COLORADO
Department of Public Health & Environment

Measuring and Mitigating Radon in Colorado

May 1, 2018

A Technical Guidance for Colorado Building Conditions

OVERVIEW: Radon Fundamentals and Occurrence

TECHNICAL GUIDANCE DOCUMENT: Measuring Radon in Single-Family Homes, Multi-Family Dwellings, and Large Buildings in Colorado

TECHNICAL GUIDANCE DOCUMENT: Installing Radon Mitigation Systems in Single-Family Homes, Multi-Family Dwellings, and Large Buildings in Colorado

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1.1 Executive Summary

This document provides a technical basis regarding what is known about the measurement and mitigation of indoor radon from soil-gas sources, particularly focused on the conditions in Colorado.

It is intended to be a reference for those working in, and making decisions about Colorado new and existing residential homes and large buildings so there is clear and consistent:

- Understanding of the technical basis for measuring and reducing radon exposure in both new and existing residential homes and large buildings;
- Awareness of the various standards and building codes and how they can best be applied or modified to address Colorado building practices;
- Knowledge of how to properly test for and reduce radon in both new and existing residential homes and large buildings; and
- Active consideration and incorporation of innovative, cost-effective, Colorado-specific approaches to reducing radon exposure in both new residential homes and large buildings during construction

Radon is a naturally occurring gas most often derived from the breakdown of natural deposits of Uranium 238, which is commonly found in many geological formations, including the granite that forms the Rocky Mountains and nearby plains. A chemically inert gas, it can be drawn into buildings due to vacuums caused by natural thermal stack effects, building exhaust systems or episodic weather conditions. Increased indoor radon levels pose a significant health concern (i.e. lung cancer) for many individuals. Applying techniques described in this document can reduce the risk of radon exposure.

All structures in Colorado have the potential for elevated indoor radon levels, regardless of building type– including homes, office buildings, schools, apartment complexes and childcare facilities. The only way to know about the radon level in a building for sure is to have the building tested for radon. Once indoor radon levels are confirmed, they can be controlled by limiting radon's entry into a structure. Radon typically is mitigated with an active radon system equipped with a fan that extracts radon-laden soil gases from beneath the building, then exhausting it to a proper location outdoors. In Colorado, there are a number of construction features not necessarily found elsewhere in the country, such as perimeter drains that can effectively mitigate radon, and large-slab expansion joints needed due to expansive clays that cause additional challenges when mitigating a home. In fact, due to large openings found in Colorado foundations, attempting to seal out radon simply by closing the openings is not effective unless combined with a vacuum mechanically applied to the subgrade to extract radon gas. Large heating, ventilation and air conditioning (HVAC) systems can exacerbate a radon concern, but also can be used to fix the problem while also addressing other indoor air quality issues. Readers confronted with radon concerns in large buildings, such as schools, should look to HVAC system repair prior to installing mitigation systems. This approach can save the owner significant costs and reduce long-term maintenance obligations by avoiding additional mechanical systems within the building.

Lastly, through the assistance and inventiveness of many Colorado homebuilders, techniques for installing radon systems during construction have been well researched. Although there is national guidance, local experience in Colorado and the Rocky Mountain West has shown that some elements of the national standards are not necessarily needed unless already prescribed for other reasons. One example is the application of a well-sealed vapor barrier beneath a slab that can cause slab shrinkage in a dry climate, which provides little benefit over the proper sealing of the slab itself. Another example is the automatic use of large aggregate under slabs, which can be expensive to import (especially in the central mountains); whereas smaller aggregate sizes have been shown to work just as well, and in some cases no special aggregate is needed if surface water collection systems are incorporated into the radon-control scheme.

These are just a few of the examples of the specific items contained within this guidance document. However, regardless of the techniques utilized, the efficacy of the systems must be verified through post-mitigation or post-construction radon testing. Furthermore, the longevity of radon-producing materials found in Colorado's geology require long-term monitoring and surveillance programs for homes, schools, etc., that have been mitigated – especially if they are modified in the future.

Yes -- radon is a concern in Colorado, as well as elsewhere; but thanks to the efforts of many researchers and practitioners, we can now say with certainty that all Colorado homes and buildings can be fixed utilizing the techniques described within this guidance.

1.2 Introduction

Since the 1980s, the private and the public sector have done much to develop methods to measure and control hazardous levels of radon in indoor environments. Initially, radon concerns were thought to be isolated to portions of the Rocky Mountain West, Eastern Pennsylvania, and New Jersey. However, as more data was collected, the areas of concern expanded until radon became a worldwide concern.

Repeated epidemiological studies confirm the health risk of radon exposure and its decay products in residential settings. A significant, yet preventable environmental health risk, radon now is classified as a Group A Carcinogenic Agent (known to cause cancer in humans). These factors led the real estate inspection industry to incorporate radon testing into its practices, as well as the birth of an industry to fix structures with elevated radon concentrations.

With the birth of the radon measurement and mitigation industry in the early 1990s, a need existed for standardized procedures to avoid inappropriate measurement and mitigation approaches. This need was initially met by the U.S. Environmental Protection Agency (EPA) and more recently by the American Association of Radon Scientists and Technologists (AARST). These efforts have produced a number of documents of benefit to the radon professional as well as the consumer. However, information in older documents may not represent currently available technology. Furthermore, these documents were written as prescriptive national standards and, understandably, do not fully detail the regional differences attributable to climatic or geological conditions and local construction practices.

Because elevated radon can affect home sales, commercial buildings and public facilities such as schools and childcare facilities, the radon industry has needed to develop innovative solutions. Thanks to progress in the field, one can now say that indoor radon levels can be reduced to less than the current U.S. EPA guidance of 4.0 pCi/L.

Now that we know how to fix radon, the next objective is to cost-effectively apply techniques that have evolved over the last 30 years consistent with Colorado construction practices to provide durable and long lasting solutions to radon concerns.

1.3 Scope

This document addresses two primary topics:

- How radon is identified and measured; and
- If found to be a concern, how radon or its decay products are reduced

These topics will be described within the context of single-family homes, multi-family dwellings and larger buildings such as schools and commercial structures. Furthermore, this document will describe how these two topics can be addressed during construction.

The document provides a foundation for understanding by decision makers and building professionals. It does not go into all the details and potential scenarios that may exist in any given building or construction project, because radon professionals have the experience and training to fill that gap and should be called upon as a resource and team member when addressing radon issues. This document is designed to provide a bridge of understanding between radon professionals and others involved in resolving radon concerns.

As a technical document with a focus on how one measures and mitigates radon, it will not deal with the health effects of radon in an exhaustive manner, nor does it need to - as there are numerous agencies that have studied and presented peer reviewed papers on the health effects of radon. Furthermore, state health departments as well as many federal and international agencies have provided guidance for exposure to radon for both the general public as well as occupational settings.

The scope of this document is first to assure that a proper assessment of radon is made so individuals can compare their exposures to guidance and if they decide to reduce those exposures, to be able to do so reliably.

1.4 Acknowledgements

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We are honored to create this document and look forward to multiple editions as innovative builders, scientists, building officials and radon practitioners continue to improve the science.

