. Sealing these areas can be difficult because of limited access even during construction. Areas of particular concern include:

1) openings in the subfloor for waste pipes including openings for tubs, toilets, and showers.
2) openings for water supply lines.
3) openings for electrical wiring.
4) openings for air ducting for the heating, ventilating, and air conditioning (HVAC) system.
5) openings around hot water heating pipes -- Check on code requirements for clearance between hot water pipes and wood floors. These may require a special sealant.
6) joints between sheets of plywood.

Any sealing around plumbing traps must be done so that the trap can still be reached and serviced.

Return air for the HVAC system should not be suppl from the crawlspace. It is best to avoid routing return air ductwork through the crawlspace, but if it must be, then it should be thoroughly sealed with duct tape at a minimum. It should be understood, however, that duct tape may dry out and fall off. A better approach would be to use seamless ductwork in these areas. The use of floor joists and subflooring as three sides of a return air plenum should be avoided because of the difficulties encountered in sealing. If the space between the joists must be used, an alternative to ducts is to use a rectangular duct to fit the space.

If isolation of the crawlspace is the primary method of radon-resistant construction being used, the number and size of crawlspace vents should be maximized. The March 1988 version of Florida's proposed interim guideline for radon-resistant construction (FL88) suggests vents of not less than 1 ft^2 of vent for each 150 ft^2 of crawlspace. The proposed guideline also requires that vents be located to provide good circulation of air across the crawlspace and should not include registers or other provisions for closure. This requirement would be impractical in cold climates with water pipes in the crawlspace. If there were no water pipes to worry

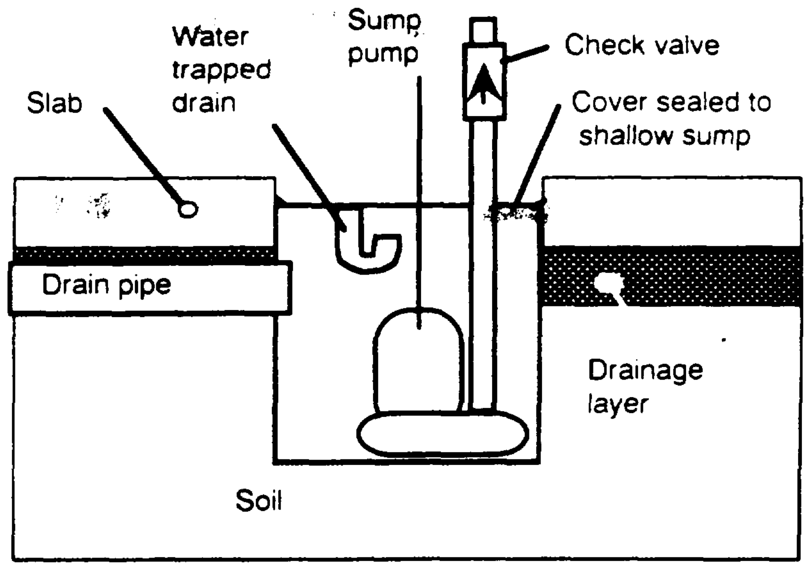

Figure 4.2 Sealing a Sump Hole to a Shallow Yet Operable Sump.

about, then the floor would need to be well insulated in order to ensure that a large energy and comfort penalty was not incurred.

Other radon-resistant alternatives besides simple isolation of the crawlspace should be considered because of the difficulties encountered in getting an adequate seal between the house and the crawlspace. These alternatives will be discussed in Section 5.

A NEWHEP builder in Denver uses an innovative foundation technique to simultaneously deal with problems of expansive soil and high soil radium and radon content. The foundation excavation is over-dug to a depth of 10 ft. Caisson pilings are driven to support the 10-ft-tall reinforced poured concrete walls. Band joists are bolted to the walls 2 ft above the dirt floor, and a carefully sealed wood subfloor, supported by steel "I" beams and standard size floor joists, is installed. The 2-ft-high "buried crawlspace" is actively ventilate by installing a sheet metal inlet duct in one corner of the basement, drawing in outdoor air through an above-ground vent. A similar duct with an in-line fan is located at the opposite corner to exhaust air through an above-grade vent. Soil gas radon at levels from 3,163 to 4,647 pCi/L was measured at three of these building sites. Soil radium-226 content was measured at 1.05 to 1.62 pCi/g. Indoor radon measurements were then taken in the buried crawlspaces and in the basements. Measurements were made during the summer of 1987 with the exhaust fan off, and after 1 day, 1 week, and 2 weeks of operation. The results are shown in Table 4.3 (Mur88).

Table 4.3. Results Using Vented Crawlspace Technique

House No.	Fan Operation	Buried Crawlspace Level pCi/L	Basement Level pCi/L
1	Off	9.9	1.9
1	On 2 Weeks	9.9	1.4
1	On 2 Weeks	8.4	1.4
2	Off	27.8	1.8
2	On 1 Week	18 6	1 2
2	On 1 Week	16.7	0.9
3	On 1 Day	26.4	1.3
3	On 1 Day	15.5	0.9

NOTE: Followup measurements were made in the basements of Houses 1 and 2 in March 1988 and levels of 0.6 and 0.9 pCi/L were obtained. The continued effectiveness of this technique is assumed to be the result of the combination of both active ventilation in the crawlspace and careful sealing and caulking of all seams, joints, and penetrations of the basement floor (Mur88).

4.6 Coatings

4.6.1 Introduction

If waterproofing or dampproofing treatments that are effective gas barriers and that can be sealed at joints and penetrations could be identified, then walls could be made radon-resistant. Acceptable dampproofing or waterproofing treatments are specifically listed in building codes in many areas of the United States; these lists are periodically amended as new materials come into use. These coatings apply primarily to basement walls.

The terms "waterproofing" and "dampproofing" are often used interchangeably. Briefly, any waterproofing material can also be used for dampproofing; the converse is not true. Waterproofing materials must resist the penetration of water under a hydrostatic load. Dampproofing materials are not expected to keep out water under pressure, but do impede water entry and block diffusive movement of water through pores.

Any material which provides adequate protection against water should at least limit convective soil gas movement. Properly applied waterproofing materials should help block pressure-driven entry of soil gas.

The most common dampproofing treatment for residential foundation walls is a parge coat covered with bituminous asphalt. The parge coat is used for concrete masonry walls but is not necessary for poured concrete walls. This two-stage treatment has been replaced by surface bonding cement in some areas.

Oak Ridge National Laboratory indicates that bituminous asphalt may be attacked by soil and groundwater chemicals, specifically acids (ORNL88). Bituminous materials may also lose their elasticity at below-freezing temperatures. These features render bituminous asphalt an undependable waterproofing treatment; in fact, it is listed by code organizations such as BOCA, CABO, and SBCCI only for dampproofing.

A number of dampproofing systems are better gas barriers than bituminous asphalt. Some are relatively new to the residential marketplace but have track records in industrial/commercial settings. Others have been introduced into the most expensive residential market or have found applications at problem sites. A common feature of these alternatives is that they are generally more expensive than bituminous dampproofing. However, a 1981 survey of 31,456 households by Owens-Corning Corporation (Da86) found that 59% of homeowners with basements reported water leaks. As the supply of trouble-free building lots dwindles, home buyers may decide that additional investment is justified, and improved dampproofing systems may be developed to address radon and water problems simultaneously.

4.6.2 *Dampproofing/Waterproofing to Achieve a Radon Barrier*

The following is a sampling of alternative waterproofing systems that are readily available to builders.

Coal tar modified polyurethane: Coal tar modified polyurethane is a cold-applied liquid waterproofing system. The HLMTM system by Sonneborn is an example of this approach to waterproofing. It is applied as a liquid at the rate of 10-15 mils/coat. The coating dries hard, but has some elasticity. This material may be attacked by acids in groundwater but can be defended by a protection board. The performance of any liquid-applied waterproofing systems is limited by the capabilities of the applicator (it is difficult to achieve even coats on vertical surfaces).

