Unit 2. Radon Entry and Behavior

Contents

Objectives

02.01 Identify radon sources, driving forces and openings into buildings as prerequisites for the entry of radon into a building.

a. Identify the major sources of radon.

b. Identify the four transport mechanisms by which radon enters a building.

c. Identify the soil types according to their permeability.

d. Identify the common radon entry points that may occur in a building foundation.

e. Identify materials within a building that contribute to radon concentration.

02.02 Identify how weather conditions, mechanical systems, building design and occupants' life-style affect and contribute to the cyclical nature of indoor radon and radon decay product concentrations.

a. Analyze how pressure differentials are created.

1. Describe how specific household mechanical equipment (such as fans, clothes dryers and HVAC systems) create pressure differentials.
2. Describe how combustion devices (such as fireplaces, wood stoves and furnaces) create pressure differentials.
3. [1]***Identify environmental conditions (such as temperature differentials and wind) that induce pressure differentials.

b. Describe how these pressure differentials affect radon entry into a building.

02.03 */**Analyze how radon sources, transport mechanisms, building soil gas entry routes and ventilation affect indoor radon concentrations for a given situation.

a. Determine how the indoor radon concentration is affected by ventilation rates and the amount of radon entering a building.

b. Analyze given situations for the various ways airflows can be induced in houses.

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[1] *These objectives are only for radon measurement specialists.

**These objectives are only for radon mitigation specialists.

***These objectives are only for measurement applicants.

****These objectives are only for mitigation applicants.

c. State the advantages and disadvantages of increasing the ventilation rates to reduce radon concentrations in a building.

d. Compare source strength and ventilation as they relate to radon concentrations in the average house.

I. Overview

Radon does not mysteriously appear in buildings - it is produced only by radium. Radium-bearing soil, bedrock sources of well water, and materials within buildings can be sources of radon in indoor air. Approximately 6 million U.S. homes are projected to have radon concentrations above the Environmental Protection Agency (EPA) guideline of 4 pico-Curies per liter (pCi/L). Whether any individual house has elevated radon depends on:

- The strength or the radon source,
- How effectively radon is delivered to the indoor spa and
- To a much lesser extent, the building's ventilation rate.

Contrary to researchers' expectations, indoor radon concentrations do not correlate well with ventilation rates. The amount and variability of radon entering a building dominates the final radon concentration, to the extent that it is often difficult to measure the effect of ventilation on indoor radon concentrations. This is probably because many of the factors which increase ventilation also tend to increase the amount of radon entering the home. For example, an exhaust fan increases ventilation, which tends to lower the radon concentration. However, it also increases the suction the home exerts on the soil, which increases the contribution from the source. In any particular situation, it is 'impossible to predict which effect will dominate.

In a typical house, most of the radon entering the building comes from the surrounding soil or bedrock and is pulled through the soil by air pressure differentials. These pressure differentials are created when air is exhausted from buildings by natural or powered ventilation. Soil gas is literally drawn in from the surrounding soil.

Less frequently, radon enters a typical building in three other ways:

- It can diffuse into the building through holes in the foundation and through the foundation material itself, because there is a higher radon concentration in the soil than in the house air.
- It can enter the house dissolved in well water that has been drawn from an aquifer containing radon.
- It can be released directly into the house air from material located in the house that contains radium.

Figure 2-1, which shows a cross-section through a building, summarizes the source locations, the driving forces that move radon into a building, and the relative contributions in the average U.S. house (Ref. 12).

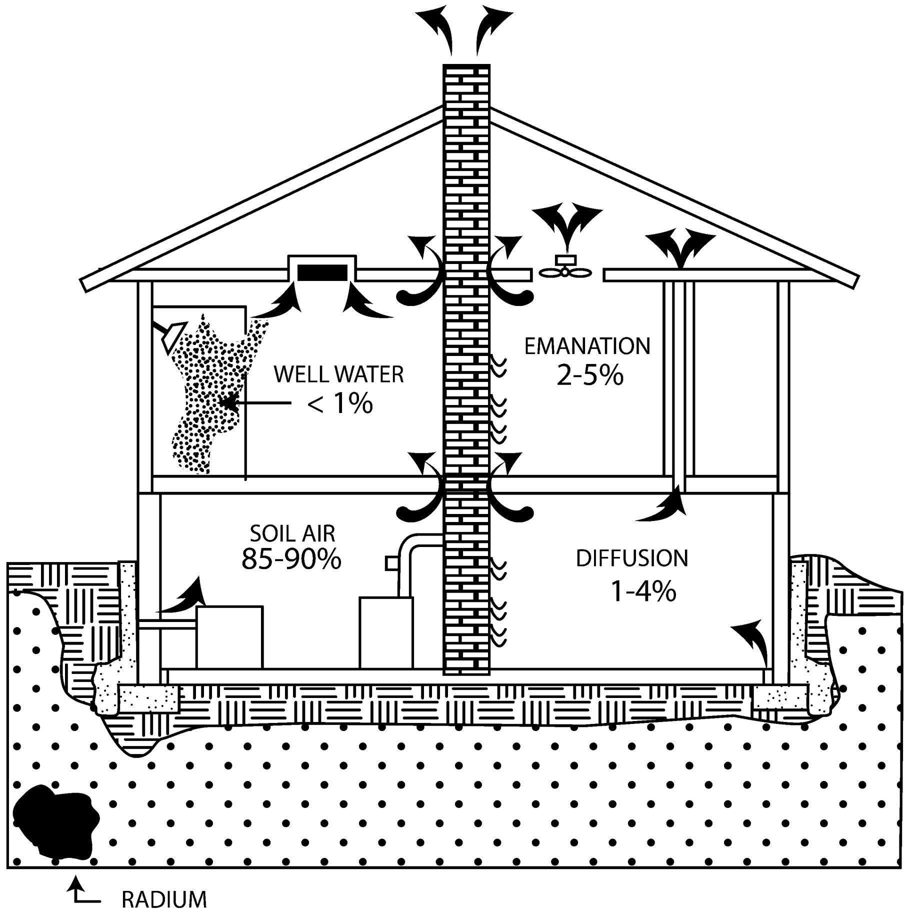


Figure 2-1. Radon Entry/Average Contributions, Source: LBL/EPA

II. Mechanics of Radon Entry

There are three prerequisites for radon entry into buildings:

- A radon source.
- A mechanism for radon transport:
  - Soil porosity.
  - Force drawing soil gas into the building.
- An opening for radon to enter the building.

A. Nearby Radon Source

Radon in a building can come from radium that is located in nearby soil, bedrock, or in the house itself. The distance radon can travel in the ground depends on the nature of the pathways open to it and the driving forces that power its travel to the house. Radon has a half-life of about 3.8 days; if it takes the soil gas 4 days to reach the house, approximately half of the radon will remain. If it takes 8 days, one quarter of the original radon will reach the house.

Soil gas can contain very high radon concentrations, however. Typical soils in "normal" areas contain about 100 pCi/L of radon, and concentrations of 100,000 pCi/L have been measured under floor slabs. It should be possible, therefore, to draw radon from a surprisingly great distance. This is especially true if there are underground passageways which allow radon transport. Very few measurements have been made to demonstrate the distances radon can travel, however.

1. Prevalence of Radium in Soils and Rock

Radium is a common element found in many soils and bedrocks. Radium is widely dispersed, and only a small amount is required for an indoor radon problem to develop. As a result, low level problems have been found in unexpected areas. Elevated levels of radon have been found in every State.

Radon Release into Soil Gas or Aquifer

Soil gas or aquifer concentrations of radon depend on:

- How much radium is in the soil and rock particles;
- The water content of the soil;
- How much radon diffuses into the above grade air; and,
- How much air from above grade dilutes the radon in the soil gas (Ref. 8).

Before radon can enter the soil gas, the radium that produces it must be near air or water in the soil pores. High soil gas concentrations are produced where a large portion of the radium is surrounded by air or water, and there is little opportunity for dilution from atmospheric air. If it is located in an aquifer with little or no exposure to air, radon will dissolve in the groundwater.

Most soils are between 15 and 55 percent pore (void) space, which is sufficient for fairly rapid transport. Weathered, fractured rocks - such as exfoliated shales, glacier-ground granites, or water-eroded, mineralized limestones - also have sufficient pore space for easy gas transport.

2. Ranges of Soil Gas Radon Concentrations

There are many factors that influence radon concentrations in soil gas. In some cases, only a few of these factors are important; in others, they all play a part. This explains the extreme variations that have been observed in soil gas measurements, ranging from about 100 pCi/L to over 100,000 pCi/L (Ref. 10). In one unusual example, soil measurements taken within 30 feet of each other differed by a factor of 250 - in one place the soil gas had 350 pCi/L. While a nearby location had 89,000 pCi/L (Ref. 6).

This extreme variation makes it possible for similar buildings - one with elevated levels of indoor radon and one with low levels - to be located right next to each other. Figure 2-2 presents a hypothetical example of two adjacent buildings where radon concentrations would be expected to vary widely. One is protected from a strong source by a layer of clay, while the other has sandy soil at the base of its foundation in contact with the source. This type of situation illustrates why it is difficult to characterize the potential for radon problems prior to construction at a single building site (see Unit Seven).

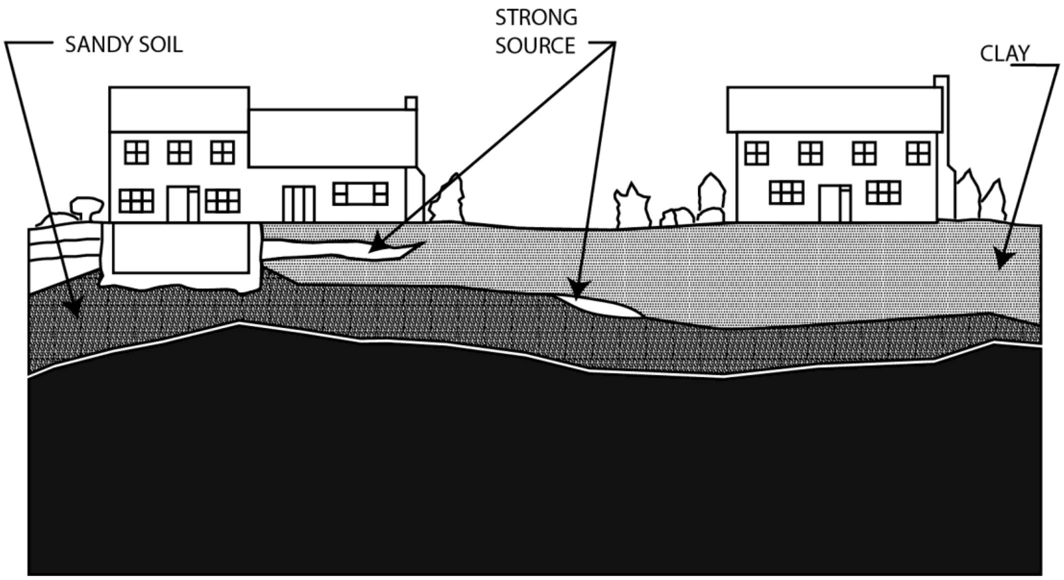


Figure 2-2. Radon Entry into Individual Homes (Impact of Localized Soil and Geology), Source: EPA

3. How Radon Moves Through Soil and Rock

Radon movement through a material is powered in one of two ways: (1) concentration gradient diffusion; and (2) pressure driven airflow.

Concentration Gradient Diffusion

Even if no air is moving, radon will diffuse through the soil from higher concentration to lower. The highest concentrations will be nearest to the radium - the radon source. In uniform soil, concentrations will generally decrease as the distance from the radium increases. The more porous the soil, the faster the radon will diffuse, and the more uniform the soil concentrations will become. The tighter the soil, the higher the radon concentrations will be near the radium source, but the concentration will drop more rapidly away from the source.