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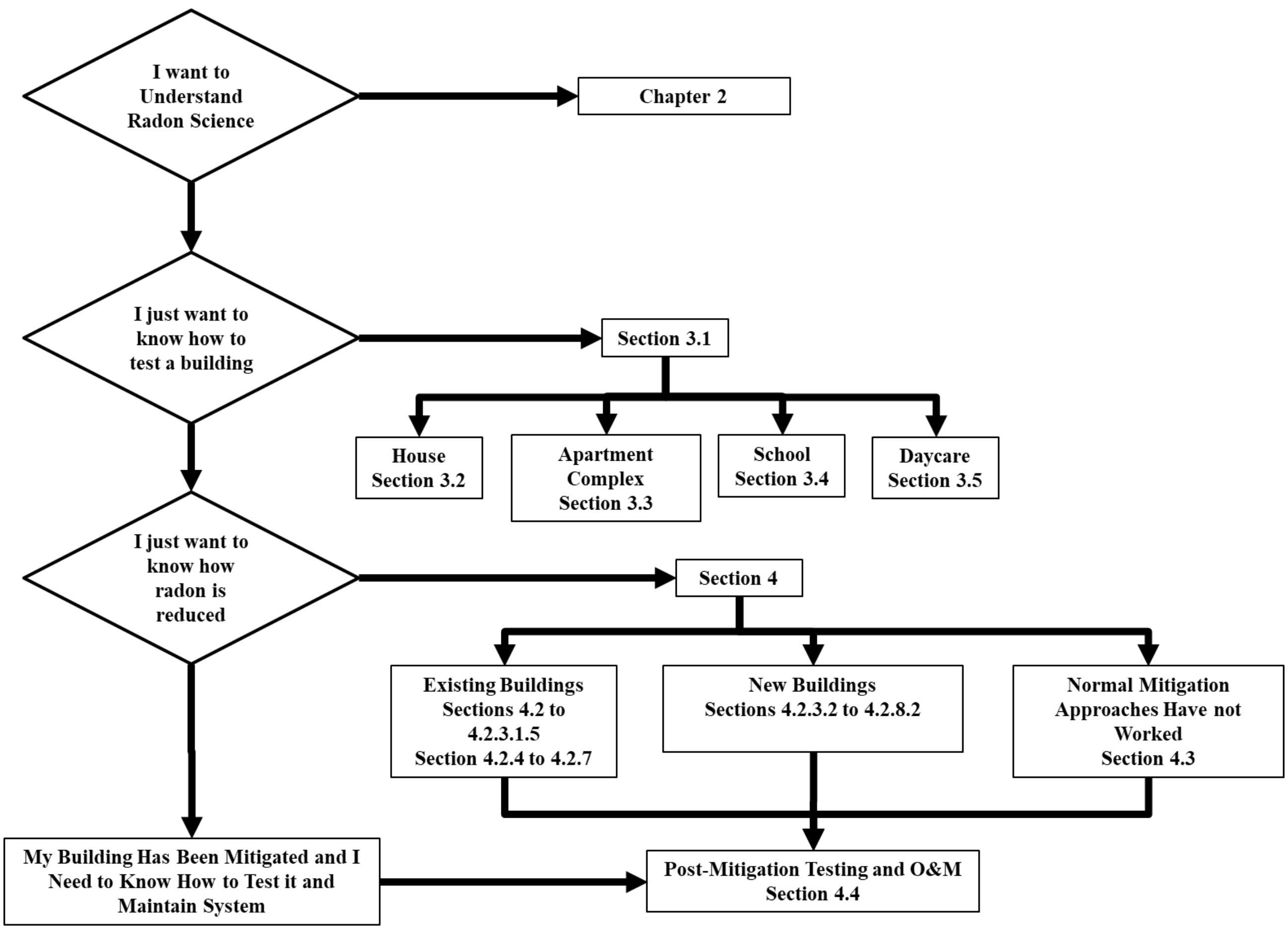
1.5 How to Use This Manual

For those who want to understand the "why" of radon measurement and mitigation and want to delve into the science of radon, Chapter 2 provides that basis.

For those who want to get the job done without getting too deep into the science, the "how to," has been provided in subsequent chapters. That does not mean if you are streamlining your efforts to get the job done that you can't refer back to Chapter 2. In fact, digging deeper may be prudent when questions arise.

The flow chart below provides a roadmap of how this document can be used without the need for reading it cover to cover.

Figure 1: Roadmap for Using This Manual



2 RADON FUNDAMENTALS AND OCCURRENCE

A Basis for Understanding:

- The Effects of Radon
- How Radon Enters a Building
- What Influences Indoor Radon Levels
- Basis for Radon Measurement and Mitigation Approaches

2.1 Radon Science

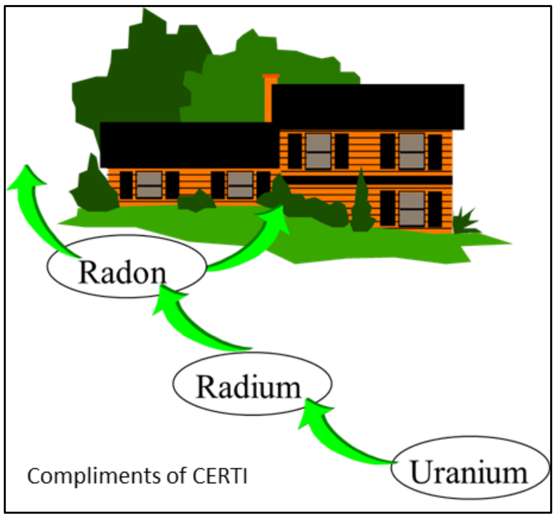
To understand how radon is measured and mitigated one must understand what radon is and how radon behaves. This chapter will cover the relevant basics without delving into higher-level physics discussions.

2.1.1 Radon: What it is and what it isn't

- Radon is a natural decay product derived from naturally occurring Uranium 238.
  - It is not a manmade pollutant.
  - It is not more prevalent around landfills or Superfund sites.
  - Uranium 238 is not the kind of uranium from which one makes bombs (that is U234).
    - So, if you have a radon concern in your house you shouldn't get excited about mining for uranium in your back yard.
    - Nor should you be concerned about eating vegetables from your yard if your home has elevated radon.
- Radon is an inert gas, which means it does not react chemically with other elements to form molecules.
  - It does not attach to other things so it is free to move through permeable soil.
  - Since it does not form molecules, it is a single atom and therefore can pass through the smallest of openings, including foundation cracks you can't see as well as the ones you can.
- Radon is a gas.
  - It moves like any other gas.
  - It can be pushed or pulled by increases or decreases in air pressure.
- Radon is an unstable atom.
  - It decays into other elements (see below).
  - The decay products of radon are highly unstable and release radiation as they decay further.
- Radon has a half-life of 3.8 days.
  - That doesn't mean it disappears after 3.8 days. The Uranium 238 under a building, which has a half-life of essentially four billion years, is constantly replenishing the supply of radon. Therefore radon is controlled through mitigation rather than source removal.
  - After a house is closed up, radon does not continue to build up, since it is subsequently decaying into its decay products and some is also being diluted due to normal house ventilation.
- Although radon is heavier than air, it does not layer out in a home like gas vapors.
  - The concentration of radon in air does not affect the overall density of air like organic vapors can.
  - Radon is indeed higher in the lowest level of the home, but that is because that is where it first enters the home before being diluted as it moves to upper levels of the home.
- Radon comes from the underlying geology containing Uranium 238.
  - Radon can enter any home in contact with the ground.

- Radon enters the outdoor air around the home.
- Radon can be measured in the outdoor air.
- The concern is when it preferentially is drawn into a building and where people can inhale the decay products of radon, which can damage lung tissue and increase the potential for lung cancer.
- Radon is measured in units of pico Curies per liter, abbreviated pCi/L.
  - This is a measure of the rate of radioactive decay per unit of time per liter of air or liter of water. (See Physics section 2.1.3 below).

Figure 2: Radon Entry from Soil



• Radon comes from the normal decay of naturally occuring uranium in the underlying geology. • As a gas, radon can move through soil and enter the atmosphere where it can be diluted, or it can enter a home where it can present a health risk.	• Radon is unstable and further breaks down into decay products that are radioactive solids that can be inhaled.. • Over time, inhaling radon decay products can increase the potential for lung cancer.