Polymer-modified asphalt: Polymer-modified asphalt is a cold-applied liquid waterproofing system. As with the HLMTM system mentioned above, the quality of the installation depends on the applicator (it is difficult to achieve an even coating on a vertical surface). High grade polymer-modified asphalt is superior to coal tar modified polyurethane in elasticity, crack-spanning ability, and resealability, but inferior in its resistance to chemicals.

Membrane waterproofing systems: Waterproofing applied as a membrane has an advantage over liquid-applied systems in that quality control over thickness is ensured by the manufacturing process. Most membrane systems are also chemically stable and have good crack-spanning ability. On the other hand, effective waterproofing demands that seams be smooth so that the membrane is not punctured. Some masons apply parging to a half-height level and then return to finish the upper half of the wall. This tends to leave a rough section where the two applications overlap and means that the waterproofing crew has to grind the wall smooth before applying the waterproofing membrane. Thermoplastic membranes may be applied in various ways--affixed to walls, or laid beneath slabs. Thermoplastic membranes are highly rated for resistance to chemicals and longevity. Rubberized asphalt polyethylene membranes have superior crack-bridging ability, compared to fully adhered thermoplastic membranes. (Loosely hung thermoplastic membranes, by their nature, have obvious crack-bridging ability in that they are not bonded to the walls.)

Seams and overlaps must be carefully and completely sealed in order for membranes to function as radon barriers. The choice of seam material varies with the type of sealant. Manufacturers' recommendations for sealant, procedure and safety precautions should be followed.

Bentonite: Bentonite clay expands when moist to create a waterproof barrier. Bentonite is sold in various forms, including panels and mats. Bentonite is not as resistant to chemicals as the thermoplastic membranes, nor is it puncture resistant. The major flaw of bentonite as a radon barrier, however, is that it is only tightly expanded when wet. This is acceptable for a waterproofing material, but not for a gas barrier.

Surface bonding cement: Surface bonding mortar or cement is mentioned in some building codes as an approved dampproofing treatment, but not as a waterproofing treatment. A number of manufacturers produce cements and mortars impregnated with fibrous glass or other fibers. Some of these may be chemically unstable in the alkaline environment of Portland cement.

One technique of assembly using surface bonding cement is to dry-stack blocks and apply the cement on both sides. As an alternative, the block wall is conventionally assembled with only an outside coating as a positive-side waterproofing.

Cementitious waterproofing: A number of additives can be incorporated into concrete to create cementitious "waterproofing." This type of waterproofing is appropriate only for interior applications because it is inelastic, does not ha good crack-spanning ability, and cannot resist hydrostatic pressure.

Interior paint as a barrier: A variety of interior applied masonry paints are available. Some of these have been tested by the AEERL laboratory at the EPA. Results of these tests are given in a paper presented at the 1988 Symposium on Radon and Radon Reduction Technology (Har88).

4.7 Membranes

4.7.1 Introduction

Membranes of plastics and rubbers that are used to control liquid water penetration and water vapor diffusion are effective at controlling air movement as well. If they can be adequately sealed at the joints and penetrations and installed intact, then they could also provide a mechanical barrier to radon entry.

Construction film is already in common use as a sub-slab vapor barrier in many areas of the country. The current prevalence and low cost of this material mean that it may be worthwhile to continue its use even though it is an imperfect barrier. It is possible to seal polyethylene vapor barriers at the overlapped edges, at penetrations, and at the footing; but it may be that the extra effort will not be rewarded with improved radon resistance.

In Sweden, sub-slab membranes are not required in high-radon areas and a tightly sealed slab is considered to be a more effective radon barrier. The difficulty of achieving a completely sealed, intact sub-slab membrane is widely acknowledged; however, a sub-slab barrier may be worthwhile even if it is imperfectly installed. Polyethylene construction film (6-mil) can serve as a backup radon barrier to the concrete slab, even though it is not a complete radon barrier by itself. The barrier may continue to function, even with punctures, if incidental cracks and holes in the slab are aligned with intact areas of polyethylene.

In summary, it is worthwhile to continue the installation of a vapor barrier that serves the added valid function of moisture barrier. More comprehensive installation measures and more expensive materials may be merited in areas where the radon source is strong because of either high radon concentrations or high soil gas flow rates.

4.7.2 Types of Membranes Available

Polyethylene film: A vapor barrier of polyethylene film is a typical sub-slab feature in many areas of the country. The intent of the vapor barrier is to prevent moisture entry from beneath the slab.

Installation of any sub-slab membrane is problematic because an effective barrier should be both well sealed and intact. Builders who use polyethylene under the slab indicate that achieving a complete seal at all laps and edges and around pipe penetrations is difficult. It is difficult to seal the polyethylene to the footing because the weight of the concrete tends to pull it away from the walls during the pour. There is also a high probability that the vapor barrier will be punctured during installation. It has been observed that even 10-mil polyethylene in a heavy felt membrane is likely to be punctured during installation.

Another issue is the stability of polyethylene vapor barriers. Polyethylene is known to be harmed by ultraviolet (UV) exposure. One radon mitigator has found polyethylene under slabs in Florida that deteriorated in less than 15 years; more frequently, polyethylene of comparable age is in mint condition.

Polyethylene films are manufactured with an array of additives selected to support specific applications. Durability varies according to the additives employed, film thickness, length of UV exposure, temperature swings, and other factors. Resins used in polyethylene manufacturing have improved over time, so that the life expectancy of polyethylene film in 1988 is longer than for the films used in the 1950s, 1960s, and 1970s. The durability of polyethylene films in current use depends on the contractor's selection and proper storage of the appropriate film for the job.

On the other hand, there is no evidence to support the assertion that polyethylene vapor barriers deteriorate with exposure to soil chemicals. Construction film is a low-density polyethylene. High-density polyethylenes are used for storage and transportation of an array of chemicals. Polyethylene is chemically stable, but may be adversely affected by aliphatic hydrocarbons (such as hexane, octane, and butane) and chlorinated solvents. It does not appear to be reactive with the acids and salts likely to be encountered in soil and concrete. No sub-slab membranes have been identified as manufactured specifically for radon control. However, several products are promising alternatives to 6-mil polyethylene construction film.

Polyethylene-coated kraft paper vapor barrier is available in 8 x 125 ft rolls. Overlaps of 6 in. are marked on the paper with a printed line. They can be sealed with polyethylene tape. This material is attractive to contractors because it is more puncture-resistant than 6-mil polyethylene construction film, but less expensive than many alternative products.

Polyethylene-based membranes are manufactured for use in hazardous waste landfills, lagoons, and similar applications. Two of these products have recently been tested to determine their effectiveness as barriers against radon diffusion. (In most cases, diffusive flow is considered of little or no significance as a mechanism of radon entry compared to convective flow.) A 20-mil high-density polyethylene tested 99.9% effective in blocking radon diffusion under neutral pressure conditions. A 30-mil low-density polyethylene tested 98% effective in blocking radon diffusion under neutral pressure conditions.

A material composed of a double layer of ***high-strength bubble-pack with aluminum foil*** bonded on both sides is available. It has a high compression strength and doubles as an insulator. Concern exists over its fragility and susceptibility to pinhole punctures. Both foil-faced membranes can be punctured, but the double bubble-pack offers some defense against complete penetration. Punctures are easily repaired with aluminum tape, which is also used at seams. A well-made seal is diffusion resistant; however, gas can migrate through wrinkles in the tape. The fragility of the material is believed to be a significant limiting factor in using it under the slab or as a perimeter insulation.

Another available product has two faces of *aluminum foil over a core of glass scrim webbing;* it is coated with asphalt. The membrane is 0.012 in. thick. This material has not been tested as a barrier against diffusive flow of radon, but its performance should be similar to that of other foil faced products. Seams are sealed with aluminum tape.

PVC membranes have been used as a sub-slab membrane during radon mitigation work in existing houses. PVC membranes are usually sealed with solvents and were developed as roofing membranes.

Another product, *EPDM™* is a rubber-like material. It comes in 60-mil thicknesses in 100 ft by 61-1/2 in. rolls. EPDM also comes in 45-mil thicknesses in 25 by 60 ft rolls. This product has gained popularity as a ground cover in crawlspaces because of its durability qualities.