Radon concentrations decrease quickly as the surface of the ground is approached. At ground level, the atmospheric concentration is very low; thus the concentration gradient is largest in that direction. If the surface covering has a low resistance to radon diffusion, then radon transport by diffusion will increase. For this reason, soil gas radon concentrations are often higher after a substantial rain or snowfall, or beneath concrete patios, driveways, parking lots, and slab floors.

Pressure Driven Airflow

Pressure driven airflow drives soil gas from areas of higher to lower pressure. Pressure differentials that drive soil gas flow in soil are produced by temperature differences, wind pressures, barometric pressure systems, and the displacement of soil gas by rainwater. The atmosphere, soils, fissures, caverns, discontinuities in soils, and building interiors comprise a network of zones that are connected to each other by air passages. Airflow between these zones is determined by the pressure differential between them and the gas flow resistance of the material comprising each zone.

Soil gas flow is poor in clay soils that have a great deal of resistance, better in sandy and gravelly soils, and best in open passages. As air the soil flows past radium, it carries radon away from its source and forms an underground gas stream of elevated radon concentration. This soil gas follows the paths of least resistance from higher to lower gas pressures.

B. Transport Mechanisms

There are four transport mechanisms that bring radon into houses:

- Air pressure differentials between soil gas and building air.
- Concentration gradient diffusion from soil to indoor air.
- Well water.
- Release of radon from a source of radium inside the house.

1. Air Pressure Differentials

Radon entry by pressure driven airflow from below grade is the dominant entry mechanism in most buildings with elevated radon levels. When air escapes from a house (exfiltration), air pressure differentials between the inside and outside are created. This results in air being pulled into the house (infiltration) to replace the air which has left. The air may be drawn out of the house by a powered ventilator such as a fan, clothes dryer, or combustion appliance. It may also escape because of the tendency of the warm air in the house to rise. In the case of rising warm air, the upper floors of the house are slightly pressurized, while the lower floors are depressurized. The place where these zones of pressurization and depressurization meet is called the neutral pressure plane. The location of the neutral pressure plane is determined by the temperature of the house relative to the outdoors, the amount of air leakage at the top and bottom of the structure, and the presence of powered ventilation.

When the lower part of a house is depressurized in this way, air enters through cracks and holes located over the building shell below the neutral prcss1irc plane. In this situation, the house substructure is under negative pressure and creates a suction on the surrounding soil (see Figure 2-3). It is estimated that between 5 and 20 percent of the infiltrating air enters from below ground level and can carry radon in with it (Ref. 5, 6, 9, 12). Figure 2-4 shows the relationship between radon concentrations and pressure differentials. As the pressure between the inside and the outside of the house decreases, less suction is being applied to the sub-grade soil beneath the basement. This condition causes less soil gas to be pulled into the house thereby reducing the radon concentrations.

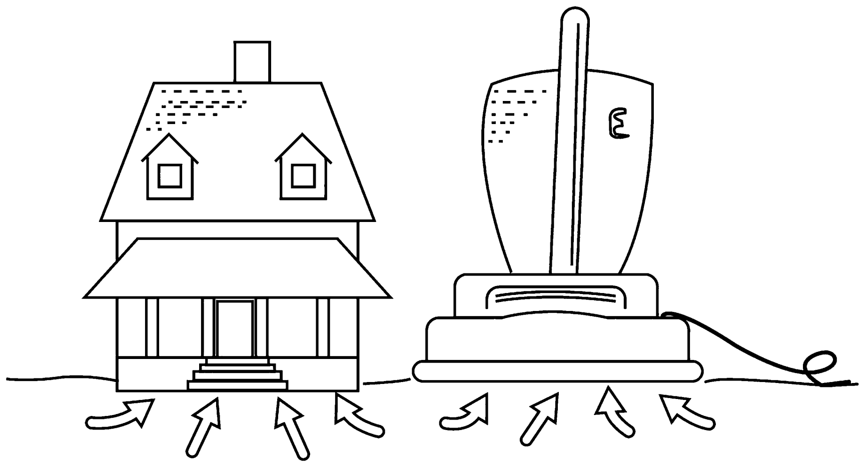
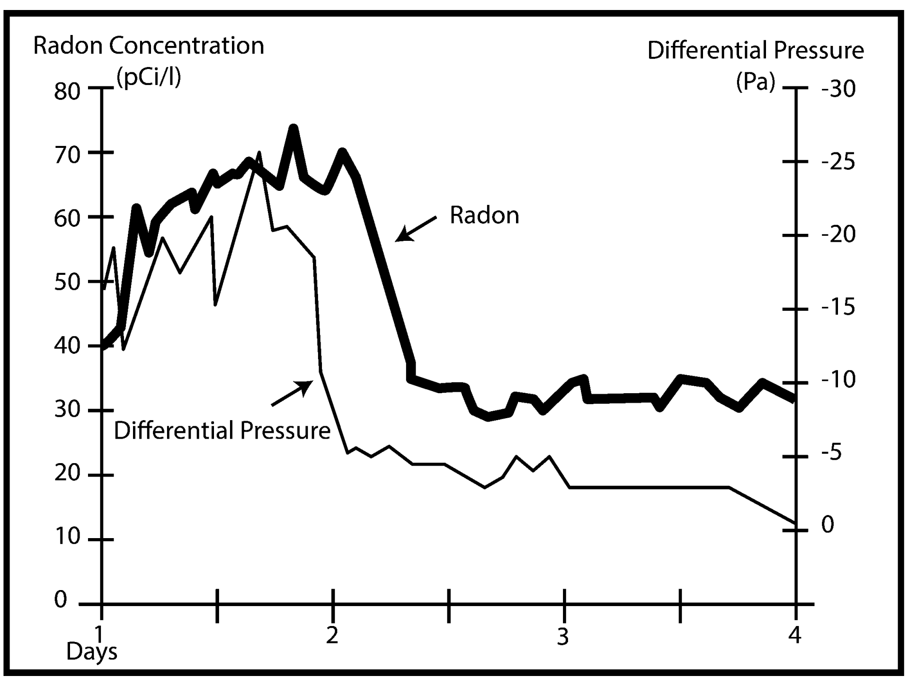


Figure 2-3. House-Induced Soil Suction, Source: EPA

Figure 2-4. Effect of Differential Pressure on Radon Concentration (Before Mitigation), Source: NYSERDA



Outside air is drawn into the house by:

- Mechanical equipment,
- Temperature differences between inside and outside air, and
- Wind.

Airflows Induced by Mechanical Equipment

Mechanical devices such as kitchen range exhausts, bath fans, dryers, and heating and cooling air distribution blowers can put a suction on a house which requires makeup air to be drawn in from outside. Combustion devices such as fireplaces, woodstoves, furnaces, and boilers also exhaust air from the house. Table 2-1 shows the typical airflows for a number of common exhaust appliances.

Exhaust Device	Duct Size (In.)	Typical Manufacturers Flow (cfm)	Corrected Flow* (cfm)
Bathroom Fan	3	40	24
	4	50	30
	7	100	60
	8	150	90
Clothes Dryer	4 or 5	135	100
Range Hood			
Interior Styles	4	50	30
	3 1/2 x 10	40	24
	7	100	60
	10	200	120
Exterior Mount	10	300	225
Central Vacuum Cleaner			110
Wood Fireplace			170
Open Wood Stove			65
Air-tight Wood Stove			30
Operating gas, oil, or Propane Appliances	3		21
	4		38
	5		47
	6		72

***** Flow is corrected for standard restrictions like 1/4 inch screening, louvers, straight duct and grease filter.

Table 2-1. Estimated Air-Flow for Typical Exhaust Devices, Source: Moffatt/Progressive Builder

Airflows Induced by Temperature Differential

When it is colder outside than inside, the warmer indoor air is lighter and tends to float out of cracks and holes at the top of the building. This puts a suction on the lower pan of the building, drawing in air. Somewhere between the point at which air leaves at the top and enters at the bottom is a level at which there is no airflow between indoor and outdoor air. This is called the neutral pressure plane. If the leaks were uniformly spread over the whole house, the neutral pressure plane would be about halfway up the wall. This plane is frequently found within a few inches of the top floor ceiling, indicating that many houses have very leaky ceiling areas.

This makes the house behave like a chimney. In fact, this temperature-driven airflow is often called the stack effect, as it is powered exactly the same way as the draft on a chimney. (A chimney draws air in at the bottom and forces it out at the top, resulting also in a neutral pressure plane somewhere along its length.) Airflows due to temperature differences are also called convective air flows. The neutral pressure plane determines the direction of interior convective airflows only. Below the neutral pressure plane (the negative side), the convective flow is towards the neutral pressure plane. Above the neutral pressure plane (the positive side), the convective flow is away from the neutral pressure plane. Airflows driven by fans and by the wind (not caused by temperature differences) are not affected by the neutral pressure plane, but, if these airflows are large, they can change the position of the neutral pressure plane. Figure 2-5 illustrates the neutral pressure plane.

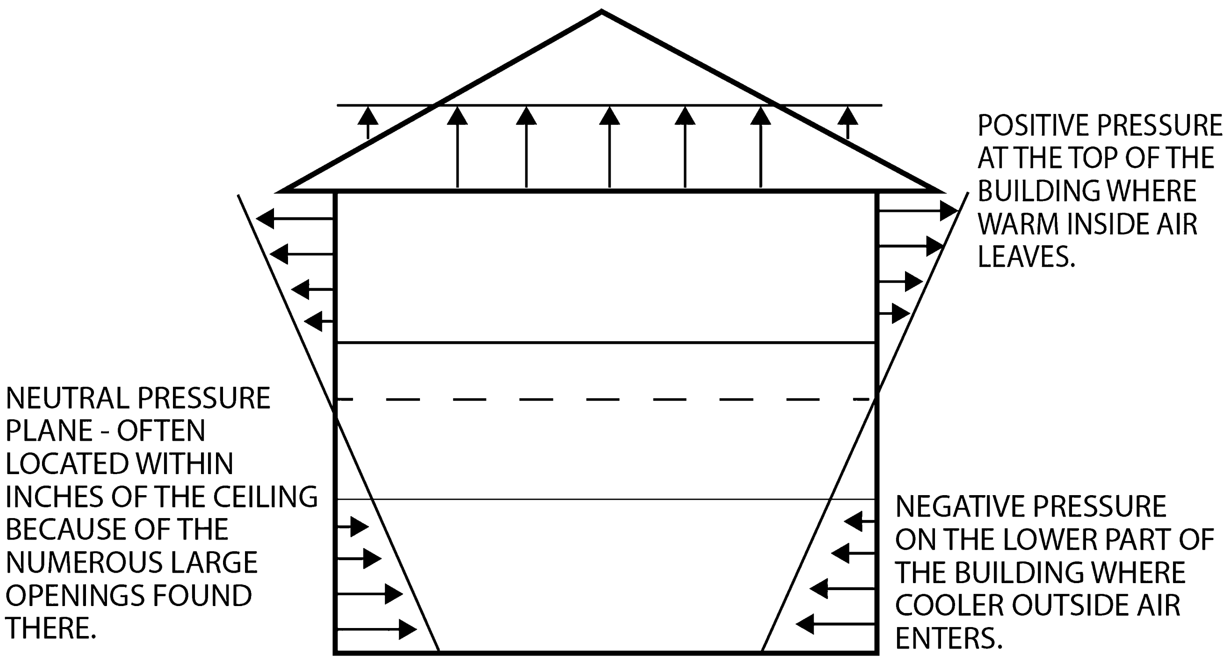


Figure 2-5. Neutral Pressure Plane, Source: Brennan/NYSEO

Figure 2-6 shows a cross-section of a house. This illustration shows a number of common chases and penetrations, which allow inside air to flow directly into the attic. These are called thermal bypasses and include these construction features:

- Recessed lighting fixtures (by code, these cannot be sealed unless designed for sealing).
- Air gap around chimneys (no combustibles allowed within 2").
- Plumbing chases (especially behind baths and showers).
- Balloon frame walls (two--story wall studs without firestops).