2.1.2 Sources of Radon

2.1.2.1 Geological

The primary source of indoor radon is from the natural occurrence of uranium in the underlying geology. In the Rocky Mountain West and other mountain regions, the granite geology that provides our tremendous vistas also can have elevated levels of radon-producing uranium 238. This mineral presents a higher potential for elevated indoor radon in structures constructed in the mountains, as well as in plains regions where the sands from the eroding mountains have settled.

Radon also can be found in many of the clay formations in the foothills and beyond. One would think these clays would retard the entry of radon laden soil gas, but numerous structures over clays and other surface soils have shown elevated indoor radon levels.

Early mapping in the 1980s fooled everyone. Attempting to determine where one should test or fix a home solely on the basis of geology does not work because there are so many additional variables that result in a building's actual radon levels.

The only way to know if indoor radon is elevated is to test the building

The only way to determine indoor radon levels is to test the building.

2.1.2.2 Radon from Water

Radon can also be conveyed into a building via a groundwater supply.

- Radon gas dissolves into the groundwater in contact with radon-producing geologies.
    - This problem affects deep groundwater rather than river water running through riverbeds containing granite rock.
    - The dissolved radon gas is held in the water due to the higher pressure in the groundwater.
- When groundwater is directly brought into the building and released at atmospheric pressure such as in a dishwasher, shower or faucet, the radon gas will come out of solution and enter the interior air of the home.
    - Radon from water that irrigates the lawn does not enter the house and is quickly diluted in the atmosphere and is not a concern.
    - Radon in water used for swimming pools also dissipates very quickly after initial filling.
- Once the radon disengages from the groundwater entering a building, it disperses into and throughout the building.
    - As radon expands into the volume of the house, its concentration decreases.
    - Radon in the indoor air, from its water supply is further decreased with normal exchange of outdoor air through ventilation.
- For a normal household with typical water usage, it takes an extremely high amount of radon in the water supply to have an appreciable increase in indoor radon levels.
    - It is assumed that 10,000 pCi/L of radon in the well water will yield, after dissipation and dilution within the building, about 1 pCi/L of radon in the air space.
        - Facilities that utilize a high volume of groundwater on a continuous basis, such as a fish hatchery, can have a significant amount of radon released into the facility and should be well ventilated.
    - Radon from water is typically a minor contributor of the overall indoor radon levels compared to the amount of radon coming from the underlying geology.
- Drinking radon-containing water is not considered to be detrimental.
    - You only drink a couple of liters of water a day compared to inhaling 20,000 liters of air a day. Therefore, airborne radon is a much greater concern than water borne radon.
    - Half of the radon is released from the water as it falls from a faucet into a glass – leaving much less to be ingested.
    - Cooking with radon-containing water will definitely strip out the radon.
- Caution: Radon-containing water may also have other contaminants such as radium or uranium. If your building has elevated radon in its water supply, you should also test for heavy metals, which can cause health impacts.

- Radon from water can be treated, but requires highly specialized skills to maintain water quality.
    - Fortunately, the need to do this is extremely rare.
    - Due to its rarity, approaches to radon in water reduction are not addressed in this document.
    - Contact the state health department and a radon professional if you have concerns about radon in water.

2.1.2.3 Radon from Building Materials

Because radon is derived from natural minerals found in the soil, it stands to reason that building materials that incorporate these materials can also be a source of indoor radon.

Examples of potential building material sources include:

- Concrete containing high-radium aggregate.
- Spent mill tailings from uranium processing plants
    - After uranium-rich ores are processed, the processed aggregate can still contain significant quantities of radon-producing minerals.
    - In the past, these spent materials were used as backfill or incorporated into concrete used for building foundations in locations near uranium processing plants.
    - The use of uranium mill tailings as building materials occurred in locations on the western slope of Colorado.
    - The use of uranium mill tailings as construction materials has been curtailed.
    - Many structures having these materials have been fixed via the Uranium Mill Tailings Recovery Act. However, older homes whose owners did not participate in this program may still have issues.
        - This is very rare and locations where this practice occurred are well known. Contact your state health department if you feel you may be affected.
- Granite materials utilized within a home such as for floor tiles or countertops have recently been implicated as radon sources.
    - Although interior granite materials can release some radon, the amount released is typically low enough that the normal air leakage into a home will sufficiently dilute it.
    - If you have granite materials in your home, they are not likely a radon concern. However, the normal radon measurement techniques identify radon contributions from both the underlying soil and building materials, and if elevated, a radon professional can conduct additional tests to determine if the contribution from building materials is significant.

Unless the building material is extremely high in radium (as in the case with uranium mill tailings used in construction), the contribution of radon from building materials is minor compared to the introduction of radon from the geology and soil beneath a building.

2.1.2.4 Radon Diffusion

Although not a significant source of indoor radon, radon gas can actually penetrate via diffusion through building materials in contact with radon-producing sources.

An example is a concrete slab sitting directly upon soil containing a high amount of Uranium 238. In this example, the soil could have extremely high levels of radon, which would diffuse through the concrete even where there are no cracks or openings. The rate of diffusion through this concrete slab would be very slow compared to the normal exchange of air into a building, which would typically dilute this contribution to where it would have a negligible effect on indoor radon levels.

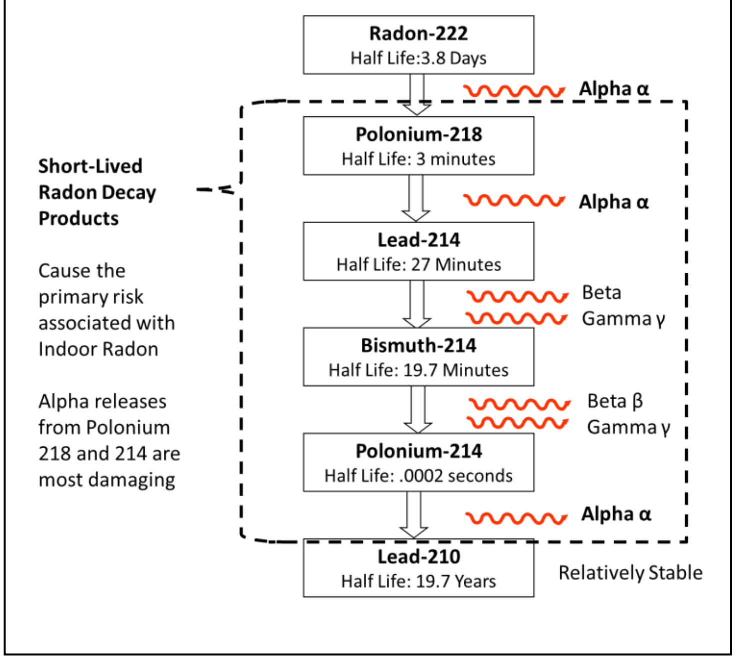
2.1.2.5 Comparison of Radon Sources

The major contributor of radon in buildings comes from the underlying, natural geology, where soil air containing radon enters via openings in the foundation and hence is the major focus for the measurement and mitigation of radon. There are exceptions, such as radon from water supplies or from building materials as well as diffusion through building materials. Fortunately, these latter occurrences are rare, but definitely require a radon professional to assess and address them.

2.1.3 Physics of Radon Decay

The concern with radon is not its chemical characteristics, as is the case with contaminants such as arsenic or lead, but rather with the particles emitted as radon decays, which can damage lung tissue. So radon measurements are essentially measuring the rate of decay of radon and its subsequent decay products, rather than a mass fraction of radon in the air or water.

Figure 3: Radioactive Decay of Radon



2.1.3.1 Radon Decay Series

This diagram shows the elements that radon changes into as it radioactively decays to a stable nuclear configuration. Note that alpha, beta or gamma radiation is released with each decay step. The alpha particles are the greatest health concern compared to the beta and gamma radiation. However, many of the laboratories that measure radon decay rates measure the gamma or beta emission rates.