Note: EPA does not endorse any brand names or products mentioned in this manual

4.8 *Mechanical Barriers Applied to the Soil*

It has been suggested that mechanical barriers could be applied to the soil beneath the foundation that would prevent the migration of radon into the building. As of this writing this is an untried approach. If it works it would have the benefit of being less susceptible to occupant behavior, future remodeling activities and mechanical failure of fans. Two approaches have been brought forward. One would use an injection of slurry composed of clay to dramatically reduce the permeability of the soil. This technique is used in the construction of lagoons, landfills and dams. The second idea is to spray the soil surface with a polymer modified asphalt. This technique has been used to cap landfills to control the release of methane and other organic compounds.

4.9 *Drainage Boards for Soil Gas and Radon Control*

Soil that was excavated from the basement is commonly used as backfill against foundation walls. This should not be the case where the site material contains clays and silts, particularly organic clays and silts. If local soils are not appropriate, the builder may use gravel to backfill.

Drainage boards are a substitute to backfilling with gravel. Drainage boards have been used for a number of years, particularly in commercial projects and underground houses. Depending on the cost of hauling sand and gravel, a drainage board may be a cost effective alternative.

It has been hypothesized that a drainage board which is laid up against a house wall might provide an air buffer that can break the pressure connection between the soil and the house interior. This is rather like having a hole in your straw when drinking through it. No systematic research has been done on this topic.

4.10 *Summary of Recommendations for Mechanical Barriers*

4.10.1 *Rules of Thumb for Foundation Walls*

- Use reinforcing to limit cracking.
- Seal pipe penetrations.
- Cap masonry walls with bond beam or solid blocks.
- Dampproof walls (interior as well as exterior on masonry walls).

4.10.2 *Rules of Thumb for Slab and Sub-Slab Barriers*

- Make a slab edge joint that is easy to seal (tooled joint or zip-off expansion joint material).
- Caulk perimeter crack and control joints with polyurethane.
- Reinforce slabs with wire mesh to help prevent large cracks and use control joints - - caulk the control joint.
- Drain to daylight if possible, or to a drywell or sewer. If you must use an interior sump pump, seal it.
- As a precaution, use interior footing drains (in addition to exterior drains) and 4 in. of No. 2 stone below the slab that drains to the building exterior. This way, sub-slab ventilation can be added easily in case a problem is discovered later (Br86).

These suggestions are illustrated in Figures 4.3, 4.4 and 4.5.

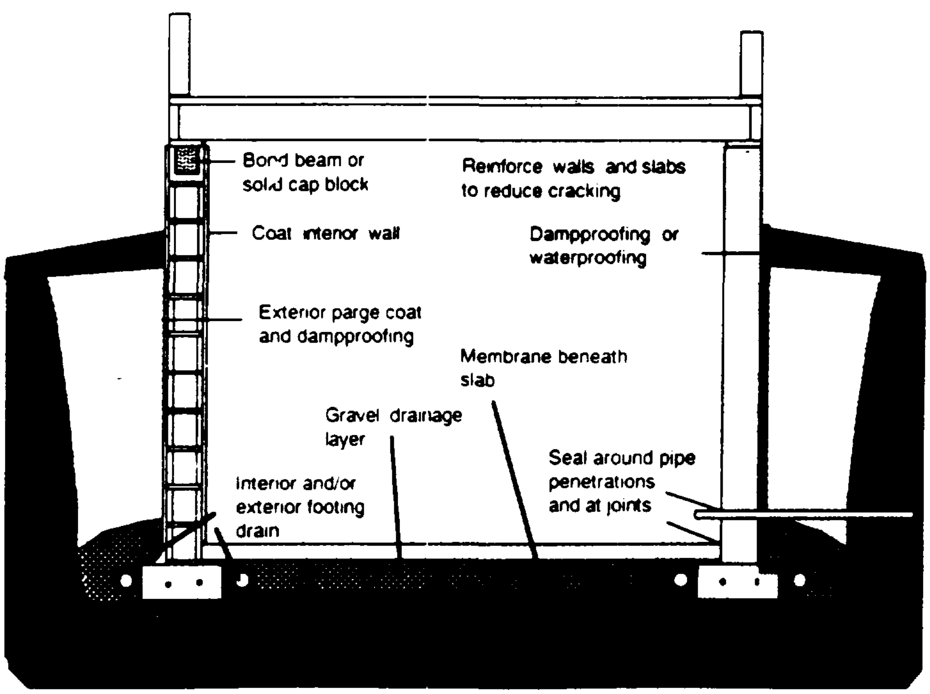

Figure 4.3 Summary of Mechanical Barrier Approach for Basement Foundations.

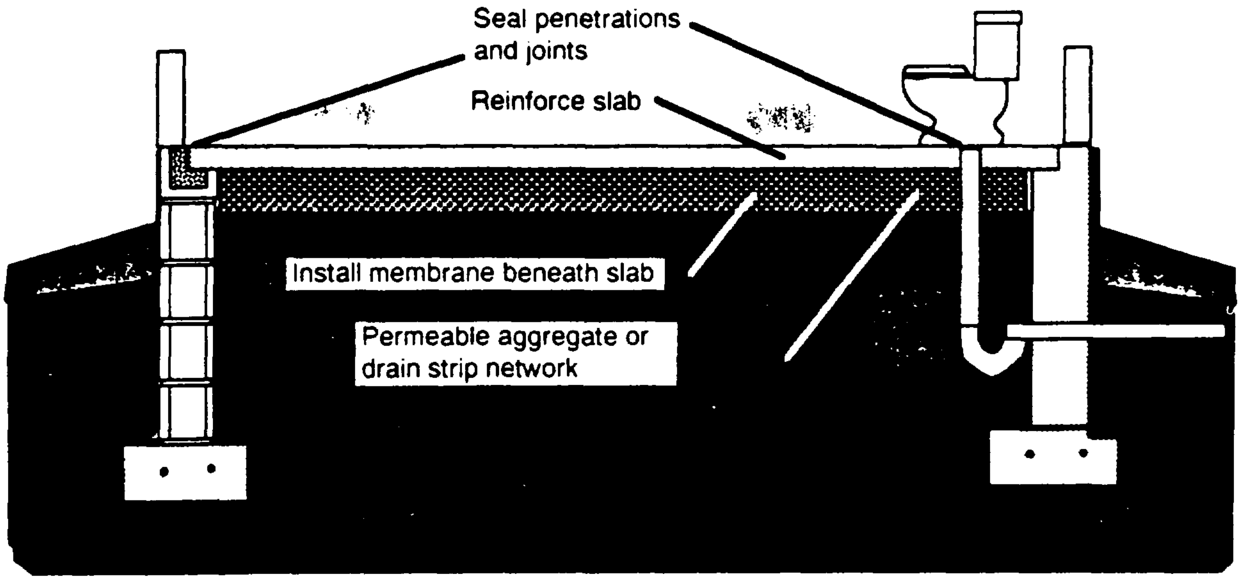

Figure 4.4 Summary of Mechanical Barrier Approach for Slab-on-grade Foundations.