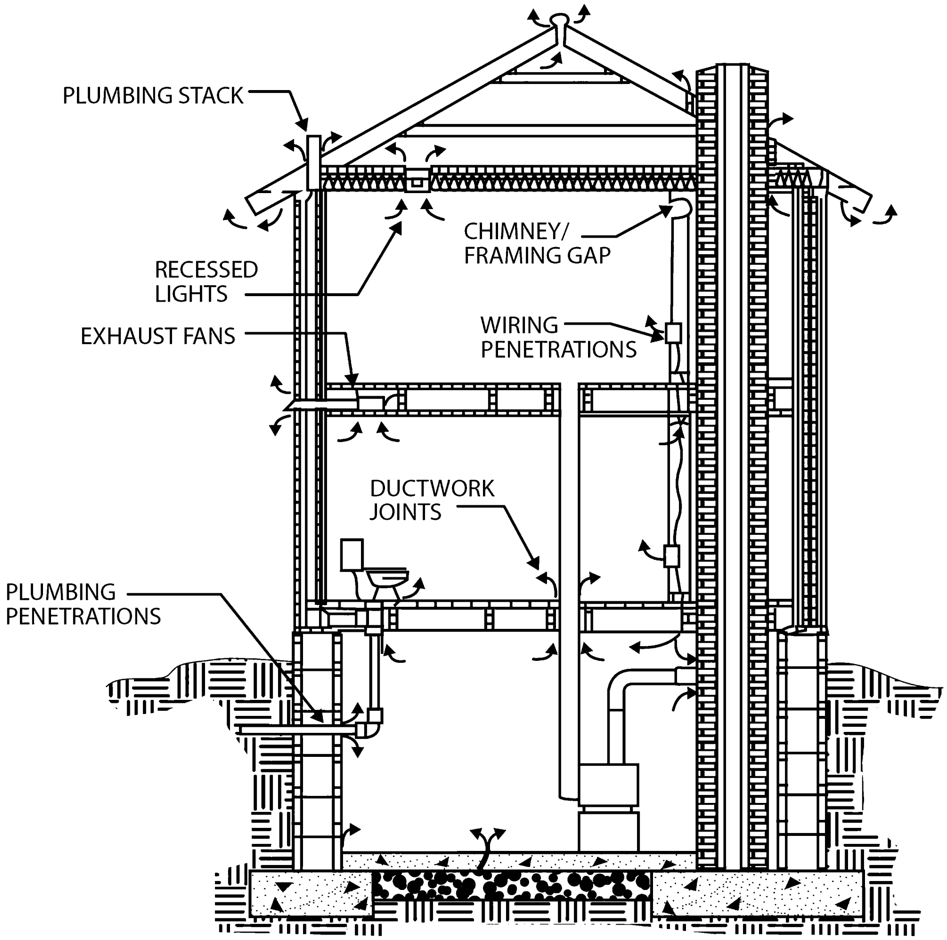


Figure 2-6. Negative Pressure Sources and Thermal Bypasses, Source: Solaplexus/NYSEO

As warm air flows up through these channels, the rest of the house is depressurized. When there is a 40° F temperature differential, the airflow due to stack effect is about 200 cfm for a house of typical size and construction (see Figure 2-7). A vacuum of about .02 inches of water column will be created in the basement under these conditions. Sealing some of these openings and bypasses to limit depressurization is sometimes a secondary activity to support more primary mitigation techniques.

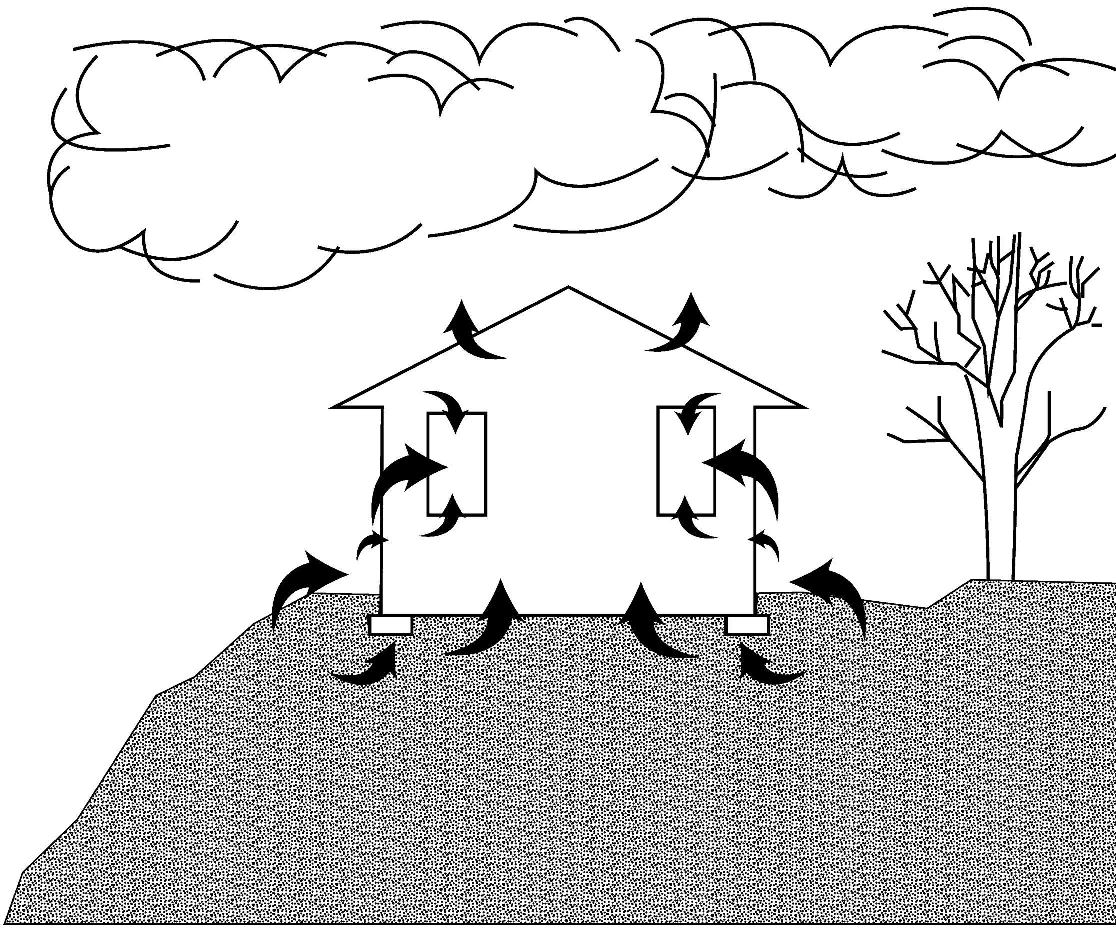


Figure 2-7. Stack Effect-Winter, Source: EPA

Note that air conditioning causes the house air-to be cooler than outside, and the air in the house tends to sink. This reverses the pressure pattern in the house, and the lower rooms tend to have higher pressure (relative to the outdoors) than the upper floors. Air tends to enter at the top of the building and exit at the bottom. This accounts for one reason that air conditioned houses exhibit lower radon concentrations.

Wind Induced Airflows

As shown in Figure 2-8, wind creates a complex pressure field around a house (Ref. 1). It can produce a positive pressure in the soil on the windward side of the building and force soil gas entry from that side. Additionally, wind often has the overall effect of producing a suction on a house. This is the case if the openings on the leeward side and top of the building are larger than those on the windward side. Even if the leaks are the same size and uniformly distributed over the walls, wind puts an overall negative pressure on a building, because of the number of large openings found at the ceiling level. The effect is similar to wind blowing across the top of a chimney and inducing a draft, even when there is no temperature-driven stack effect.

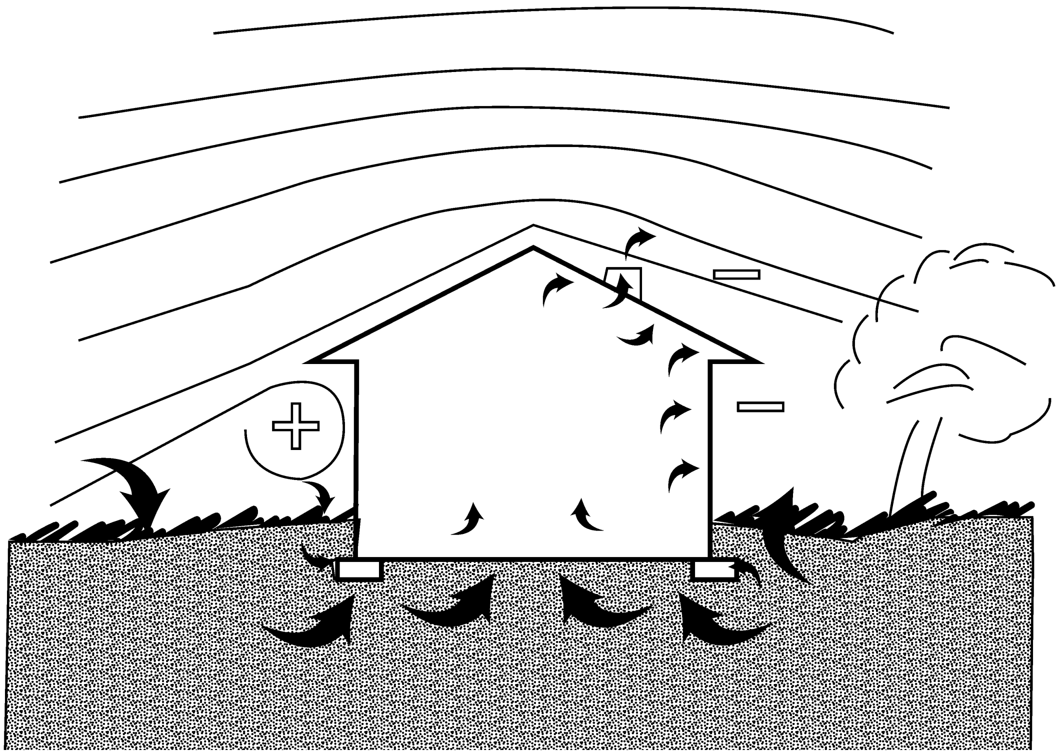


Figure 2-8. Windblown Effect, Source: EPA

Other Environmental Effects

Spikes in radon levels have been observed to be associated with rainfall. As shown in Figure 2-9, rainwater saturates the soil, which displaces soil gas and prevents radon from diffusing into the atmosphere. Consequently, the concentration of radon in the soil may increase. This "sealing" of the soil surface has the effect of extending the strength and area of the negative pressure field generated by the house, providing for transport of soil gas over greater distances. The displacement of soil gas by rain may also tend to force radon into houses by hydraulic pressure.

Hydraulic pressure also correlates with radon levels, probably for the same reasons that spikes occur in periods of rainfall. As water tables rise, more soil gas is forced into houses.

Studies relating barometric pressure to indoor radon are scarce. Since low barometric pressure is often associated with rainfall, low pressure is likely to track with higher radon levels for the same reasons· as for rainfall.