The relative stability of the elements in the decay series is represented by their half-lives, which is the amount of time it would take for half of a given quantity of that element to transform into the next decay product. The lower the half-life the more quickly it will decay and release its radiation after it is formed.

2.1.3.2 Radon Decay Products

It is actually the decay products of radon (polonium 218 and 214) that present the primary health risk associated with indoor radon, because they have such short half-lives and emit alpha particles that can damage sensitive lung tissue when inhaled (Section 2.1.4).

Given the fact that radon decay products represent the primary health risk, it is worth describing their characteristics in more detail.

- Once formed, the radon decay products (RDPs) have strong electrostatic charges and will readily attach to particles suspended in the air or to objects such as walls and floors.
- The effect of this attachment is to alter the amount of RDPs available for inhalation, increasing or decreasing the health risk associated with a given amount of radon present.

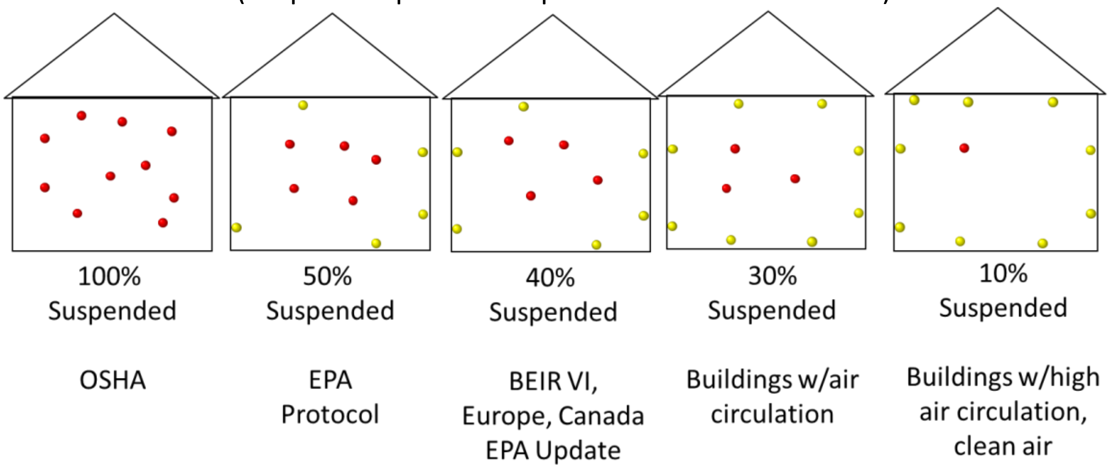
Table 1: Factors Affecting Radon Decay Products Suspended in Air

RDP Attachment to	Physical Effect	Health Effect for Constant Indoor Radon
Suspended Dust	Increases RDPs in the breathing space	Increases Exposure
High Air Circulation Rates	RDPs more easily come in contact with surface of ductwork, walls, floors, etc., to which they attach and reduces RDPs in the breathing space	Decreases Exposure
Stagnant Air	Fewer RDPs come in contact with ductwork and objects — more stay suspended in air	Increases Exposure
Air Cleaners	Higher air circulation and passage through air cleaners or higher grade furnace filters reduces RDPs in air via attachment to filter media as well as room objects	Decreases Exposure

- It is assumed that in the average home, 40 percent to 50 percent of the radon decay products formed stay suspended in the air and are available for inhalation.
- Figure 4 illustrates the different assumptions that have been made by agencies or have been observed in different buildings as to the percentage of RDPs that remain in the indoor air for inhalation for a constant level of radon.

Figure 4: Percentage of Radon Decay Products in the Air

(Suspended particles represent the inhalation risk)



- By making an assumption, one is able to estimate the exposure risk from radon decay products by measuring radon gas.
  - Radon gas levels are easier to measure than RDPs.
  - A radon gas measurement estimates the potential exposure.
  - RDP measurements can estimate exposure if building conditions remain constant.
- Recent improvements in buildings to increase air circulation or reduce particulates such as asthma triggers by use of whole-house air cleaners can have a collateral benefit of reducing radon decay product exposure as well as improving indoor air quality.

2.1.4 Health Effects of Radon

There are a number of studies[1] that characterize radon as a health risk, including but not limited to studies conducted by the National Academy of Sciences, the World Health Organization, and other countries. It is not the intent of this document to describe all of these studies, but rather to provide recognized guidance for exposure for the interpretation of measurement results and determining the need for mitigation as well as a method to gauge the success of mitigation efforts.

Prolonged exposure to the decay products of radon increases the potential for lung cancer. Although there have been studies to suggest that other diseases may be caused or induced by radon, the vast majority of research has linked radon to lung cancer and due to the severity of lung cancer, it is considered the primary health concern associated with radon exposure.

[1] World Health Organization, WHO Handbook on Indoor Radon, 2009 (radon-worldhealth.org)
U.S. EPA and American Medical Association, Physician's Guide to Radon (https://www.epa.gov/radon/physicians-guide-radon)
National Academy of Sciences, 1991. *Comparative Dosimetry of Radon in Mines and Homes.* National Academy Press, Washington, DC
A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon, (https://www.epa.gov/radon)

2.1.4.1 Mechanism of Radon Induced Lung Cancer

In contrast to many cancer-causing substances, the mechanism by which radon decay products cause lung cancer is known. It basically goes like this:

- Radon enters a building.
- It mixes with the air in the structure and remains in the breathing space.
- Radon naturally decays into its decay products (see Figure 3).
- The radon decay products (RDPs) that do not attach to physical objects but rather stay suspended in the air can be inhaled into the lungs.
- The RDPs have short half-lives, which means those that enter the lungs will radioactively decay before your lungs can clear them out.
    - Radon gas that is inhaled is exhaled with the next breath so there is no accumulation in the lungs.
- When RDPs decay, they emit alpha particles that can impact the unprotected lung cells.
    - If this decay occurs while the decay product is the lung, a lung cell can be damaged.
- When an alpha particle strikes a cell there can be a few outcomes.
    - It kills the cell, which has no consequence because your body can easily replace it.
    - It is absorbed into the cytoplasm where some free radicals can be formed, but of lesser consequence.
    - It strikes the DNA within the cell’s nucleus, which can cause the cell to mutate.
- Alpha particle hits can impact how the cell reproduces, otherwise known as cancer.
    - They can impact the cancer-suppression genes, which makes the cell more susceptible to cancer.
    - They can cause single strand, or worse, double-strand breaks that are essentially impossible to repair.

Perhaps the key thing to understand is, if you are exposed to radon, it does not automatically result in lung cancer. Rather ***radon increases the potential for lung cancer***. This makes radon a long-term health risk rather than a short-term, acute health risk. Radon plus other insults to the lungs like smoking, industrial fibers, chemicals etc. all add up to a bad cocktail of exposures. Fortunately, radon is one of the easiest exposures to test for and to mitigate.

Because radon is a long-term, rather than a short-term health risk you can take a considered approach to dealing with radon. You do not need to evacuate a building as you would with a natural gas leak or a carbon monoxide leak. This allows for the following approach to address radon:

1. Do a quick short-term test to check for potential radon.
2. Confirm radon levels.
3. Develop a mitigation plan for reducing radon exposure.
4. Mitigate the building within a reasonable time.

That is not to say you should procrastinate and not test or mitigate an identified radon concern, but it does allow for a reasoned approach. Also, the higher the radon concentration, the more quickly you should address it; however, it is not an emergency situation.

To put radon risks in perspective, the U.S. EPA has developed a table comparing lifetime risks of death from common causes such as drownings to lifetime exposures at different radon levels for both smokers and non-smokers. This table can be seen in many health department publications as well as in EPA's "Citizen's Guide to Radon," which can be downloaded at www.epa.gov (search for Citizens Guide to Radon).