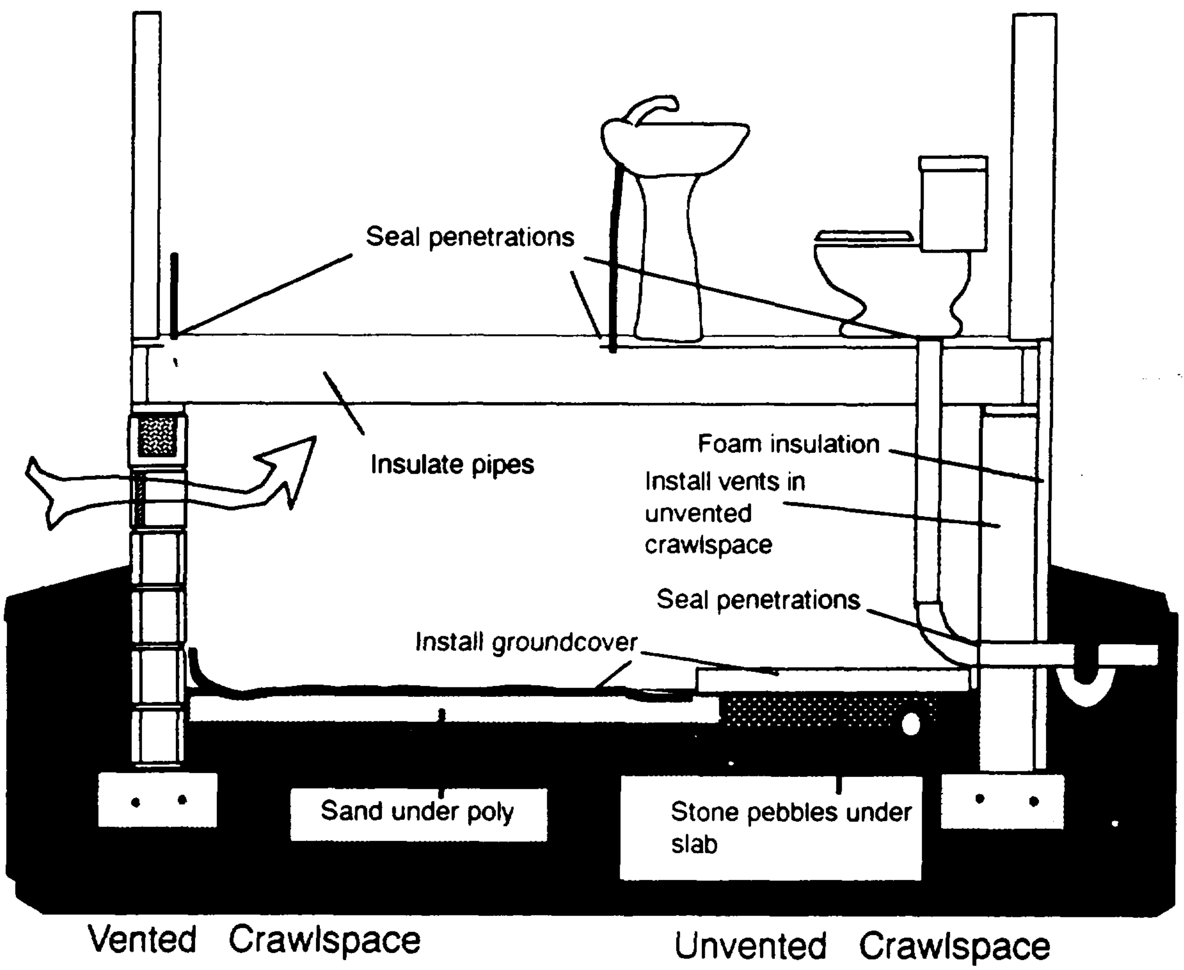

Figure 4.5 Summary of Mechanical Barrier Approach for Crawlspace Foundations

Section 5
Site Evaluation

Introduction

When siting new residential construction, builders would like to determine the potential for radon problems associated with each building site. Unfortunately, at present there are no reliable, easily applied methods for correlating the results of tests made at a building site with subsequent indoor radon levels contained in a house built on that site. Houses vary significantly in their ability to resist radon entry. Bedrock and soils interact in complex ways with dynamic house behavior and environmental factors. There are too many combinations of factors that cause elevated indoor radon concentrations for simple correlations to exist.

In an effort to evaluate the risk of an indoor radon problem occurring in a home built on a particular site, researchers have made many types of measurements. The measurements commonly made include:

- soil and bedrock radium concentrations
- radon measurements in the interstitial soil and bedrock pores
- permeability of the soil or bedrock
- airborne radiation measurements.

In addition to the above measurements, indexes using soil concentrations in combination with permeability measurements have been suggested by some researchers (Ku88, Pe87). As elaborated on later in this section, these methods have been successful in establishing relationships between some of the site measurements and indexes, and indoor radon concentrations for specific areas and regions.

Although substantial progress has been made by investigators using geologic, radiation and other site data to predict areas of high radon risk, it still requires many site measurements to adequately assess a particular site. The judgement that needs to be made is whether or not it is more cost effective to make the building radon-resistant to begin with, or to put the money into site evaluation and possibly avoid the need for radon-resistant construction techniques.

5.2 Radon in the soil

In buildings with indoor radon concentrations greater than 4 pCi/L, the majority of the radon is produced in the soil and enters the building through foundation openings. The radon gas found in soils is a product of the decay of radium-226, a radioactive chemical element present in trace levels in many types of soils and rocks. Radium and radon are elements that are part of the uranium-238 (U-238) decay series. See Figure 2.1 for details. Uranium-238 decays through a chain of radioactive elements. Radiation is released as each element decays. Radon will move through the porous soil or shattered bedrock by convection and diffusion because it is a gas. The other elements in the U-238 series will not easily move through the soil because they are particles and not gases. The amount of radon that enters the house depends on the amount of radon gas or radon parent compounds found in the soil beneath the house. The permeability of the soil, the presence of faults and fissures in underlying and nearby rock, openings between the house and soil, and the driving forces that move soil gas along pathways into the house also contribute to the total radon levels. To have a radon problem requires radium nearby, a pathway for the gas to move through the soil or rock, a driving force, and openings in the foundation.

5.2.1 Attempted Correlations Between Indoor Radon and Measurement Made at Sites

Several studies have attempted to make simple correlations between radon or radium concentrations in the soil and indoor radon concentrations (ERDA85, Na87). No significant correlations were made between these variables.

The Florida Statewide Radiation Study performed by Geomet (Na87) illustrates the variability of radon-resistant construction and the resulting problem of trying to correlate soil radon levels with indoor radon levels. The study reports over 3,000 paired soil radon and indoor radon samples. A total of 77 soil radon readings were greater than 1,000 pCi/L. The two highest soil radon values were 6587.0 and 6367.2 pCi/L. Interestingly, corresponding indoor radon levels for the two highest sites were 6.8 and 0.2 pCi/L, respectively. In addition, almost half of the houses with soil radon levels in excess of 1,000 pCi/L had indoor radon levels of less than 4 pCi/L.

The Florida data reported by Geomet have been evaluated and the houses listed in order of highest measured indoor radon levels. This analysis is shown in Table 5.1 (Pu88 and Na87).

It is clear from Table 5.1 that soil radon measurements which varied over an order of magnitude produced significantly less than a factor of 2 difference in the indoor radon levels. Predictions of radon potential based on soil radon measurements would be highly suspect based on these data.

In Sweden, soils have been classified as having high, normal, or low radon risk potential based on soil radon concentration and soil permeability. The soil radon values and permeability characteristics used to establish the soil classifications and the corresponding construction requirements are given in Table 5.2 (Sw82). Factors other than soil radon that are considered before classification in Sweden are permeability, ground humidity, and soil thickness. Clearly Sweden has decided that a number of factors must be addressed to evaluate the radon problem potential of a site. Using the suggested soil radon concentrations but not the permeability guidelines included in the Swedish soil classification scheme, no building restrictions would have been required for many of the houses surveyed in Florida with indoor radon measurements greater than or equal to 4 pCi/L.

Fifteen of the houses in the Florida study with measurements greater than or equal to 4 pCi/L had soil radon concentrations less than or equal to 200 pCi/L. This corresponds to 13.5% of the houses with soil gas less than 270 pCi/L being above the EPA action level of 4 pCi/L. Nineteen of the 48 houses (39.6%) that had radon in the soil over 1,350 pCi/L had radon levels in the house less than 4 pCi/L. This means that almost 40% of the houses that would have been required to be built "radon-safe" under the Swedish guidelines were already below 4 pCi/L using standard construction practices.

Table 5.1 Florida Survey Soil Radon and Corresponding Indoor Radon Concentrations.

Indoor Radon Concentration pCi/L	Soil Radon Concentration pCi/L
32.4	1591.[illegible]
29.5	1846.9
28.0	786.9
25.3	555.9
25.3	200.[illegible]
25.0	353.9
24.1	439.7
22.9	3561.3
22.9	2144.5

Table 5.2 Swedish Soil Risk Classification Scheme and Building Restrictions.