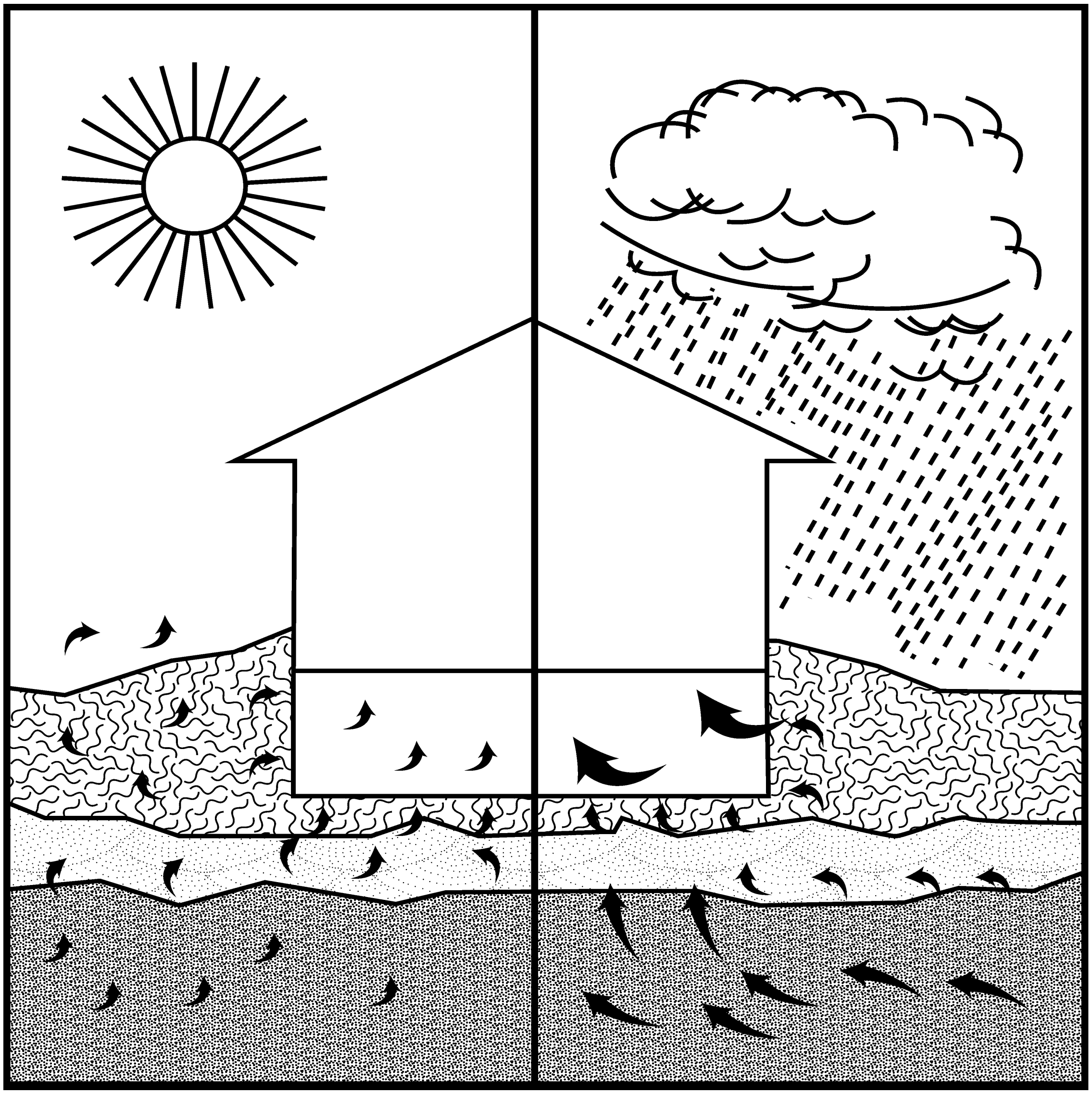


Figure 2-9. Effect of Rainfall on Radon Transport, Source: EPA

Pathways for Pressure Driven Transport

The critical characteristics of a radon transport pathway are:

- Ease of air movement,
- Proximity to radium, and
- Interconnection to other airflow passages.

There are several ways that air passes through a source of radium in the bedrock or soil on its way from a higher pressure to a lower one. For example, many water drainage methods, used to prevent surface or groundwater from entering a building, also connect large surface areas of soil and bedrock with passages that have little resistance to airflow. When digging to place a foundation or utility entrance, the resistance to airflow in the surrounding soil can be changed. Among the pathways allowing easy airflow are:

- Sand
- Gravel
- Cracks in soil
- Cracks, fissures, and caverns in rock
- Uniform stone pebbles (#1, #2, #57, pea gravel)
- Perforated pipe (as used in drainage systems).

A simple example is when both the radium and house are in a sand or gravel soil. Given this high permeability soil, a suction point on the basement by stack effect or mechanical equipment easily draws soil gas through cracks and holes in the foundation as radon enters with the soil gas. The situation is often more complicated, however, because soil and rock conditions around houses are not uniform.

There are many airflow routes through seemingly impermeable soils:

- A layer of shattered shale below 4 feet of clay.
- An area of sand found in only one comer of a basement.
- A water service or sewer line from the street, backfilled with sand or loose fill.

Many houses have bidden airflow routes which interact with each other. When suction is put on the basement, the pressure differential results in air being drawn in from the outside through soil pathways. As described above, the. air movement through these pathways is complex and changes direction and magnitude with a variety of factors including wind, temperature, and the operation of home appliances such as ventilation fans or furnaces.

Table 2-2 summarizes some rough correlations that have been observed between indoor radon concentrations, geologic features, rock and soil types, and expected hot spots and regionally elevated areas. *Note that there are many exceptions to these situations.*

	Hot Spots	Regionally Elevated
Indoor Radon Levels	100-300 pCi/L	20-200pCi/L
Geologic Features	Rocky Nearby Fracture Zone Hilly Sites	High Permeability Soils Hilly Sites
Rock and Soil Types	Granites Gneiss Dolomites Limestones Phosphate Rock	Gravels Coarse Sands Residual Soils Dark Shales Phosphate Rock Granites

Table 2.2. Correlation Between Geology and Radon Concentration, Source: Tanner/USGS

2. Radon Transport by Concentration Gradient Diffusion

Even if no air is flowing through the soil into the house (an unusual case), radon can enter the building by concentration gradient diffusion. This diffusion of radon from high concentration soil gas into the house occurs via:

- Cracks and holes in the foundation (molecular diffusion of a gas through a mixture of gases).
- Solid concrete walls or slabs (molecular diffusion through a porous solid).

Diffusion is not usually the primary entry route for radon into buildings. If diffusion through the solid concrete and cracks and boles in the concrete were the only transport mechanism, a typical concrete slab would reduce the flux from bare earth by a factor of 25 to 50. It would take only 1/3 to 2/3 of a cubic foot of 1,000 pCi/L soil gas per hour entering the building through cracks and holes to equal the amount entering by diffusion through a 1,600 square foot slab (assuming an emanation rate from the concrete surface of .02 to .04 pCi/M^2/sec and an emanation rate from the earth under it of 0.7 pCi/M^2/sec).

3. Well Water Transport

Radon dissolved in groundwater is released when the water is exposed to air. In the case of a drilled well the water drawn bas very little access to air; consequently, any radon in this water will remain there until it decays or bas the opportunity to be released in air. When occupants shower or wash dishes and clothes, radon is released into house air. Since the volume of water used by an average household each day is small compared to the volume of air in a house, it takes very high concentrations of radon in water to produce an airborne radon problem. Figure 2-10 illustrates that it takes approximately 6,000-10,000 pCi/L of radon in water to give an airborne concentration of 1 pCi/L (Ref. 4). Radon in water is covered in more detail in Unit Six.

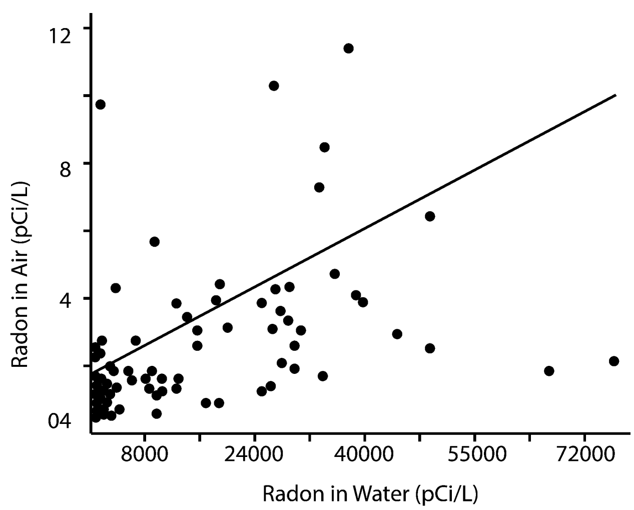


Figure 2-10. Radon in Air vs. Radon in Water, Source: Hess

4. Materials Within the Building

If radium is already inside the house, there is no need for a complicated entry pathway. Radon will be released directly to the house air as the radium decays. Although materials containing radium are not the most common sources of elevated levels of radon in buildings, releases happen occasionally.

Materials that have been found in some instances to be sources of radon in buildings are:

- Concrete and concrete products made from uranium mine tailings.
- Building materials containing radium.
- Exposed bedrock within the building.
- Fireplaces constructed of radium-bearing stone.
- Rock used as thermal mass for solar beating system.

C. Radon Entry through the Foundation

Radon entry through the foundation depends on four key factors:

- Substructure type
- Design
- Construction details
- Materials.

There are five basic substructure types common in the United States: pier, crawl space, slab, full basement, and combination. Basements are found more frequently in the north and east, most crawl-space homes are found in the southeast and northwest, and slab-on-grade homes tend to be concentrated in the west, in Florida, and in other areas with high water tables.

Pier foundation homes, as depicted in Figure 2-11, have a well-ventilated substructure and provide no direct pathway for pressure-driven airflow between the soil and the building interior. Consequently, they do not facilitate radon entry from the soil gas pathway. However, conduits for electrical and plumbing can be radon entry routes.

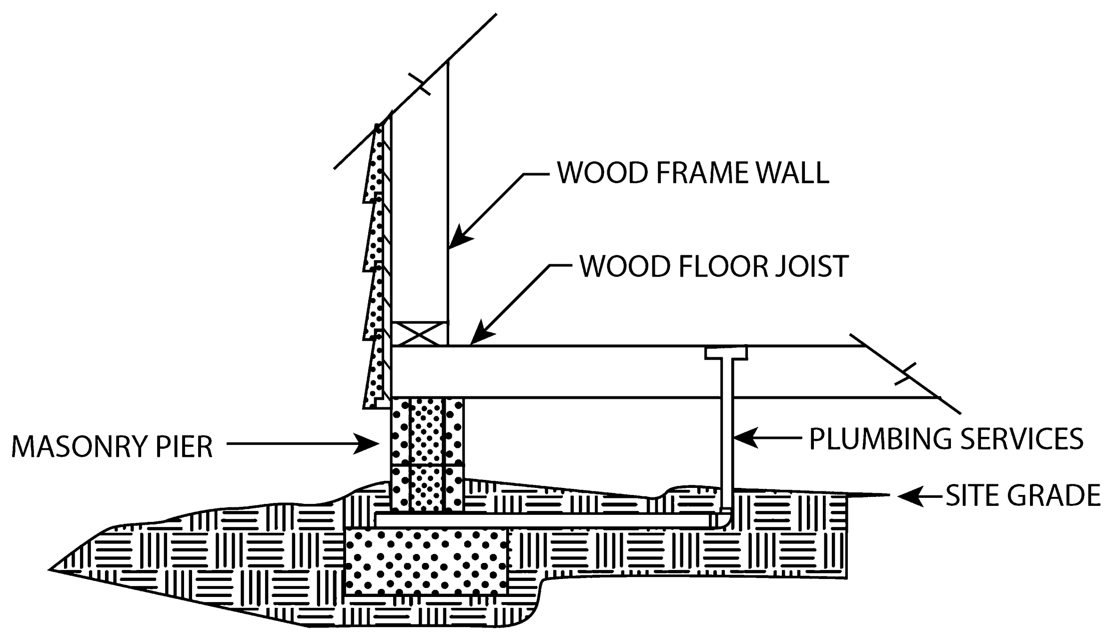


Figure 2-11. Pier Foundation, Source: EPA

Crawl spaces often facilitate radon entry, particularly if the crawl space has a dirt floor and block walls. As shown in Figure 2-12, crawl spaces may be ventilated or non-ventilated and may have a floor or vapor barrier. Particularly high radon levels are often found in unventilated crawl spaces open to the soil.