2.1.4.2 Radon Exposure Guidance

The EPA developed an exposure guidance that has been in use in the United States for more than 30 years. That guidance, which is supported by the U.S. Surgeon General, is as follows:

People should not have long-term exposure to indoor radon levels of 4.0 pCi/L or more.

There are several items of note regarding this guidance:

- 4.0 pCi/L is **not** a safe exposure.
- Health risks exist at levels below 4.0 pCi/L.
- EPA health risk estimates indicate that two thirds of the radon-induced lung cancers occur from long-term exposures of less than 4.0 pCi/L.
- The 4.0 pCi/L was derived as a level to which one could economically reduce radon during the 1970s. Fortunately, technology has improved to where reductions to less than 2.0 pCi/L are achievable.
- 4.0 pCi/L is a guidance rather than a regulation in most cases.

4.0 pCi/L of radon is an economic guidance rather than a level below which no risk exists.

The EPA evaluates the risk from radon exposure using the linear no-threshold model, which states that risk increases proportionately to exposure, and the only time there is no risk is when there is zero radon. Consequently, when the United States or any other country sets guidance, they are weighing relative risk versus the technical feasibility and cost of mitigation. Similarly, each homeowner can weigh the cost of mitigation and the risk they wish to assume.

On the other hand, although 4.0 pCi/L is a guidance, many entities such as real estate relocation companies, lenders and most recently U.S. Department of Housing and Urban Development (HUD), have adopted policies to require certain structures to have indoor radon levels below 4.0 pCi/L. Therefore, although not a formal regulation, the 4.0 pCi/L has become a criterion for many financial transactions.

Other countries and agencies around the world have adopted their own guidance for radon exposure. This does not mean they have better science to assess the risk, but rather they have made different evaluations of the cost versus benefit assessment for their particular situation. For example, in an underdeveloped region where basic sanitation and drinking water is scarce, those environmental concerns would likely be a higher priority than reducing radon exposure. The following table provides a listing of some radon guidance around the world.

Table 2: Radon Guidance Levels

Entity	Guidance	Discussion
United States	4.0 pCi/L Radon	• Initially proposed by EPA • Is now the guidance for federal agencies including U.S. Department of Defense (DOD) and HUD
United States	0.020 WL of RDPs	• Alternate guidance for radon decay products • Clean up standard for contaminated sites
Canada	5.4 pCi/L	• Canada and other countries use SI units (Becquerel per cubic meter of air) for measuring radon where their guidance is 200 Bq/m3 which is equivalent to 5.4 pCi/L
United Kingdom	5.4 pCi/L	• Similar to Canada with guidance at 200 Bq/m3 (5.4 pCi/L)
Germany	2.7 pCi/L	• Lower than U.S. and other European countries • Guidance is actually 100 Bq/m3 (2.7 pCi/L)
World Health Organization	2.7 pCi/L	• This reference level is for developed countries • Actual guidance in SI units is 100 Bq/m3 (2.7 pCi/L)

As indicated, all guidance levels are very close, with the WHO guidance being less than the U.S. guidance. Other radon levels of interest in the United States are:

Table 3: Radon Benchmark Levels

Average Radon in the Outdoor Air	0.4 pCi/L
Target Radon Level for Radon Mitigation Repairs	2.0 pCi/L
Proposed Maximum Contaminant Level for Radon in Public Water Supplies	300 pCi/L of water

2.2 Factors Affecting Measurement and Mitigation Approaches

As described in more detail in Section 2, radon is an inert gas that is predominantly created in the soil or geology beneath a building. As a gas it can freely move through soil, being pushed, or pulled as a function of varying pressures. If a radon source exists under a building, the degree to which radon enters depends on the air pressures that either cause radon to enter or retard it from entering through the foundation. Once radon has entered a building, it can either build up or be diluted, depending upon the ventilation rate of the building. All of these factors cause radon levels in buildings to be highly variable.

Knowledge of how radon enters a building provides a basis for how radon is both measured and mitigated.

2.2.1 Variability of Radon Source

- Radon is derived from Uranium 238 in the underlying geology.
- Given the long half-life of U-238 (approximately four billion years), the rate of radon generation from a given chunk of rock containing U-238 is constant and very long lived.
- The amount of U-238 producing radon can vary from location to location.

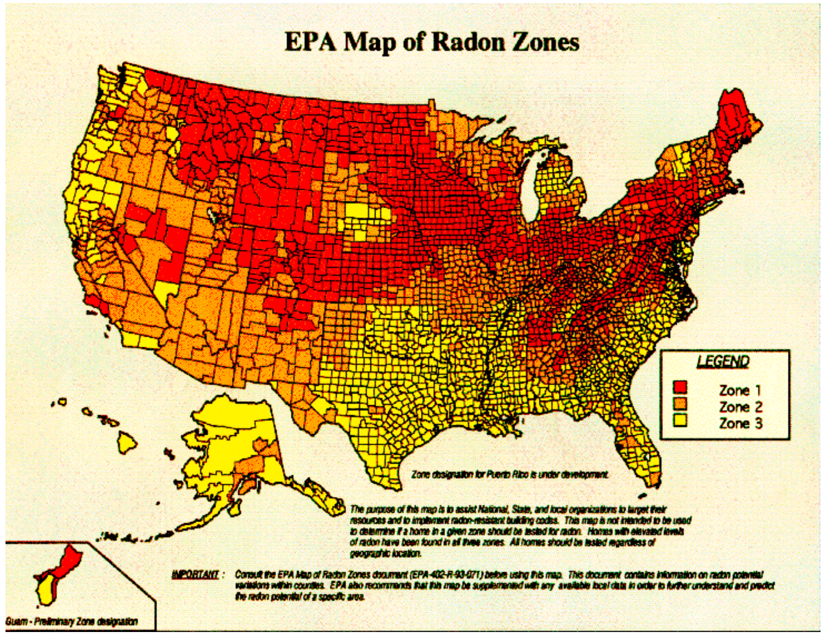
Not all geologies contain radon-producing uranium. However, if the geology around your building produces radon it can be drawn in. In this case:

- The rate radon is generated beneath your building is constant.
- The pathways and varying pressures can cause varying amounts to enter the building.
- The greater the amount of radon generated, the more radon that can potentially enter the building due to air pressure.
- Areas having higher uranium-238 content have a greater potential for elevated radon.
    - Mountainous regions such as the Rocky Mountain West are one of those areas where higher Uranium-238 content can be found.
- The higher the radon potential, the higher the radon variability can be within a given building.
- Pressures that cause radon to enter a building are generally exerted beneath the structure and only a few meters around its perimeter. In other words, the source is very localized.
    - For this reason, one home may have significantly higher radon levels than another home in the same subdivision.
    - Radon levels in a given building should not be assumed to be the same as levels measured in a nearby structure. Test each building separately because they can be widely different — especially in areas of high radon potential.

The EPA Map of Radon Zones was developed several years ago to indicate areas of the country where indoor radon levels are most likely to be elevated. The darker areas indicate higher radon potential. But this map can be deceptive in that many homes, schools and office buildings located in lower radon potential zones have been identified as having elevated indoor radon levels.