Soil Radon Concentration pCi/L	Permeability of Soil	Risk Classification	Building Restrictions
< 270	Very low permeability (e.g., clay and silt)	Low	Use conventional construction
270-1350	Average permeability	Normal	Use radon-protective contruction
>1350	High permeability (e.g. gravel and coarse sand)	High	Use radon-safe construction

The Florida survey was an ideal opportunity to compare soil radon and corresponding indoor radon levels in slab-on-grade construction. By looking exclusively at slab-on-grade houses, additional variables, including depth below grade of basements, and height and ventilation rates of crawlspaces, are eliminated. These variables, which are inherent in common construction techniques used throughout much of the rest of country, exaggerate the difficulty correlating indoor air radon and soil radon levels.

The major drawback in using the Florida study to support the correlation between indoor and soil measurements was that the indoor measurements were obtained from 3-day closed-house charcoal measurements, and soil radon was obtained from 1-month alpha track measurements buried 1 ft beneath the soil surface. Comparisons of charcoal and alpha track data are generally not recommended since they are quite different measurement techniques, and represent radon levels over different time periods. However, the study was subjected to numerous quality control checks including deployment of alpha track detectors in 10% of the houses to obtain a check on indoor air measurements made by charcoal canisters. In spite of the measurement drawbacks, the study indicates that soil radon measurements taken alone are not a dependable predictor of potential indoor radon concentration.

5.2.2 Indexes using Permeability and Soil Radon Concentrations

By making an index from the product of soil radon concentrations and soil permeabilities, a better assessment can be made of the risk of a problem on a given site. A Radon Index Number (RIN) has been applied to three are in New York state that have sandy, gravelly soils and predicted with some confidence the geometric mean of indoor radon concentrations using the geometric mean of the soil radon concentrations and the geometric mean of the square root of the soil permeability (Ku88). The results of this effort are summarized in Table 5.3. This research also points out barriers when applying this technique more widely without a substantial amount of additional work. First, the index must be modified by a depth factor when the soil depth to an impermeable layer (water table, some bedrock, clay) is less than 10 ft. Second, the *soil radon concentrations in all three areas were typical of most soils in New York state only*. They ranged from slightly below to slightly above the statewide average for radon levels in gravel.

Using the permeability and soil radon measurements for the gravel soils in New York state to compare to the Swedish guidelines would result in a recommendation for radon-resistant techniques to be used in a large fraction of new houses in all the areas listed except Long Island.

Table 5. 3 Geometric Means for Soil Gas Radon-222, Soil Radium-226, Permeability, RIN and Indoor Radon- 222.

Study Area (Soil Type)	Soil Gas Rn-222 pCi/L	Soil Ra-226 pCi/g	Permeability cm2 x 10-6	RIN*	Basement Rn-222 pCi/L
Cortland Co (Gravel)	551	NA	12.0	19.0	17.2
Albany Co (Gravel)	675	1.0	6.7	18.0	20.2
Rensselear Co (Gravel)	1,003	1.0	1.1	11.0	9.4
State Wide (Gravel)	602	1.2	4.1	12.0	NA
Long Island (Sand)	164	0.4	0.22	0.8	1.0
Onondaga Co	1,671	2.8	0.12	9.0	6.1

* RIN = 10 [soil gas radon (pCi/L)](permeability) 0.5

In EPA Office of Radiation Program's New House Evaluation Program (NEWHEP), two builders in the Denver area, two in Colorado Springs, and one in Southfield, Michigan, installed various radon-resistant features in houses during construction. A sampling of subsequent measurements of indoor radon, adjacent soil gas radon, and soil radium content is summarized in Table 5.4 (Mur88).

The major difference between these data and the Florida survey data in Table 5.1 is that this portion of the NEWHEP data was collected from newly constructed houses where passive radon-resistant construction features were being tested. There are no data on control houses in the same area that did not have those built-in features, making it difficult to compare soil radon measurements to indoor radon concentrations. It appears, however, that passive-only building techniques do not consistently result in indoor radon levels below 4 pCi/L. All five of the builders in the NEWHEP are currently experimenting with or are considering the installation of active, fan-driven sub-slab ventilation systems. Results are being monitored (Mur88).

Table 5.4 Indoor Radon and Soil Radon Measurements In Colorado and Michigan.

House No.	Indoor Radon in Basement pCi/L	Soil Gas Radon pCi/L	Radium-226 in Soil pCi/g
HECO 7300	5.9	—	1.3 (90 cm)
HECO 7395	14.5	—	1.3 (Surface)
HECO 7395	16.7	—	1.9 (90 cm)
HECO 7419	5.7	710	—
HECO 7423	7.9	1002	1.3 (90 cm)
HECO 7423	—	1779	1.4 (90 cm)
HECO 7425	1.5	620	1.3 (Surface)
HECO 7425	—	—	0.7 (90 cm)
HECO 7427	3.0	1430	1.1 (Surface)
HECO 7427	—	1316	1.4 (90 cm)
HECO 7448	11.8	930—	
HECO 7455	0.7	1240	0.4 (Surface)
HECO 7456	2.3	996	0.6 (90 cm)
HECO 7458	7.2	2030	—
HECO 7458	3.5	388	—
HECO 7459	0.9	1095	1.0 (Surface)
HECO 7459	—	1014	1.9 (30 cm)
HEMI 30001	1.8	—	*
HEMI 30002	0.9	—	*
HEMI 30003	4.2	—	*
HEMI 30004	1.7	—	*
HEMI 30005	3.6	—	*

* Radium-226 in soil was measured at two lots in this housing development. One lot measured 0.79 pCi/g and the second lot measured 0.91 and 1.2 pCi/g on two soil samples. These measurements were not made at the same houses where indoor radon was measured, so no direct correlation is possible. The soil test results are only indicative of some radon existence in this same geological area.

5.2.3 Variations in Spatial and Temporal Soil Gas Concentrations

Aside from the difficulty correlating soil radon measurements with indoor radon measurements, various field studies have also shown that obtaining a representative soil gas measurement is difficult. Soil gas radon measurements were made with a permeameter in seven central Florida houses in November 1987 (Pe87). A permeameter is a soil-gas and permeability measurement device that allows soil-gas to be sampled at various depths. In this study the radon concentration was the average of samples collected at depths of 60, 90, and 120 cm. Four to six samples were collected in the yard of each house at distances of 0.5 to 4.5 m from the house foundation. Soil radon concentration measurements in each of the seven yards varied by factors of 1.3 to 6.4, with an average variation of 3.1. In another study in the Piedmont area of New Jersey (Ma87), soil radon was measured in the front, side, and back yards of seven houses. Grab samples and 3-month alpha track samples were obtained from a depth of about 1 m. The grab sample radon measurements varied by a factor of 50 between houses and by as much as a factor of 46 between test sites at a single house. The average variation for each of the seven houses was 12.9. The alpha track results showed seasonal variations of approximately an order of magnitude difference between fall and winter/spring soil gas levels. The soil alpha track results did not compare in general with the results obtained by grab sampling. For example, a factor of 30 increase in radon from the front to back yard was observed in one house by grab sample data, while alpha tracks taken in the front and back yards were similar. In a second house, the opposite was observed: grab samples collected in the front and back yards varied by less than a factor of two, while alpha track measurements in the same yards varied by a factor of 14 (Ma87). In another seven home study in the Piedmont area (Se89) large variability in permeability measurements and soil gas radon concentrations was seen. Spatial variation in soil permeability at individual homes ranges from a factor of 10 to 10,000. Temporal variations in soil permeability at a given test hole ranged from a factor of 2 to a factor of 90. Spatial variations in soil gas radon ranged from less than a factor of 2 to a factor of 200 for a given site. Temporal variations in soil gas radon from less than a factor of 3 to a factor of 40 for a given test hole.

As indicated from the data, indoor radon concentrations cannot yet be predicted from soil radon values. The possibilities are not promising for designing a device and/or technique that builders can rely on to exclude building sites as potential indoor radon problems. As shown by the Florida and New Jersey data, *multiple measurements* would be required at each building site, and even those measurements can vary by orders of magnitude. Until the lot has been cleared, rough grading completed, and the foundation hole dug, access to the soil that actually produces the radon gas in the house is difficult, if not impossible. Few builders would decide not to build on a lot after they have incurred the costs of purchasing the lot and digging the foundation. In addition, many houses use fill dirt brought in from other locations. Unless the fill dirt is also characterized, additional radon potential may be missed or, on the other hand, the actual potential for radon entry may be overstated.