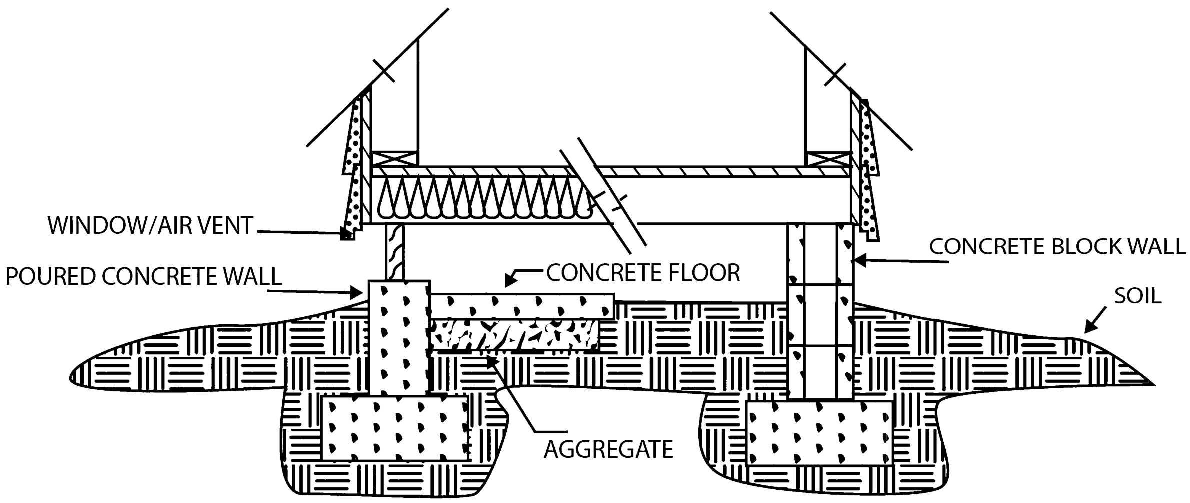


Figure 2-12. Crawl Space Ventilated/Non-Ventilated, Source: EPA

Houses constructed on *concrete slabs* can also have elevated radon levels. Slab foundations generally have numerous service or plumbing penetrations through the slab that allow radon to enter. Interior perimeter joints, where the floor slab meets the stem or frost wall, offer a potential entry route, which is especially difficult to seal in finished homes. Numerous openings are likely to exist, depending on the specific home construction. Since there is little potential for a water problem above grade, little attention is paid to sealing openings to the soil (see Figure 2-13). (This also contributes to termite problems in slab-on-grade houses.)

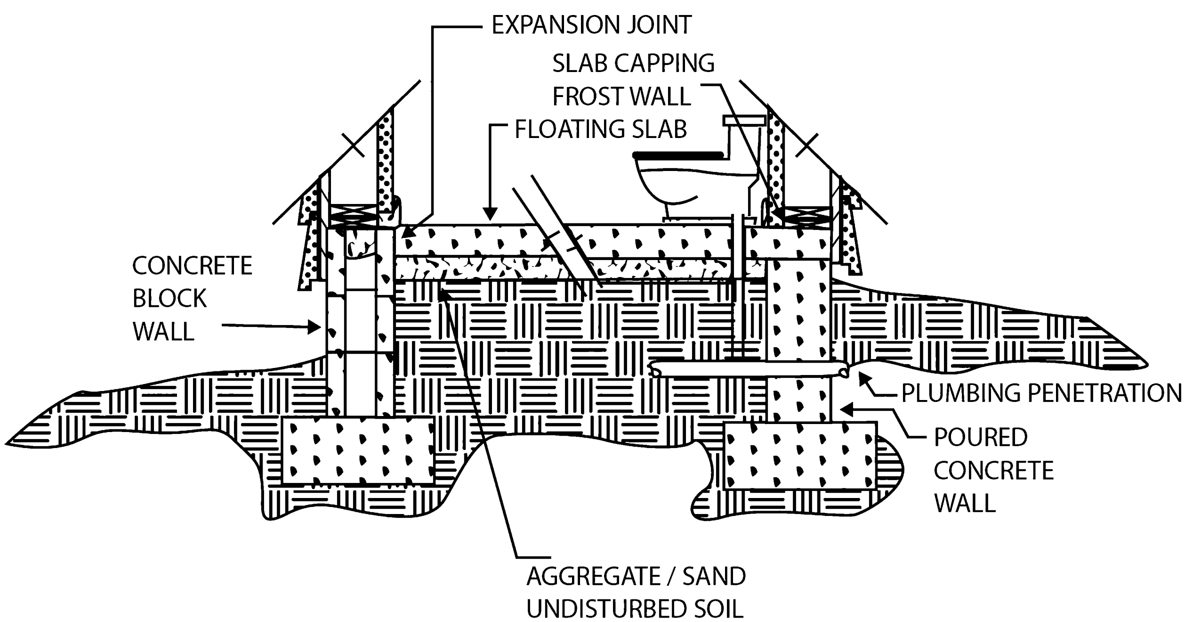


Figure 2-13. Slab-on-Grade with Stem Wall, Source: EPA

Basement construction often results in the creation of a highly permeable zone surrounding a very large below-grade surface area. For this reason, basement foundations are likely to have elevated radon levels. Basement walls, as shown in Figure 2-14, may be either block or poured concrete. Numerous potential entry routes exist in basement foundations depending on the materials and design: the top and sides of block walls, form-tie openings in poured walls, slab-wall joints, and service penetrations are typical openings. Where high radon concentrations exist in homes with finished basements, it can be difficult to reach entry routes and mitigation options may be limited.

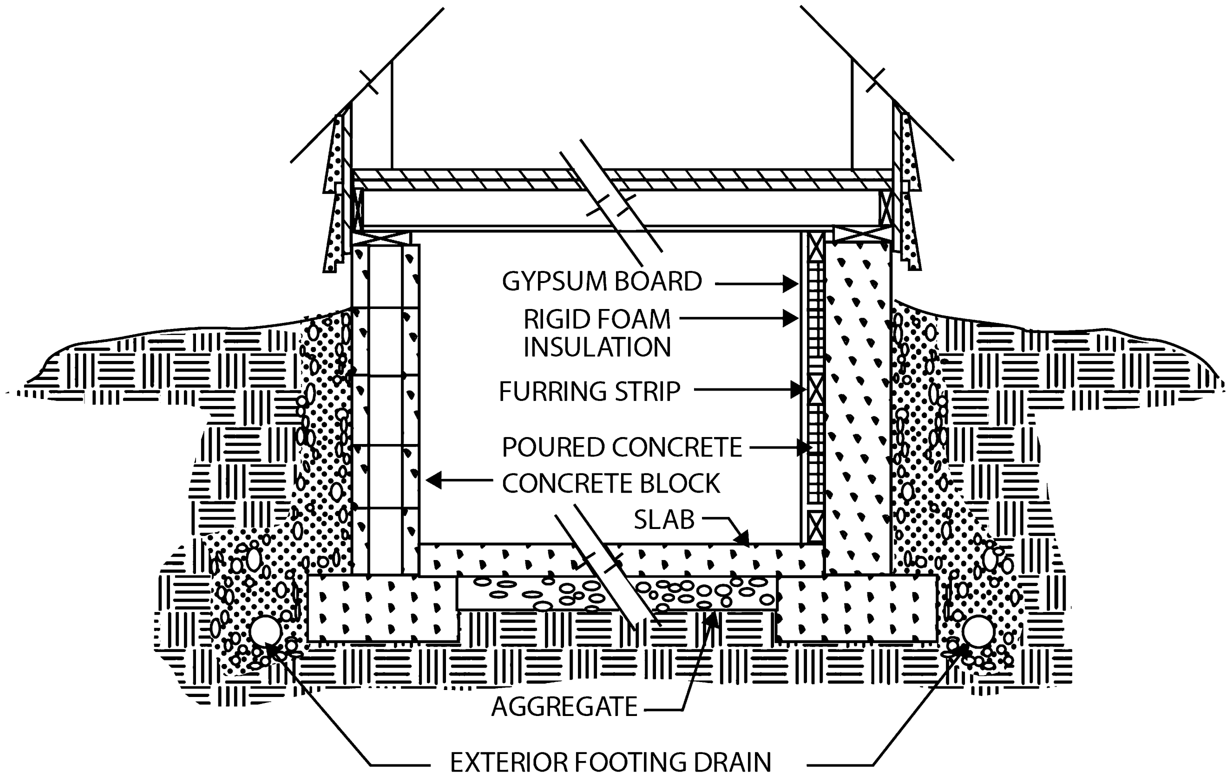


Figure 2-14. Basement Finished/Unfinished Walls, Source: EPA

Combinations of foundation types can present special situations. For example, elevated radon concentrations are often associated with basements having adjacent slab-on-grade areas.

The following foundation openings may allow soil gas to bring in radon:

- The opening between the basement and crawl space.
- Cracks in concrete slabs and walls.
- Sump holes (may be connected to earth, gravel drainage, perimeter drain
- pipes, waterline, or a variety of other transport paths).
- Floor drains (connected as above).
- Holes through slabs under tubs, showers, or toilets where space was left around traps.
- Holes in the slab around pipes.

- Heating ducts run under slabs.
- Pores, cracks, gaps in mortar, and open tops in concrete block walls.
- Holes in slabs where wooden stair stringers or pieces of blocking penetrate the slab.
- Cracks in slab around support columns.
- Support walls for fireplaces.
- Cracks at the floor-wall joint in a basement (especially the perimeter expansion joints and canal drains).
- Cracks around water, gas, and utility entry lines.

Figure 2. -15 summarizes radon entry into buildings, by reviewing transport mechanisms and many of the building openings that typically facilitate radon entry.

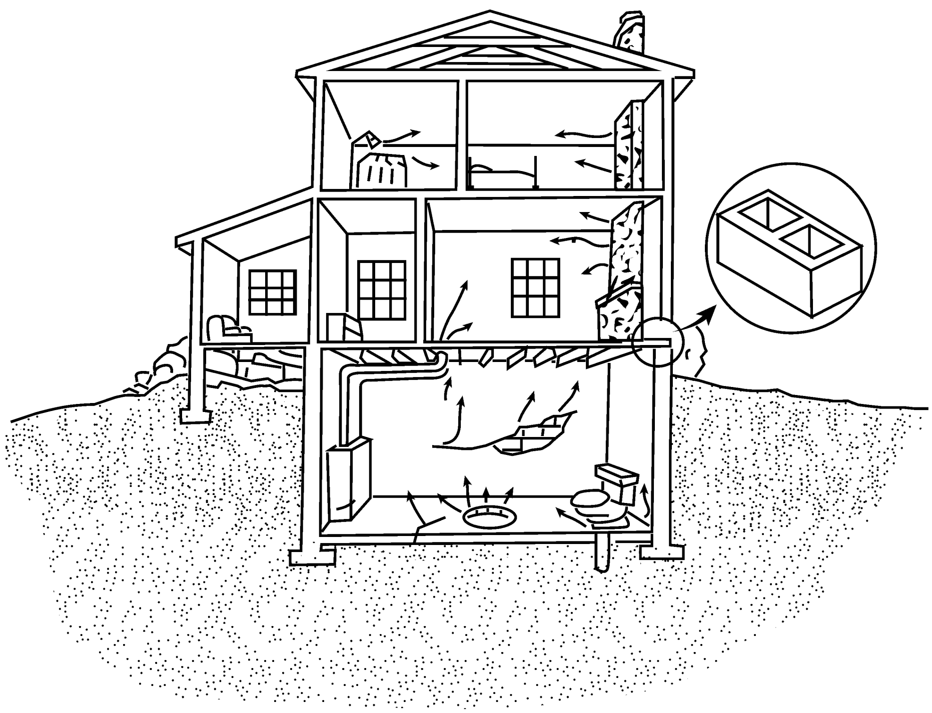


Figure 2-15. Radon Entry Routes, Source: EPA

III. Radon Entry in High-Rise Residential Structures

A. The Problem

In southern Florida, approximately 25% of the radon tests reported to the State from residences on or above the 6th floor exceed 4 pCi/L. Analyses dating back to the late 1980s had determined that concrete would probably not be a primary radon source in Florida residences.