Figure 5: EPA Map of Radon Zones

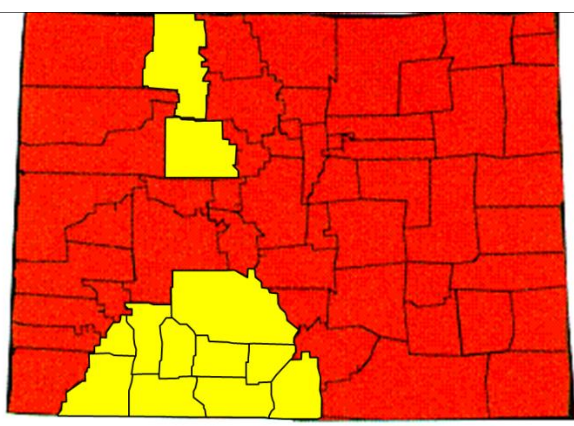
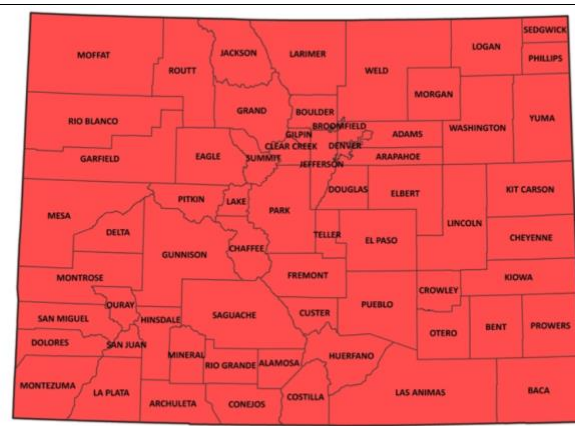
Higher radon potential areas shown in darker colors. This can be very deceiving. All locations should be tested



The purpose of this map was to indicate where it would be prudent to install radon systems during new construction as a means of dealing with the issue up front.

Since this map was developed in the early 1990s, many states such as Colorado have performed additional sampling and determined there are indeed more areas of high radon potential. For example, in Colorado the entire state is now at the highest radon potential rating.

Figure 6: Updated Colorado Radon Potential Maps

Colorado Radon Zone Map – 1991	**Colorado Radon Zone Map 2014**
Mix of Moderate to High Radon Potential	All Areas at Highest Radon Potential
	
1991	**2014**

Additional Data since 1991 has caused CDPHE to rank all Colorado Counties as Zone 1

Additional data from the 2014 Colorado study concluded that[2]:

- Approximately 50 percent of Colorado homes have indoor radon levels in excess of 4.0 pCi/L.
- Most counties can have radon levels more than six times the EPA guidance level of 4 pCi/L.
- All areas of Colorado should be tested and radon-control techniques should be incorporated during new construction.

2.2.2 Effect of Interior Negative Pressures/Vacuums

In the absence of large mechanical ventilation systems or smaller systems that mechanically introduce outdoor air into a building, most homes and older buildings exert a negative pressure on the underlying soil. In other words, the inside of the home is under a slight vacuum compared to the earth it sits upon. It is this vacuum that can draw radon-laden soil gas into a building. Interior vacuums can be caused by one or more of the following situations:

2.2.2.1 Thermal Stack Effect

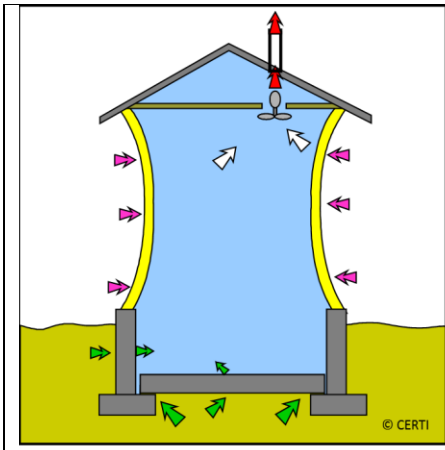
- A natural convective airflow occurs when the building interior is warmer than the outdoor air.
- The colder outdoor air is denser and literally moves down through the outside soil, entraining radon within the air spaces in the soil. It then enters the foundation and pushes the warmer, less dense, interior air upwards in the home.
  - This is the same phenomenon that causes damp air to enter a basement or a crawlspace from the soil beneath.
  - If radon is being created under the building, this movement of air from outside to inside can convey radon from the soil into the building.
- The strength of the stack effect increases as the outdoor air becomes colder — as experienced in the winter in Colorado or elsewhere.
- The longer or more severe the heating season is, the greater the driving force is that can bring in radon from the underlying soil.

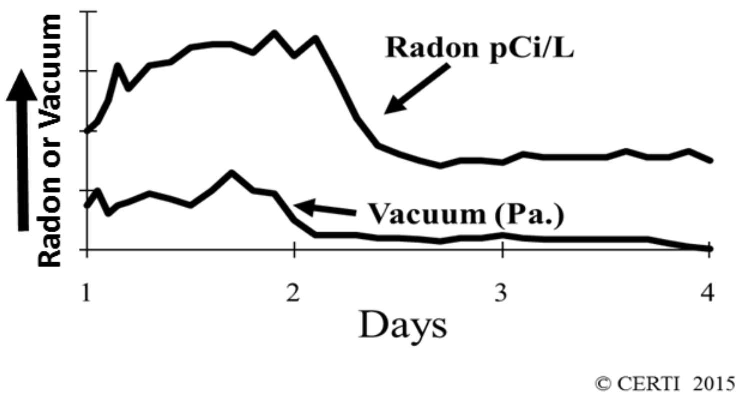
2.2.2.2 Mechanical Exhaust Systems

- Spot exhaust systems extract air from specific rooms, but also have the effect of creating a vacuum inside the home, which is exerted on the foundation. This can cause radon-laden soil gas to be drawn in through the foundation and into the home or building.
- Examples of systems that exhaust air out of the home or building and can draw radon in:
  - Bathroom fans
  - Kitchen exhaust fans
  - Chimney or water heater flues
  - Fume hoods in school laboratories or shop areas
- Exhaust systems typically run intermittently and can cause varying rates of radon entry.

[2] Colorado Department of Public Health and Environment, 2014 Radon Study

Figure 7: Effect of Interior Vacuums/Negative Pressures





Natural thermal stack effect (cold outside) and mechanical fans create vacuums that can draw radon soil gas in through extremely small openings in the foundation.	If radon is being generated beneath the home, interior vacuums can draw radon in. Higher rates of radon entry occur when the vacuums are the highest. Since vacuums are variable, the radon entry is also variable.

Figure 7 is an over-dramatized illustration of the effect of interior negative pressures. Also shown is a graph plotting the indoor radon levels as a function of the strength of the interior vacuum.

As indicated in the graph above, radon levels are not constant, changing as mechanical systems turn on and off and as outdoor temperatures fluctuate. Therefore, quick air samples, or tests lasting less than two days are unreliable in determining the need for radon mitigation. Actually, the longer you can test — the more confidence you have in characterizing the average radon exposure in a building.

2.2.3 Effect of Interior Positive Pressures

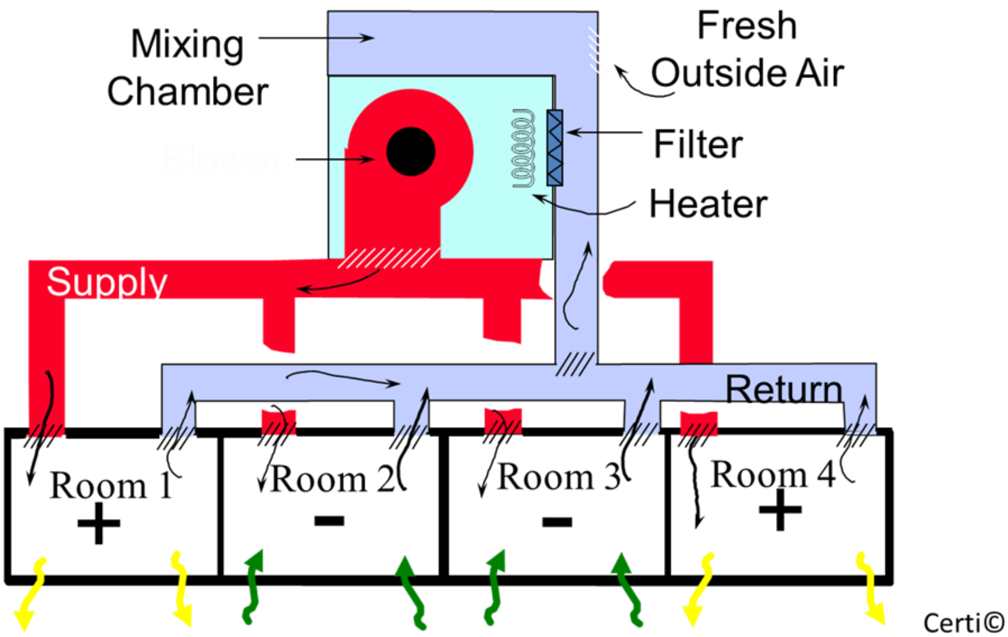
Systems that force fresh, outdoor air into a building have two impacts, both of which reduce indoor radon:

- Adding outdoor air can pressurize the building, retarding the entry of radon-laden soil gas from beneath the foundation; and
- Outdoor air can dilute radon in the structure to lower levels of exposure.