In summary, at present *individual* building lots cannot be characterized reliably for radon potential, and because of the inherent problems that have been identified, builders should not expect to be able to make these measurements or pay someone else to make them reliably in the near future. Aggregate data on radon in soils can only be evaluated on a *community wide* basis at this time. There is hope that these data can be used statistically to predict large areas with a high probability of residential radon problems. Work to enhance the accurate prediction of radon-prone areas is continuing within EPA and among other research organizations.

5.3 Radon Observed in Nearby Houses

Another approach to estimating the risk of a radon problem on a particular site is to examine measurements from nearby existing houses. In EPA's Radon Reduction Demonstration Program for existing houses, those with elevated radon levels generally have been identified through prior high-radon measurements in other houses in the neighborhood. Although it is possible to have isolated pockets of radon gas in the soil beneath a single house, most radon-prone houses are located in a geological setting common to most other houses in the general vicinity or region. Because of the many variables that affect radon entry into a house, homes with elevated radon can be found adjacent to houses with very little radon. However, statistically, the presence of an elevated radon house in a neighborhood or a significant number of elevated houses in an area as large as a county or ZIP Code area increases the likelihood of other elevated radon houses in the same area.

A classic example of one elevated radon house leading to the discovery of other elevated houses in the area occurred in Clinton, New Jersey, in March 1986. A homeowner in the Clinton Knolls subdivision read about the radon problem in the Reading Prong area of Pennsylvania and decided to obtain a charcoal canister and measure the radon level in his own house. When he received a very high radon reading, he notified the New Jersey Department of Environmental Protection (NJDEP). The NJDEP surveyed the neighborhood, making charcoal canisters available to homeowners who were willing to have the radon level checked in their houses. The survey showed that 101 out of 103 houses tested had radon levels above the EPA action level and over half of the houses had more than 25 times the action level (Os87a).

The Clinton experience can be contrasted with radon observations in Boyertown, Pennsylvania, where houses with radon concentrations over 500 times the EPA action level were found adjacent to houses below the action level (Py88). Therefore, the presence of elevated radon houses in a neighborhood is at best only an indication that the probability of having a radon problem has increased.

5.4 Airborne Measurements

The State of New Jersey has been able to correlate airborne radiation measurements to clusters of buildings with elevated indoor radon (Mu88). In this study, researchers compared airborne gamma-ray spectrometer data to indoor radon data to see if any trends emerged. For the conditions in New Jersey it was found that areas with airborne anomalies of 6 ppm equivalent uranium or greater were likely to have clusters of homes with elevated radon. This could be a valuable tool for health officials who are trying to make the greatest public health impact for the most reasonable cost. Inasmuch as it alerts a region to be wary, it is helpful, but it is probably not of much benefit in the assessment of an individual site.

5.5 Radon in Water

Between 2% and 5% of the radon problems found in the U.S. can be attributed to radon in water (EPA87). The most significant radon-in-water problems observed so far in the United States have occurred in the New England states. Houses with individual or community wells seem to have the greatest potential for a problem since the water in those systems is usually not well aerated.

Radon dissolves into groundwater from rocks or soils. When the water is exposed to the atmosphere, some of the dissolved radon is released. As a rule of thumb, there is an increase of about 1 pCi/L in the air inside a house for every 10,000 pCi/L of radon in the household water (EPA87). Higher radon levels have been observed in individual rooms when water is heated or agitated, such as during shower use (Os87c). Builders should be aware that houses that require groundwater as the house water supply could have a radon problem. The only way to be certain that the groundwater is not a potential radon source is to have the water from the well tested. Some states and private companies provide test kits for this purpose. It should also be noted that rad concentrations in water, like radon concentrations in the air, can vary significantly.

If a well has not been drilled, a nearby well may be an indicator of potential radon problems. Identifying potential radon-in-water problems by using the results from adjacent wells is subject to the same problems that were mentioned in Section 2.3.3. There is no guarantee that the neighbor's well is producing water with the same characteristics as the new well will produce since it may not be from the same stratum. The limited data available on houses with radon-in-water problems indicate that adjacent houses with similar wells sometimes produce similar radon-in-water problems and sometimes do not. However, few isolated radon-in-water problem houses have been observed.

In summary, because of the small percentage of houses with radon-in-water problems, few builders will have to deal with this issue. However, if a house is being built in an ar known to have many houses with radon-in-water problems, drilling the well and testing the water supply prior to construction are advised. If a house is built prior to identifying a radon-in-water problem, resolving the problem can be more difficult since space will not have been allowed for the radon-in-water mitigation techniques available.

5.6 Radon in Building Materials

A small percentage of the buildings in the United States with indoor radon concentrations in excess of 4 pCi/L can be attributed to building materials. Most of the building material problems have arisen from the use of known radium- or uranium-rich wastes such as aggregate in block or as backfill around houses. None of the houses studied in the EPA Radon Reduction Demonstration program have had any identifiable problem associated with radon from building materials.

Builders should be aware that this is a potential problem but, unless building materials have been identified as radium- or uranium-rich, the chance of obtaining radon from building materials is very slim.

Section 6
Planned Ventilation: Mechanical Systems

Introduction

New construction offers the opportunity to plan and install mechanical equipment so that fresh outdoor air is supplied to the living space and so that the air pressure relationships between the inside of the building and the outdoors reduce the influx of soil gas. This approach requires a better understanding of moisture and airflow building dynamics than the others covered in this manual. For example, it is important to understand what effect manipulating interzonal air pressure differences will have on the risk of condensation in the building shell, the entry rate of soil gas, the comfort of the occupants or the risk of increased spillage and downdrafting of combustion devices. By careful planning, the risk of these and other potential problems can be reduced; *however, no systematic research has been done to evaluate this approach for radon control.* Many variables come into play in trying to design a mechanical system and building shell that interact with the environment in the ways best for the health of the occupant and the building itself.

6.2 Interdependence of Mechanical Systems and Climate

Traditionally, residential mechanical equipment has been treated as independent devices which have little or no impact on the rest of the building other than the obvious stated purpose. Bath fans, dryers and kitchen ranges are assumed to exhaust moisture, lint and cooking by-products, but to have no impact on the performance of chimneys. Instances have been reported that show this is not the case, that in some houses fireplaces and other combustion appliances backdraft (CHMC84) when one or more of the exhaust fans are in operation. Houses have been reported in which the operation of exhaust devices increases the radon concentration (Os87b). Houses have been found in which pressure differences between different rooms of the house caused by HVAC distribution fans have increased energy costs (To88), occupant discomfort (To88, Ne88), condensation in the building shell (Ne88) and radon concentrations in parts of the houses (Hu88, Ru88). All of these effects are the result of air pressure relationships created by the interaction of mechanical equipment, indoor/outdoor temperature differences, wind velocity, and moisture and radon availability.

To a large extent wind, temperature, moisture and radon are beyond the control of the residential designer or builder. True, good drainage practice and the techniques outlined earlier in this manual can divert moisture and radon from a building, but the amount of rainfall or radon produced is independent of anything a builder can do. The pieces of this house dynamics puzzle that the builder or designer can affect are the mechanical devices used in the building.

6.3 Guidelines for Planning the Mechanical System

Specific guidelines for planning mechanical systems so that they minimize problems resulting from their interaction with each other and other climate-driven building dynamics are impossible to determine at this point. The major reason for this is that buildings constructed on different sites in different climates have very different behavior. For an example, a ranch house built in Florida has a warm, humid climate with which to work. This means that the space conditioning system is probably dominated by air conditioning and may also incorporate dehumidification. If the same house were located in Arizona, the cooling need would be there but there would be no need for dehumidification. If the same house were built in Minnesota the space conditioning would be a heating system and might require dehumidifying in the summer and humidifying in the winter. In the Florida house a case can be made for locating a vapor barrier on the outside skin of the building because the risk of condensation in the building shell is near the cooler indoor surface. In Arizona, there is seldom the risk of condensation because of the small amount of water present in the environment. In Minnesota, the risk of condensation in the building shell would be at the cool outside surface near the siding. In terms of risk of condensation it would be acceptable to pressurize the Florida house to control radon, because, as the outgoing cool interior air is warmed up, the risk of condensation decreases. Pressurizing the house in Minnesota is almost certain to result in condensation during the winter months, as the warm interior air cools down on the way through the building shell.