In July of 1988, Florida initiated a comprehensive research program that would produce a radon-resistant building code for new construction. The major focus of research at that time was the elimination of soil gas entry into buildings through their foundations and slab-on-grade floors. The broad-based consensus process common to building code promulgation combined the results of several years of focused scientific research with the practical realities of the construction industry, and developed a standard that did not attempt to regulate the radon production potential of building materials.

As the number of elevated radon measurements from upper floor residences increased, so did concern that a significant radon source or soil-gas entry path was not being addressed. Additional ventilation was introduced to mitigate these residences, and there was a concern that this might create problems of moisture or excess energy consumption. This study attempted to determine the source of the radon and suggest approaches to design or construction that would alleviate the problem.

B. The Study

The Florida Department of Health analyzed the radon measurements database and identified a two-county target area in southwest Florida. Through mailings and a website announcement, each with an invitation to participate, approximately 11 condominium units in a total of 8 buildings were incorporated into the initial pool of possible study units. The members of the project team met and reviewed the characteristics of the initial pool of study units, and agreed upon a target pool of 7 units in 4 buildings for further work (Table 1).

A 3-dimensional representation, or "virtual model," of each of the seven study units was developed and used to calculate the air volumes and surface areas. The primary physical characteristics of each unit are summarized in Table 2-3.

ID	Floor Level	Floor Area (ft^2)	Ceiling Height (ft-in)	Volume (ft^3)	Total Perimeter (ft)	Mitigated
A	20	3,112	9'-2"	28,527	334	Y
B	18	2,282	9'-2"	20,918	245	Y
C	16	2,030	8'-2"	16,579	192	N
D	4	2,772	9'-2"	25,410	281	Y
E	3	2,460	8'-5"	20,705	226	N

Table 2-3. Characteristics of Units Studied

Owners were sent a minimum of 2 radon detectors prior to the inspection to establish a basis for initial radon concentrations in the units. Building information was also gathered from other sources, including active and archived Internet sites such as permitting, property appraiser, and GIS offices within municipal governments. Upon arrival, key measurements were made of each unit and compared to the permit drawings to identify possible chases and hidden floor penetrations, and to establish the areas and volume for the blower door tests. Attempts were made to inspect known or suspected mechanical chases or wall cavities with a borescope where floor or ceiling penetrations would be present. Standard ventilation measurements were made using a Minneapolis Blower Door. Additionally, gamma and radon data were collected in the units, and thermal imaging was used to help identify concealed leakage paths.

C. High Rise Findings

The results of these measurements are summarized in Table 2-4. The total surface area of all interior concrete (slabs, columns, shear walls), concrete masonry walls, and granite materials was tabulated for

ID	VOLUME (ft^3)	FLOOR SLAB AREAS (ft^2)	CONCRETE COLUMNS AND WALLS (ft^2)	TOTAL INTERIOR CONCRETE SURFACE (ft^2)	MASONRY WALL SURFACE (ft^2)	TOTAL CONCRETE AND MASONRY SURFACE (ft^2)	GRANITE SURFACE (ft^2)	ACTIVE SURFACE TO VOLUME RATIO	VENT. RATE (ACH)	MEAS. Rn (pCi/L)
A	28,527	5,640	944	6,584	1,161	7,745	192	0.272	0.16	4.1
B	20,918	4,208	606	4,814	943	5,757	168	0.275	0.18	4.1
C	16,578	3,742	976	4,718	74	4,792	134	0.289	0.09	5.0
D	25,410	5,112	439	5,551	1,282	6,833	167	0.269	0.05	2.4
E	20,705	4,134	759	4,893	1,050	5,943	136	0.287	0.16	4.0

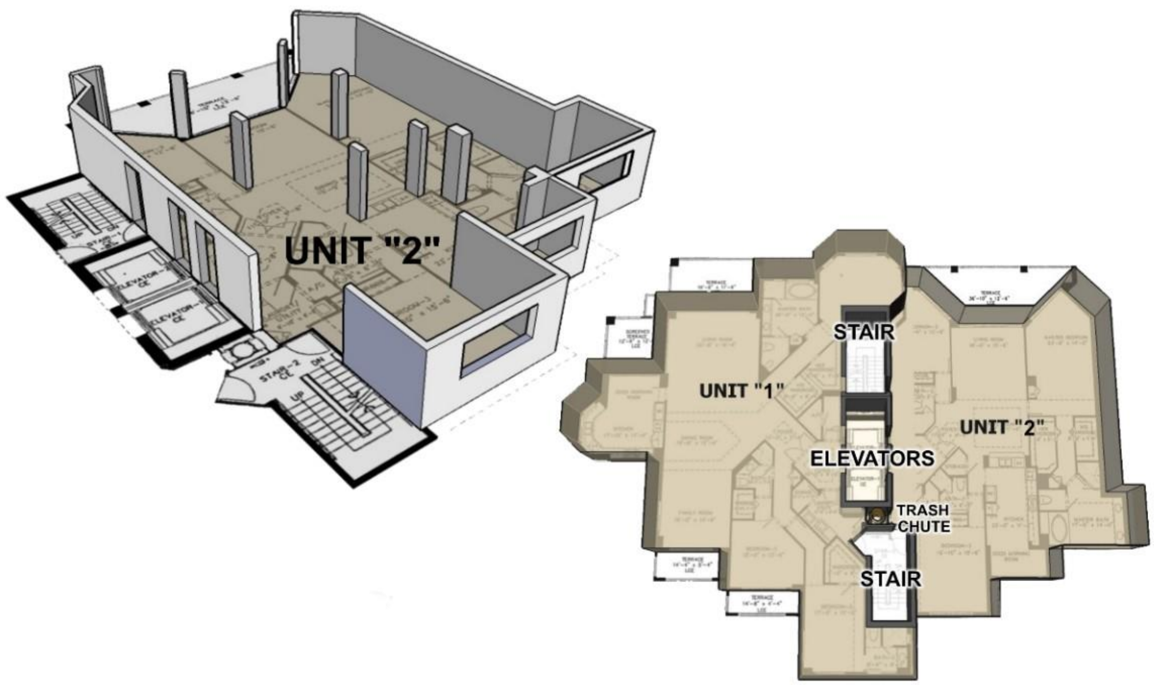
each unit. This was then compared to the volume of the unit, the radon concentration, and the ventilation rate. However, as shown in Figure 2-16, there is substantial room for error in determining the entire contributing area of these materials, since, relative to radon transport, the units are not completely isolated from elevator shafts, stairwells, or one another.

Table 2-4. Radon Levels and Physical Characteristics of Units Studied

Figure 2-16. Architectural representations of floorplans

Interestingly, there is not a particularly strong correlation between any of these characteristics and the radon concentration. Since the data set is small and the measured ventilation is independent of occupant effects, this is not unexpected. Also, it was not possible to measure the pressure differential between units, or the leakage through the planes separating units from one another, because to do so would require access to at a minimum, all the units on a floor.

A concrete core was obtained from the cast-in-place concrete wall of building "E", which, coupled with the ventilation measurements allowed us to make reasonable approximations of the role of the structural concrete as a radon source. Tests were conducted on the concrete sample at the Florida Department of Health laboratory and determined the radium concentration to be 3.1 + 0.2 $pCig^{-1}$.



Using the measured ventilation rates for the study units and assuming 3pCi/g Radium concentration for all cementitious materials based on the test results from the core sample, the effect of increased ventilation on these units can be estimated. An analysis of Florida building materials by others (Nielsen, EPA/600/SR-96/107 December 1996) derived the following simplified equation for estimating the indoor radon concentration attributable to building materials:

$$C\lambda = \frac{3{,}600}{V} \sum_{i}^{n} J_i \cdot A_i$$

where: C = indoor radon concentration caused by concrete materials ($pCi \cdot L^{-1}$)

λ = the building ventilation rate (h^{-1})

V = interior occupied volume (L)

Ji = radon flux from surface i (pCi·m-2·s^{-1})

Ai = area of interior concrete surface i (m^2)

The radon flux (*J*) has been shown by empirical evidence to be closely approximated as 0.041·R where R is the radium concentration of the concrete (pCi·g^{-1}). Substituting accordingly:

$$C = \frac{150}{V\lambda}\sum_{i}^{n} R_i A_i$$

By substitution, the estimated contribution to the indoor radon concentrations from the building materials in each unit are shown in Table 2-5.

ID	Calculated Rn Concentration from Materials (pCi/L)	Measured Indoor Radon (pCi/L)	Percentage Of Indoor Radon Attributable To Materials	Ventilation Rate (ACH)
A	2.6	4.1	63%	0.16
B	2.3	4.1	57%	0.18
C	4.9	5.0	98%	0.09
D	8.2	2.4	342%	0.05
E	2.4	3.4	70%	0.16

Table 2-5. Estimated radon concentration from CEMENTITIOUS Materials

D. Ventilation Issues

Results indicate that at the extremely low natural ventilation rates encountered in these buildings, even moderate radon generation by the structural concrete can produce the measured indoor radon concentrations. Furthermore, previous estimates of the surface area of concrete that contributes to the indoor radon concentration may be substantially understated.

The extremely low ventilation rates are an area of concern, especially because the areas of air-leakage are not well defined. Clearly substantial flow occurs between the units and the elevator lobbies, stairs, and one another. It is reasonable to assume that air coming from these sources carries approximately the same radon concentration of that in the unit being ventilated which effectively increases the emanating area of concrete by a factor of 2 or more. In addition, the foundations of these multi-floor structures consist of drilled piers, which have not been studied in detail with regard to radon. Drilled pier foundation systems should be considered for further study because they could have a substantial effect on the radiological properties of the soils directly beneath the building. Buildings such as those in this study typically have 200 or more piers, usually ranging in size from about 16 to 32 inches in diameter. These piers are frequently drilled to a depth of 30 feet or more. In the largest of the structures incorporated into this study this practice could account for more than 600 yd^3 (500 m^3) of soil beneath the ground floor slab, which may be a concern because phosphatic materials are extensively mined in the study area, and radium-rich soil could conceivably be brought to the surface during the drilling operation.

In these structures, the very low ventilation rates and the large surface areas of concrete in communication with each unit appear to be capable of producing radon concentrations >4pCi/L. Managing the ventilation rate and intra-unit sealing is probably a cost-effective means of avoiding these problems, and may preclude the need for regulating the radium concentration of concrete.

E. References

Contributions of Building Materials to Indoor Radon Levels in Florida Buildings - Project Summary, Kirk K. Nielson, Rodger B. Holt, and Vern C. Rogers, Research and Development EPA/600/SR-96/107 December 1996

IV. Indoor Radon Concentrations

A. Daily and Seasonal Variations in Radon Concentrations

The amount of radon entering the building depends on the factors discussed in the previous sections on radon production, transport, and entry. Due to the number of variables dependent on environmental conditions (pressure differentials and soil gas concentrations depend on wind speed and direction, indoor/outdoor temperature differential, recent rainfall, and operation of mechanical equipment), indoor radon concentrations vary over time (Ref. 5, 6, 9, 12). Figure 2-17 illustrates radon concentrations in a building over a period of several days.

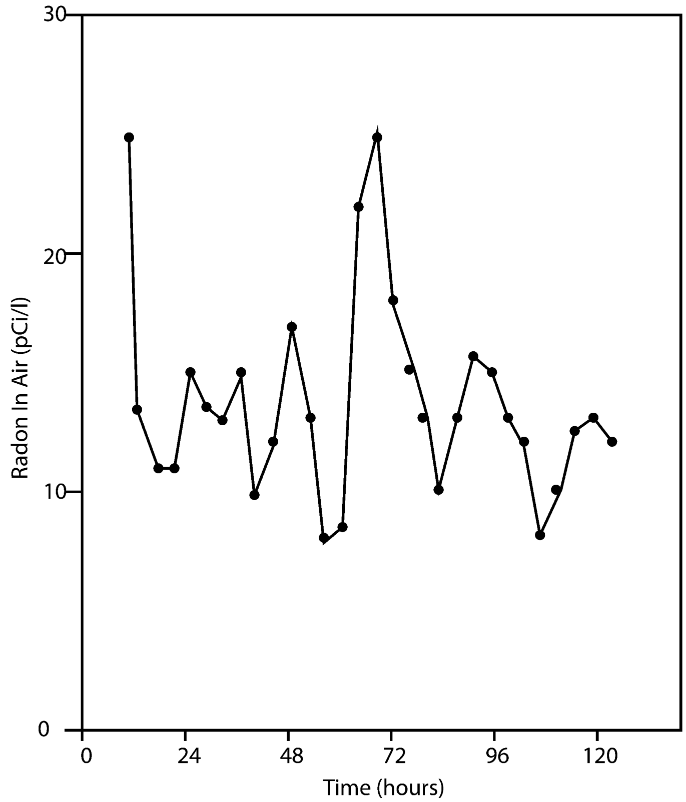


Figure 2-17. Radon Concentration over Several Days, Source: EPA

Notice the extreme variability of the concentration. This diurnal cycle has been observed in many buildings throughout the year. The diurnal cycle does not coincide with ventilation rates, as might be expected; at this point, there is no good model to explain this phenomenon.