2.2.3.1 Effect of Positive Fresh Air Make-up in Large Buildings

Most schools and workplaces have mechanical systems that, per American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standards, provide fresh, outdoor air during occupied periods. The introduction of fresh air can have the overall effect of reducing radon entry within the building. However, the effect of this can vary from room to room, depending upon on how well the air is distributed or "balanced." In the case of large buildings where the air handlers are robust, an unbalanced system can cause widely varying radon levels from one room to the next, which is why we test every ground floor room when we test schools and commercial buildings. Figure 8 demonstrates the effect of an unbalanced HVAC system, while Figure 9 demonstrates the impact of the addition of fresh, outdoor air on indoor radon levels.

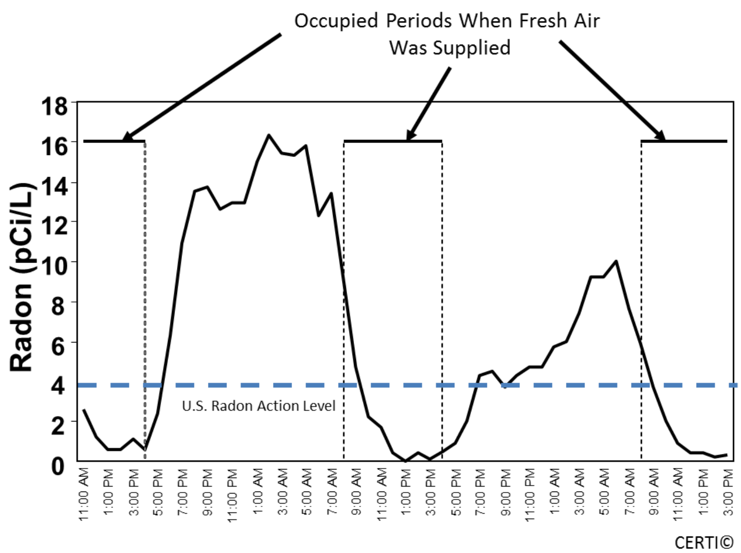
Figure 8: Large Mechanical Systems with Fresh Air Make-up



The introduction of outdoor air can retard radon entry as well as dilute radon. However, if the air is not properly distributed, significant variations in radon levels can occur from room to room.

A + sign indicates positive pressure and a - sign indicates negative pressure or vacuum

Figure 9: Effect of Fresh Air Make-up on Radon Levels-Large Buildings



Radon levels dropped significantly when fresh air is supplied to the building.

Figure 9 clearly shows the effect that adding fresh air can have in reducing indoor radon levels. However, radon levels can increase quickly when the fresh air is shut off. Controlling occupant exposure to radon can be a strong function of how well a Heating, Ventilation, and Air Conditioning system (HVAC system) is maintained, such as ensuring timers are properly set to allow fresh air make-up to occur during occupied hours.

The HVAC system in a large building, such as a school, can have a dramatic effect on radon test results and therefore require different testing approaches than might be used in a single-family residence or apartment where such robust air handling systems do not exist. Here are some key impacts of large HVAC systems:

- Radon measurements are to be conducted in 100 percent of ground contact rooms.
    - A random sampling can easily miss those rooms where an unbalanced HVAC system is causing elevated radon levels. (See Figure 8)
    - A room to be tested would be any frequently occupied area that has floor-to-ceiling walls where an HVAC unbalanced condition could exist. Including but not be limited to:
        - Classrooms / Study rooms,
        - Offices / Teacher prep areas
        - Music practice rooms
        - Gymnasiums and cafeterias, etc.
- Radon measurements should be conducted during occupied periods.
    - Testing done on a weekend when the building is unoccupied and fresh air make-up is OFF can bias the radon measurements to the high side and may cause one to make radon repairs when they are not warranted.
    - A two-day test during occupied periods that indicate elevated radon can be followed up with a device that measures hourly to determine if radon levels are indeed elevated during occupied periods (see Figure 9).
- If initial radon testing shows a few rooms elevated, they should be addressed. However, such a result also indicates that other portions of the building could be elevated in the future if the HVAC system became unbalanced in those areas as well.
- Efforts to reduce building energy costs by reducing or even eliminating fresh air make-up should be avoided because these quick budgetary fixes can cause significant radon exposures to occupants.
- A radon survey should be conducted after the modifications are made or major renovations occur, especially in high radon-potential areas. This is particularly true if revisions have been made to the HVAC systems.

2.2.3.2 Effect of Positive Fresh Air Make-up in Residential Structures

An increasing number of homes are being constructed in conformance with ASHRAE 62.2, which calls for the addition of fresh outdoor air. The amounts of fresh air added are lower than what would be seen in a school or an office building, but can reduce indoor radon levels nonetheless. Typically, these systems operate intermittently on a timed basis.

Because these systems are integral to the home HVAC system they should be operated during radon testing, but their presence should be noted on the test report so future owners are advised that radon levels may increase if they are not maintained.

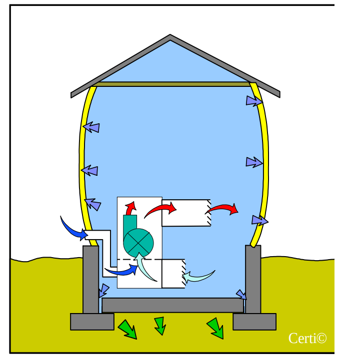


Figure 10: Fresh Air Make-up in Homes

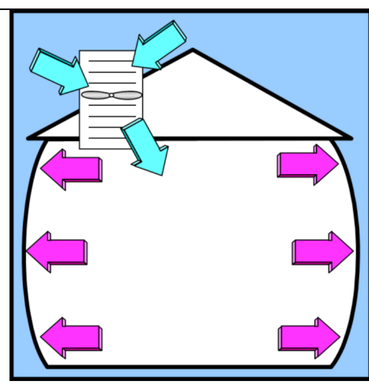
Can Reduce Radon if Operational

2.2.3.3 Evaporative (Swamp) Coolers

Evaporative coolers are often installed in homes in warm, arid climates such as Colorado and other parts of the Southwestern U.S. to provide a less expensive alternative to air conditioning. These systems operate by forcing large quantities of outdoor air through a water soaked medium, where it is cooled, and then introduced into the home. The side benefit a swamp cooler is that it reduces radon while operating.

Swamp coolers are only used during the summer months and not in the winter when radon entry is likely to be the highest. Consequently, due to this intermittent and seasonal use they are not considered to be radon-reduction systems and should be shut-off during short-term radon measurements.