At this time a cohesive body of knowledge that has enough depth to make recommendations for different site conditions within the several U.S. climatic regions does not exist. However, many individuals do have enough insight to design intelligently for their own regions, and there are guiding principles that are general enough to apply for all situations.

Guidelines: Preserve the intended purpose of all mechanical devices. A heating system should still deliver the required amount of heat in a short amount of time. Exhaust fans should remove the moisture, fumes and contaminants.

Be sure applicable codes and standards are followed: Begin with the life and safety codes. The intent of this manual is to reduce the risk resulting from radon, but not in a way that increases other risks. Especially important in this regard are the National Fuel Gas Code (NFPA54), National Fire Protection Code (NFPA1) and the National Electric Code (NFPA70). Also the CABO One and Two Family Dwelling Code (CABO86) will be very helpful. There are thousands of code jurisdictions in the U.S., therefore many issues will have to be dealt with locally.

Plan to reduce soil gas entry: If possible, plan the mechanical systems so that soil gas is not drawn in by lower air pressure in the basement or ground floor rooms (slab-on-grade and crawlspace). Efforts along these lines can be made by minimizing the amount of air drawn from those rooms by exhaust fans, conditioned air return ductwork leaks and grills and sealing bypasses that penetrate floors. Air can also be supplied to these spaces to make up for the amount of air exhausted. If the exhaust air rate equals the supply air rate for a single zone, then pressure differences should be minimized. Supply air can cautiously be increased to pressurize these spaces and prevent soil gas entry, but the effect on moisture dynamics, combustion equipment and code acceptability must be kept in mind. An example of this is the relatively common practice of opening warm or cool air supply grills in a conditioned basement. This uses conditioned air and the air circulation blower to pressurize the basement (or at least reduce the negative pressures).

Plan to supply air to the areas of the house that need fresh air: A planned mechanical system also allows the builder to direct fresh air into the living spaces. This will reduce radon concentrations by diluting it with outdoor air. Depending on how it is supplied, it may also reduce the driving forces that draw soil gas into the building. Supply air will be drawn in by the mechanical devices, stack effect and wind pressures that exhaust air from the building. The incoming air will enter either through the unintentional cracks and holes left in the building or through passive vents that can be installed in the building shell. Passive vents allow the builder to let the fresh air in where it is wanted. Bedroom closets are a typical location. Supply air can also be powered by a fan and ducted to the areas where it is wanted. Heat recovery ventilators are a well established method of doing this. In either case fresh air will be added and the pressure difference between inside and outdoors will be reduced.

Caution: *Take no risks with carbon monoxide.* This is a special warning to carefully ensure that combustion products are properly exhausted from the house. Of course the place to begin is with the appropriate codes (UMC, NFUC, CABO, NFC) but keep in mind that even though something is not against code it may still be dangerous. For example, a system that backdrafts a fireplace because it removes air from the upstairs of a house might not violate any codes, but is certainly a hazard. Many new heating plants either are power vented or have dedicated outdoor combustion air.

The two most generally applicable and useful guidelines for planning are :

- *Air moves from higher to lower pressures*
- *Lowering temperature increases relative humidity*

These two rules help to predict the effect of air exhaust and supply on the transport of radon and moisture and whether or not to expect increased or decreased risk of condensation.

6.4 Two Illustrations

Here are two situations illustrating the issues involved in trying to understand the interactions between the mechanicals and the climate. These are illustrations. They do not apply to every house in the climates described.

First, consider a house in a cold, humid climate. The way it ordinarily operates is as follows. The warm inside air exits through cracks and holes at the top of the building. The warm air leaving through these cracks and holes is cooling down as it leaves, increasing the possibility of condensation. The suction placed on the lower part of the building increases the flow of radon laden soil gas into the basement where it is drawn into the leaks in the cold air return and distributed to the rest of the house by the warm air circulation system. All of the pieces in this scenario are likely to occur. Other things that could present problems might be bathroom fans that do not have much airflow or are vented into the attic.

If the upstairs portion of the house had the area of cracks and holes into the attic and walls reduced, then exhausting a small amount of air from the house would draw outdoor air *in* through the remaining cracks and holes. This would reduce the risk of condensation in the building shell because the air being pulled in would become warmer, lowering its relative humidity. However, exhausting air from a tighter house might increase the amount the furnace downdrafts and the influx of radon.

Using a furnace that draws combustion air from outdoors, or that is power-vented, solves the downdraft problem and probably has little effect on the radon influx when compared to a furnace that uses indoor air for combustion purposes. If it is desirable for the upstairs part of the house to run slightly negative to eliminate moisture, ensure that the heating system has been designed so that backdrafting will not occur when bathroom, laundry, and kitchen fans are used. If a centralized exhaust ventilation system is used, remember *to vent dryers and kitchen ranges separately*. It is poor practice to have grease soaked lint with a fan blowing air over it in the event of a fire.

If the air exhausted from the upstairs part of the house is diverted into the basement, the basement might be slightly pressurized and the influx of soil gas stopped. If the air leaks between the basement and upstairs and the basement and outside have been sealed, then a smaller volume of air will be able to pressurize the house. If the basement is insulated along the perimeter walls, it would be possible to use the air distribution ductwork to pressurize the basement and depressurize the upstairs. This could be done by planning the distribution ductwork so that it is easy to seal the joints and then opening grills in the supply ductwork. For this to be an effective radon control, the fan would have to run all the time. A two speed distribution fan could be used that would run on low speed all the time and be boosted to high speed when heating or cooling is called for.

Ventilation systems could further reduce indoor radon levels by dilution with outdoor air, and, depending on how it is distributed, could reduce driving forces that draw in soil gas. If outdoor supply air is added to the return-air side of the ductwork then some (50 to 100 cfm) ventilation air would be introduced and distributed to the house whenever the fan was running. Some new heating systems combine heat recovery ventilation (HRV) with warm air space conditioning. This would add about 200 cfm of fresh air whenever the HRV was operating and 50 cfm whenever the circulation fan was running. The American Society of Heating Refrigeration and Air Conditioning Engineers is currently revising their residential ventilation guidelines to recommend the capability of providing one-third of an air change per hour (ACH) for residences. An HRV would provide that for a 4500 ft² house with 8 ft ceilings, and makeup air for the return ductwork would meet that for an 1100 to 2200 ft² house with 8 ft ceilings. In addition to radon control this amount of ventilation has the benefits of control of the unavoidable contaminants released by washing, cooking and body functions. In a heating climate where there is moderate to heavy rainfall, powered ventilation in the winter can be used for humidity control.

Summarizing, a mechanical system that is planned to control indoor air contaminants (including humidity, radon, combustion gases and body odors) and reduce the risk of condensation in the building shell in a cold humid climate should include:

- power-vented or dedicated outdoor combustion air heating systems
- depressurized upstairs / pressurized basement (possibly using the distribution system)
- air supplied to the building with or without heat recovery
- tightened building shell to minimize the amount of air needed to pressurize the basement and to lower neutral pressure plane

Situation Two is a house constructed in a warm humid climate. It is a single story slab-on-grade house with air conditioning in the attic. There is a single return air grill located in the hallway that leads to the bedrooms. When the air handler is not moving air, the conditioned indoor air mass tends to create a reverse stack effect preventing soil gas from entering. When the air handler is running the house at 2 Pa negative pressure, it overwhelms the reverse stack effect because the supply ducts in the attic are far more extensive than the returns and have more leaks. When the bedroom doors are closed the entire living area goes to about 10 Pa negative pressure. In both of these lower indoor air pressure conditions soil gas is drawn in through the many cracks and penetrations of the floor slab. Space heat, when it is needed is supplied by a heat pump cycle through the air conditioning ductwork. In the summertime when it is warm and humid outdoors, the negative pressure in the building draws air in through the cracks and holes in the building shell. As the air gets closer to the cool interior, the relative humidity increases, and the risk of condensation in the building shell near the interior sheetrock increases.