Radon concentrations in houses also vary on a seasonal basis. The year's highest radon concentrations may be expected in the heating season, when suction placed on basements is at its greatest and windows and doors are closed. The lowest rates are expected when houses have their windows and doors open so that ventilation rates are high and pressure differentials are equalized. There is some evidence that air conditioning may reduce soil gas entry in warm climates. However, during periods of air conditioning, radon can accumulate to higher levels than those for winter in warmer climates. The colder indoor air is denser than the outdoor air and exerts a positive pressure on the soil. Figure 2-18 shows the winter-summer radon measurements for a group of houses in Spokane, Washington. Here, part of the explanation for the large differences is the open house conditions found in summer in cold climates.

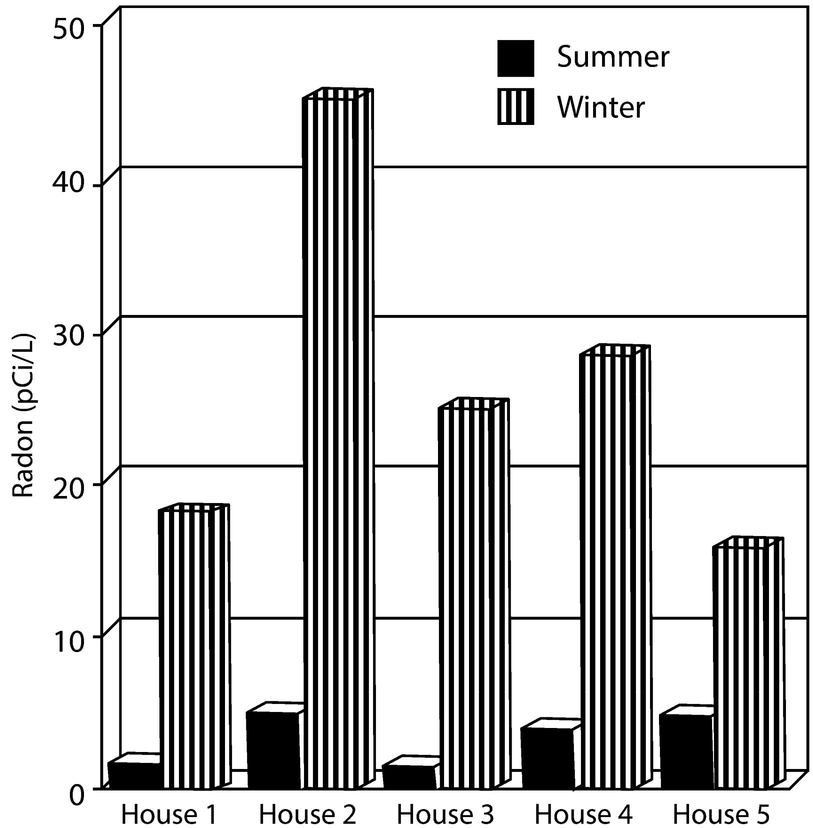


Figure 2-18. Winter and Summer Radon Concentrations, Source: LBL

B. Ventilation Rates and Radon Concentrations

Indoor radon concentrations depend on two factors:

- The amount of radon entering the building.
- How much dilution occurs when radon mixes with house air and ventilation air.

1. Ventilation Rates

The *ventilation rate* measures how much air flows through a building. It is measured either as a volume per. unit time (cubic feet/minute - cfm - or cubic meter/second - ems) or as the number of times the enclosed air volume changes in an hour (air changes per hour - ACH). For the purposes of this course, air changes per hour will always mean air exchange *with the outdoors.* In commercial heating and ventilation, air exchange *wholly within the building* is also given in air changes per hour. This kind of air exchange only affects radon distribution within the building. This must be carefully distinguished from air exchange with the outdoors. In commercial work, air brought in from the outside is often called make-up air. Here, we are interested in radon removal from the building, so we will be concerned mainly with air exchange with the outdoors.

As with airflow through soils, the differences in air pressure between inside and outside of the house drive airflow into or out of a building. These pressure differentials are produced by the same mechanical and environmental factors involved in soil gas entry (see Section II.B.1, Air Pressure Differentials). These are:

- Mechanical equipment
- Temperature differentials between inside and outside air
- Wind.

Air enters and leaves a building through the cracks and holes in the building shell. The typical U.S. house built within the last 30 years has an *effective leakage area (ELA)* of between 1 and 2 square feet, resulting in average infiltration rates of 0.4 to 1.0 *air changes/hour* (Ref. 9, 10, 11). Some newer houses are much tighter, with air exchange rates of 0.1 ACH and ELA's of 10 to 50 square inches. The greater the pressure differences, the greater the airflow through the house.

2. How Ventilation Rates Affect Radon Concentrations

It is often assumed that the lower the air exchange rate in a house, the greater isthe radon concentration. This assumes that radon's source strength does not change. Several studies have been conducted by measuring radon concentrations and air exchange rates over the same time period. *Studies where ventilation rates were actually measured showed no correlation between tightness of house and elevated radon concentrations.* This is because changes in the ventilation rate of a house cause many side effects: the neutral pressure plane will be moved; and the negative pressure driving the radon entry will be changed. Reducing the air exchange may even involve sealing of some of the radon entry routes, since these openings also contribute to air exchange.

The following sections present relevant data drawn from studies of groups of houses and studies of individual houses.

3. Studies of Groups of Houses

Figure 2-19 shows air exchange rates plotted against radon concentrations for 250 buildings. The houses are scattered across the country, and the data was taken from three studies. Contrary to expectations, houses with lower air exchange rates do not seem more prone to elevated radon levels. Very low radon concentrations are· commonly seen in very tight houses, whereas elevated levels of radon are often seen in the leakiest of houses.

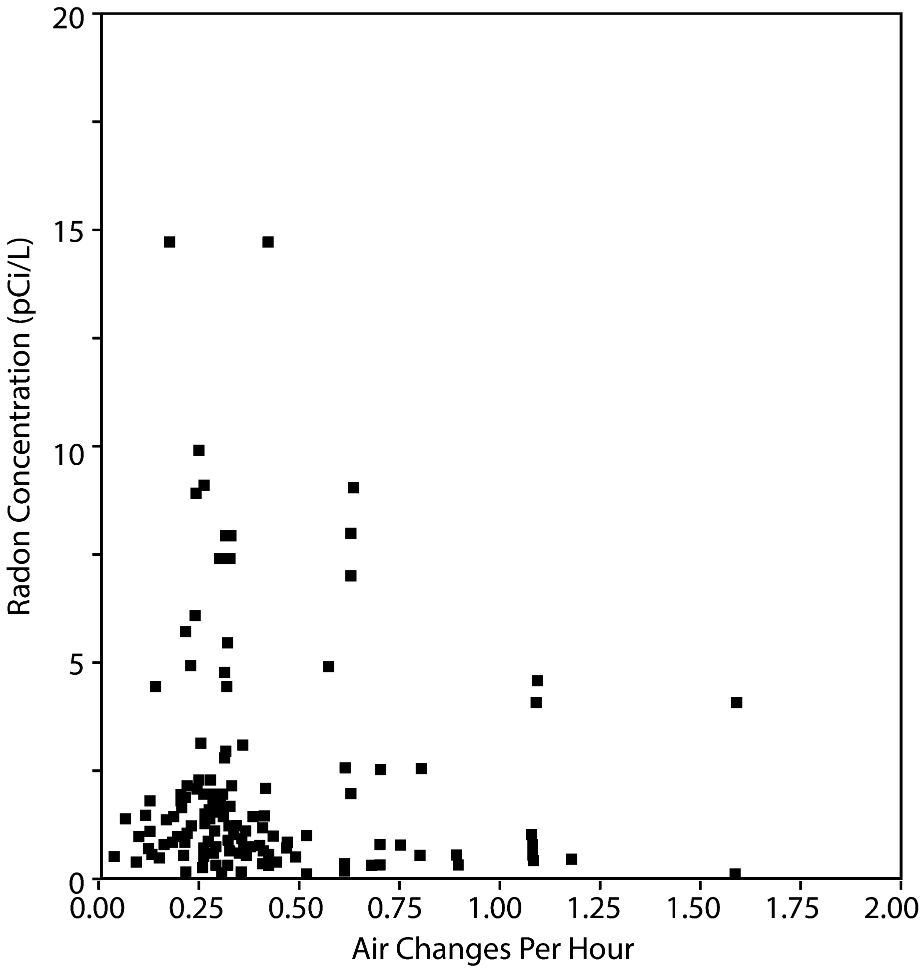


Figure 2-19. Air Changes vs. Radon Concentrations (Three Studies: LBL, S.S. Flemming, Wagner)

Figure 2-20 presents the results of a study completed by the Bonneville Power Administration (BPA) on 250 experimental and control houses (Ref. 3). The experimental houses were built to a model energy conservation standard and are identified by a circle on the graph. The control houses were normally constructed houses, with no special energy conserving features. All these houses were constructed within the three-state-BPA service area. This graph is very similar to the one in Figure 2-19; there is a great deal of scatter and no trend showing a dependence of radon concentration on air exchange rate.

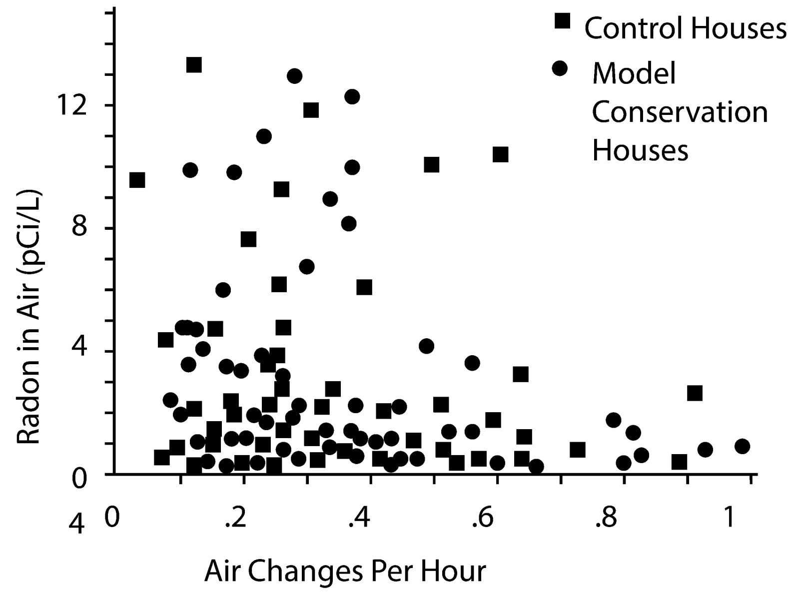


Figure 2-20. Air Changes vs. Radon Concentrations in Control and Model Conservation Houses, Source: Harris/BPA

The simple model doesn't work for groups of buildings, because it assumes somewhat similar source strengths for every house, which is simply not the case. For groups of houses, the variance in radon source concentrations and entry rate (the product of radon source concentration and ventilation rate) is much larger than the variance in the ventilation rate. This leads to the conclusion that *ventilation rate is not a variable which can be used to predict radon concentrations in houses.*

Like many other indoor air contaminants, it is the source strength which determines levels found in the building. If there is no source, a building can be virtually airtight and have no problem. If there is a strong source, even the leakiest of buildings may have a problem. For example, to dilute one of the higher buildings found in New

Jersey or Pennsylvania from 1,000 pCi/L to 4 pCi/L, you would have to increase the air exchange rate from 0.75 ACH to 187.0 ACH.