Pressurizing the house would reduce both the soil gas entry and the chance of condensation occurring. This could be accomplished by planning the ductwork so that it could be easily sealed to reduce losses, running a more extensive return air system, and using dampers so more air is supplied to the house than is exhausted. The difference between supply and exhaust will be lost through the building shell. By making the building shell as airtight as possible, the amount of air it takes to do this will be smaller. If more air is supplied to the building than is removed by the return air ducts then the difference must come through leaks in the return air ductwork. It is possible that an outdoor air supply duct will have to be run to the return air side of the air handler to make the pressurization (and coincidentally ventilation) air available. The incoming air must be cooled down to house temperature resulting in a sensible and latent heat gain energy penalty. In this case two approaches could be made to reducing the cooling energy penalty. A high efficiency cooling coil using dehumidifying heat pipe technology could be used to precondition the incoming air. Second, a heat pump domestic hot water heater could be used to precool the incoming air and heat the hot water at the same time.

The bathroom, laundry and kitchen exhausts would have to operate as normally installed and enough pressurization air would have to be added so that the intermittent operation of these exhausts would not overcome the time averaged benefits of house pressurization.

Combustion products are probably not an issue because there is no combustion device in the house.

Summarizing the system :

- Pressurize the house using the air handling system (concurrently adding ventilation air)
- Reduce the cooling load penalty by preconditioning the incoming air (reducing the indoor humidity and/or heating the domestic hot water)

6.5 Conclusions

It is obvious that an approach in new construction that matches mechanical system design and installation to the multiple needs of occupant health, safety, and comfort and to building longevity requires an understanding of how the climate and building interact. This approach is both more comprehensive in effect and complex in design and installation than the other techniques outlined in this manual. This line of attack should only be pursued by qualified people who have training and experience in mechanical systems, because it is too easy to overlook an important aspect of the interconnections involved. In many ways it is a more sophisticated control strategy than soil depressurization or mechanical barriers.

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Appendix A

Current Radon-resistant New Construction Research Efforts

There are several U.S. EPA, AEERL radon-resistant research projects that are ongoing or recently completed. Some of these are in cooperation with other research agencies, for example the New York State Energy Research and Development Authority and the U.S. EPA jointly pursued a research effort involving 15 newly constructed houses with radon-resistant features and 5 control houses.

The lack of a reliable method to estimate indoor radon concentrations in a new house before it is built makes the results of radon-resistant new construction research difficult to interpret. Without pre-test data, how can a new house with a successful radon control method be distinguished from the 9 out of 10 new houses that are below the EPA Action Guideline of 4 pCi/L ? Several approaches have been made to develop confidence in the results of projects. They are :

1) Make measurements in a large number of experimental and control houses so reliability can be estimated using statistical methods.
2) Build the test houses in neighborhoods known to have elevated indoor radon levels in a large fraction of the existing houses. In some neighborhoods >50% of the houses are over 4 pCi/L.
3) Study a small number of new buildings with radon control features in detail. Phase the study to separate the radon control features and establish how effective they are. For example, a soil depressurization method can be tested by monitoring indoor radon with the vent stack open and the blower off, with the vent stack open and the blower on, and with the vent stack blocked off. Tracer gases can be used to test the effectiveness of mechanical barriers or the amount of airflow through a soil depressurization system that comes from inside the basement.

Lastly, and as it seems to be turning out, if buildings with radon-resistant new construction features end up having elevated indoor radon concentrations, then the features didn't work well enough. There is no way to tell if the features were partially successful and the elevated indoor radon would have been higher yet had they not been used.

Table A1. Current EPA/AEERL Radon-resistant New Construction Projects.

	Walls		Site		Methods Tested		
Project	Block	Pour	Char.	Barrier	Pass.SSD	Act.SSD	Comments
EPA1b	0	10		10	10	5	
NYSERDA	15	0	Highly perm.	8	8	8	controlhou es (NY) averaged 34.4 pCi/L
NAHB-NRC (NJ)	4	6	Highly varied	0	0	0	
EPA2 (VA/PA)	0	4	2 clay 2 perm.	4	4	4	% indoor air in exhaust estimated

- EPA1b - *Passive and Active Soil Depressurization*
- NYSERDA (NY) - *Barrier/Active/Passive*
- NAHB-NRC (NJ) - Passive and Active Soil Depressurization
- EPA2 (VA/PA) - *Barrier/Active/Passive/Energy Penalty*

Table A2. Preliminary Results from Current EPA Research Projects.

Project	Average Basement Radon (pCi/L) Barrier	Passive	Active	# of Houses
EPA1b 14.5	6.0	<1	10	
NYSERDA (NY)	15.8	13.9	2.8	15
EPA2 (PA)	1.3	0.7	1.1	2
EPA2 (VA)	1.4	7.0	1.1	1

- EPA1b - Passive and Active Soil Depressurization
- NYSERDA (NY) - Barrier/Active/Passive
- EPA2 (VA/PA) - Barrier/Active Passive/Energy Penalty

It should be kept in mind that the results of these research projects are preliminary. However, it is clear that in all the projects at least some of the buildings that had radon resistant features built in also ended up with elevated radon levels. Whether this is the result of failure of the systems at conceptual, design or installation levels is unknown at this point.

Appendix B

Other Radon-resistant New Construction Guidelines

Several other groups are currently working on or have already issued guidelines to control radon in new buildings. These groups are usually either Professional or Trade Associations or government agencies.

There are thousands of local, state and national codes jurisdictions in the United States. It is their job to enforce existing codes. Many legal, enforceable codes are based on model codes that have been developed by model codes associations. The model codes often reference standard practice as recommended by industry associations.

Developed and Available:

DOE, Oak Ridge National Laboratories, ORNL/Sub/86-72143/1, "Building Foundation Handbook," 1988. An impressive publication that addresses nearly all imaginable aspects of foundation design and construction. Chapter 10 is devoted to radon control in new construction.

National Forest Products Association, "Radon Reduction In Wood Floor and Wood Foundation Systems," 1988 - A 20-page booklet describing radon control strategies for permanent wood foundations. National Forest Products Association is a trade association for the producers of wood products.

U.S. EPA, Office of Radiation Protection - National Association of Homebuilders Research Foundation, "Radon Resistant New Construction - An Interim Guide," August 1987, OPA-87-009 - A 10-page pamphlet that covers fundamentals and recommendations.

In Process, Not Yet Available :

American Society for Testing and Materials (ASTM), "DRAFT-Standard Guide for Radon Control Options For New Home Construction, "White Paper," - Currently in process. ASTM is an organization composed of users, producers and interested parties who work together via a consensus process to produce voluntary industry guidelines. All publications go through extensive peer review. This document is being developed by Committee E-06.41.08, Reduction of Radon Intrusion Into Buildings. Contact Bion Howard at the National Association of Homebuilders Research Center, 400 Prince George Blvd., Upper Marlboro, MD 20772. Ph. (301) 249-4000.

Florida - The State Legislature mandated in 1988 that the Florida University system develop a model building code for radon control methods in new and existing buildings. The preliminary planning has occurred for this effort. Contact Thomas Pugh at the Florida A & M University School of Architecture, Tallahassee, FL 32308. Ph. (904) 599-3000.

U.S. EPA, Office of Radiation Programs - Currently mandated by Federal legislation to develop a model code for radon resistant new construction, ORP is in the process of writing a draft of a radon resistant new construction code. Contact Dave Murane, U.S. EPA, ORP, 401 M St. S.W., Washington, DC 20460. Ph. (202) 475-9623.

Washington Energy Extension Service, "Northwest Radon Ordinance" - In process. This is a model radon resistant new construction code being developed by the Washington Energy Extension Service with extensive review by interested parties. Contact Mike Nuess, WEES, N. 1212 Washington St., Spokane, WA 99201. Ph. (509) 456-6150.

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