4. Studies of Individual Houses

Studies measuring natural ventilation rates (infiltration) and radon concentrations concurrently in an individual building do not show a connection between radon concentration and air exchange rates.

Figure 2-21 presents a graph of radon concentrations versus air change rates for a single building in the Pacific Northwest. The measurements are 7- to 10-day averages (Ref. 13).

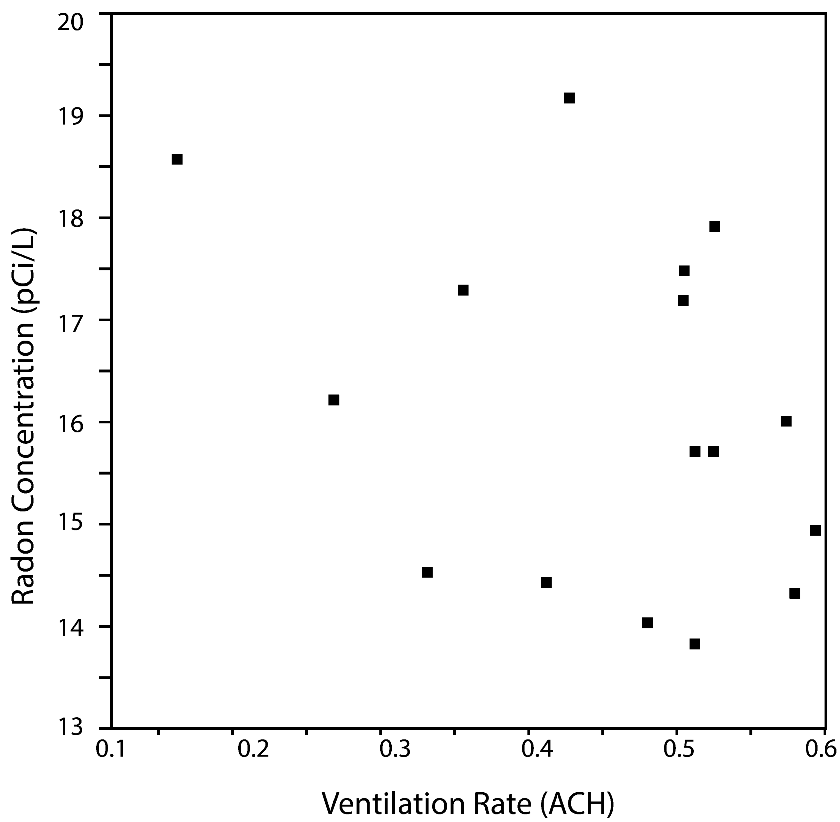


Figure 2-21. Radon Concentration vs. Natural Ventilation Rate for an Individual House, Source: Lawrence Berkeley Laboratory

Another study tracked a house in Maryland monitoring for several indoor air contaminants (Ref. 7). When the house was retrofitted to cut the leakage rate in half, the levels of radon didn't double as expected but went up by 20 percent. The other contaminants didn't show any change greater than the experimental error of the measurement methods used.

Part of the explanation for the scatter in the data in individual houses is because the same variables that affect ventilation rate also affect the entry rate of radon. Pressure differentials produce the airflow through houses which dilutes the radon but also produce the airflow through soils which brings a large part of the radon into the house. The resulting concentration will depend on how much the entry rate increases relative to the increase in ventilation rate. Even that could change depending on wind direction, the location and size of the leaks in the building, where the radon source is located, and how entry paths are connected to each other. This is a complex problem with many variables.

In summary, there are two important factors in understanding why the simple air contaminant/ventilation rate model is incorrect for radon in buildings:

- *The source strength varies substantially from area to area and largely determines the concentration of radon.* For ventilation to be an important indicator of radon concentrations, houses would need to be built with a range of ventilation rates 10 times greater than they are at present.
- *The same mechanical and environmental factors that power air exchange rate (wind, temperature differential, and mechanical exhausts) also power the entry rate of radon*. The effect of increased ventilation is counteracted by increased radon entry.

Activity: Radon Entry and Behavior

Directions: The drawing below (Figure 2-22) depicts the home of a potential client at the time you first arrive to investigate a reported radon problem. List each factor you see that will affect radon concentration at the specific time shown on the drawing and indicate what effect it will have.

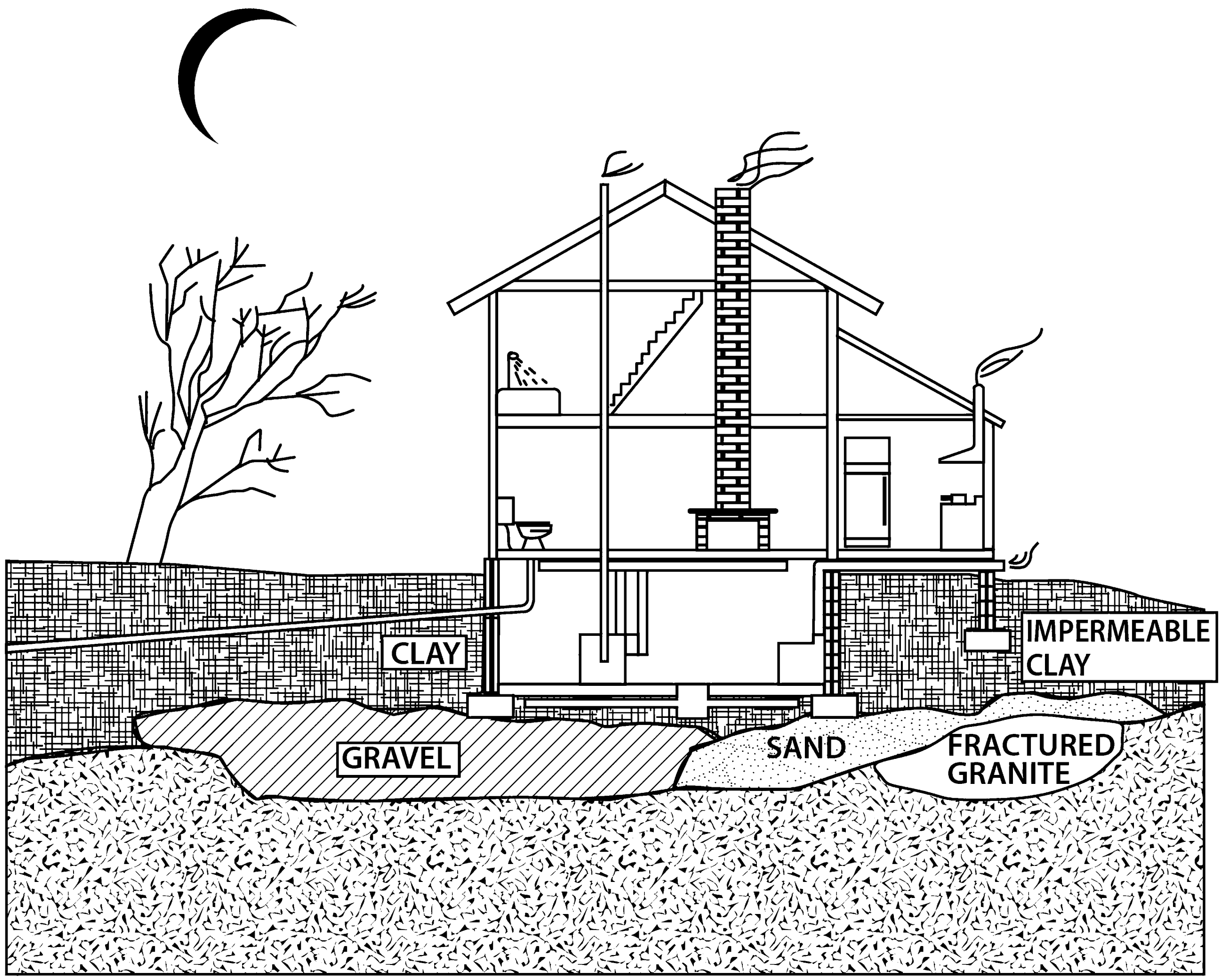


Figure 2-22. Radon Dynamics, Source: EPA

References

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Review Questions, Unit 02, Dec 2003, Form A

1. Which of the following driving forces is always present?

   A. high pressure weather systems

   B. rain-induced soil gas convection

   C. wind-induced air pressure differentials

   D. concentration gradient diffusion from soil to indoor air

2. What building construction features increase stack effect?

   A. crawl space foundations, hollow block walls, plumbing chase

   B. electrical wiring penetrations, plumbing chase, recessed lights

   C. frame construction, monolithic slab floors, sub-slab heating and air conditioning ductwork

   D. hollow block walls, monolithic slab floors, recessed lights

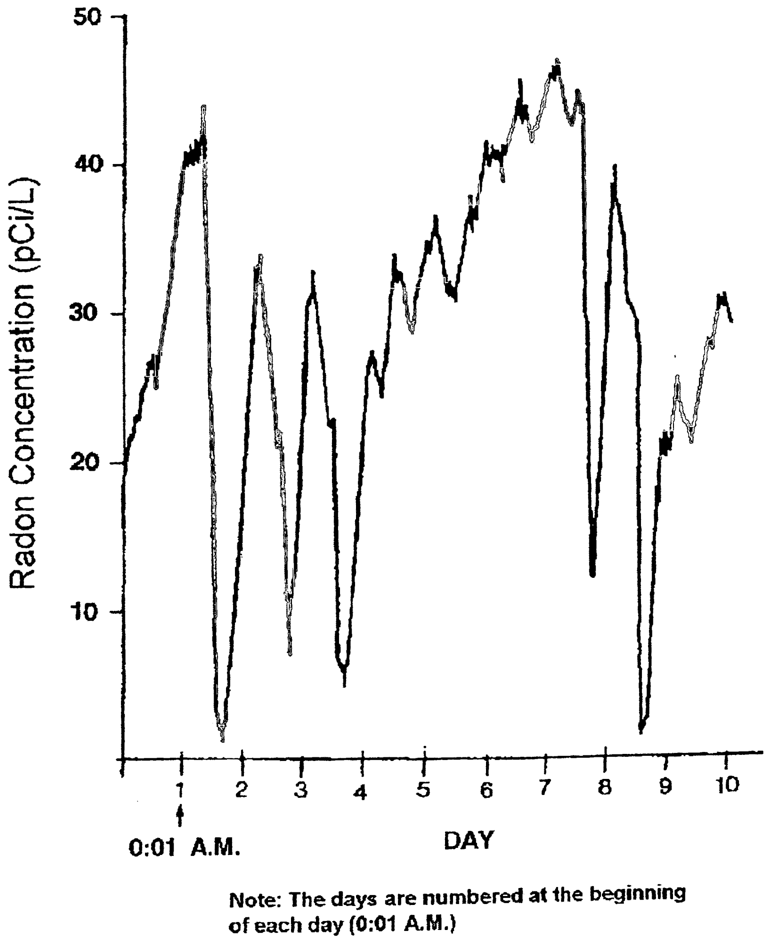

Figure 203.

3. What factor BEST explains the variations of diurnal radon concentrations from day 1 to day 4 illustrated in figure 203?

   A. highly variable winds occurring from day to day

   B. rain showers occurred each evening

   C. the radon concentration in the soil gas varied diurnally

   D. all the windows were opened to ventilate the house during the day

Answers to Review Questions, Unit 02

Review Question	Answer	Student Manual, Unit 02, Page Number
02. 1	D	5-17
02. 2	B	9-11
02. 3	D	21-28