Figure 11: Evaporative/Swamp Coolers

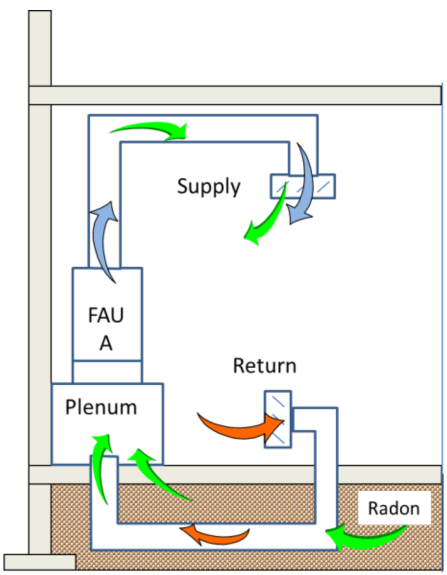
		• Evaporative coolers will reduce indoor radon when they are operated • Typically,evaporative coolers only operate in summer • These should be shut off during short-term testing, as they can cause false negative results

2.2.4 Effect of Buried Ductwork

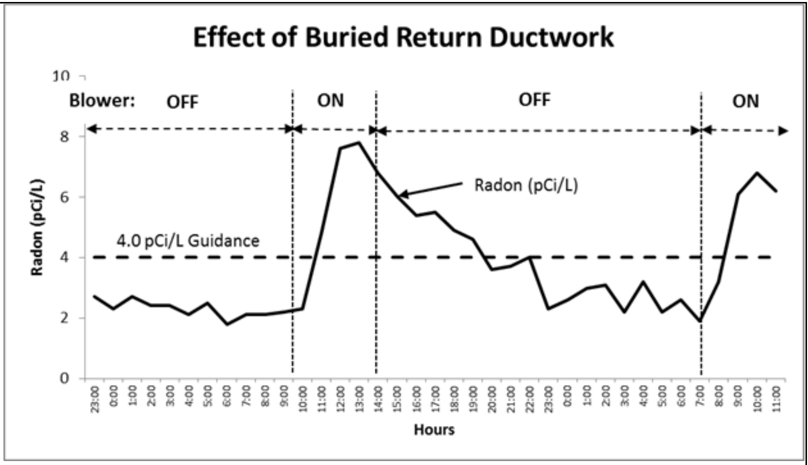
Another aspect of a building's mechanical system that can have a major effect on indoor radon is ductwork buried in the soil. This is true for both large buildings and residential homes. Ductwork is sometimes buried due to space restrictions or the desire to reduce air noise within the structure, but it can cause problems if radon is generated within the soil around the ductwork.

- Buried return ductwork can cause a significant radon concern.
- Mechanical air handlers create a large vacuum within the return ductwork.
- Regardless of how well one tries to seal the ductwork, radon and other soil gases can enter through joints or where the furnace cabinet sets upon the slab opening.
- Radon entering leaks in buried ductwork is mechanically pushed into living space.
- As ductwork deteriorates, additional leaks can occur.

Figure 12: Effect of Buried Return Ducts



Forced Air Unit with buried Return Duct can import radon from soil



Ductwork buried in the soil can provide an easy pathway for radon to enter from the soil. This is especially true if the return ducts, which are under significant vacuum, are located under the slab. Buried return ducts will suck radon into a forced-air system and blow it into the building.

Sharp increases in indoor radon are apparent when the blower operates.

Figure 12 provides an example of how buried return ducts can mechanically import radon into the home. This effect can be pronounced in the heating season when the blower operates more frequently.

- The practice of installing ductwork in the soil should be discouraged in high radon potential areas.
- Radon measurements made during seasons when the air handler is not running frequently can be significantly different from other seasons when its duty cycle is higher.

2.2.5 Effect of Weather Conditions

Weather conditions can have a significant impact on test results when radon measurements are conducted over short periods of time, commonly two days in duration.

2.2.5.1 Cold Weather

Cold weather can have several impacts:

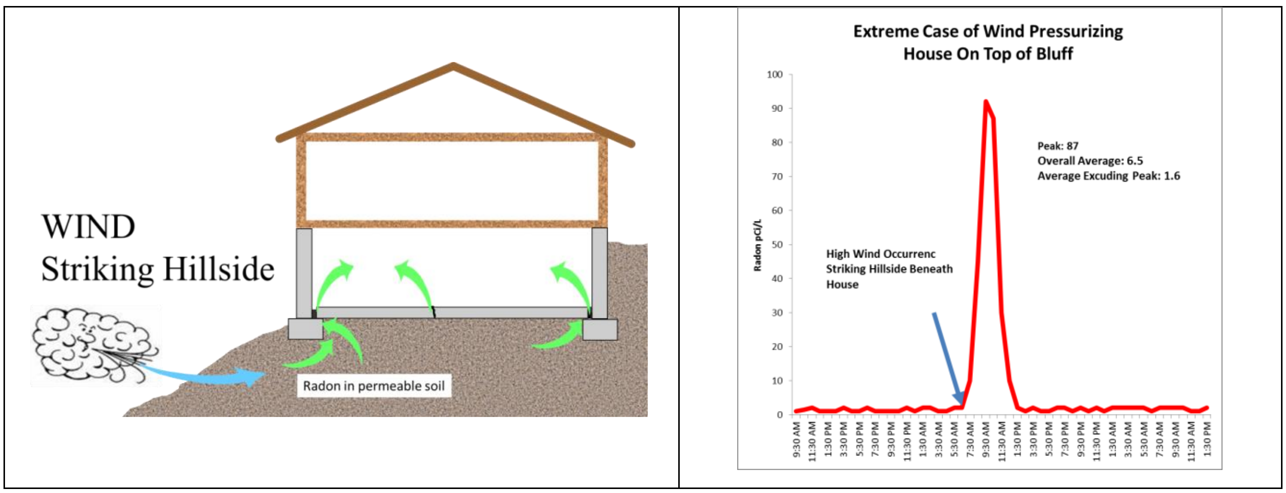
- Colder outdoor temperatures increase the stack effect that can draw in more radon laden soil gases.
- Occupants are more likely to keep windows and doors closed, reducing radon dilution.
- Furnaces can run more often, creating localized vacuums in the lower level of the home.
- If a forced-air unit has ductwork beneath the slab, the higher frequency of operation can significantly increase radon entry rates.

2.2.5.2 Windy Conditions

Wind can cause varying pressures within a building, affecting the forces that draw or retard radon entry. Short-term (two- to three-day testing) is generally discouraged during unusually windy conditions.

Another common effect in mountainous areas where soils are permeable (e.g. Rocky Mountains) is where wind striking a hillside can cause significant soil pressures under a structure, forcing radon into the building. Figure 13 provides an example of a home in Boulder, CO where radon levels dramatically increase when the wind came from a particular direction, forcing radon into the home.

Figure 13: Effect of Wind on Hillside



Wind can cause variable radon measurements and also can create significant challenges to radon mitigation.

2.2.6 Radon Pathways

Radon exists as a single atom and moves like a gas. Therefore, it can move from the soil through the tiniest of openings -- even those you cannot see. Furthermore, there are a myriad of openings in a foundation that can allow radon to enter. Therefore, attempting to seal radon out is not possible, especially on a long-term basis as the foundation ages.

> ***Caulking and sealing of foundation openings is not a stand-alone technique for reducing radon.***

Although caulking and sealing may be part of a mitigation approach, it is totally inadequate on its own. Also if you are successful in sealing some of the openings, it will come in at a faster rate through other openings that you cannot access to seal. There are many foundation openings through which radon can pass. Having these openings does not mean you will definitely have elevated radon levels. The only way to know is to test the home.

2.2.6.1 Common Entry Pathways (not in order of magnitude of contribution)

- Slab floor to wall joints
- Slab control and expansion joints
- Up from crawlspace (regardless of having crawlspace vents)
- Through drainage tile connected to interior sumps
- Up around plumbing penetrations under cabinets and tubs
- Through slab stress cracks
- From root cellars
- Via groundwater supplies that pass directly into the building

All homes, regardless of construction type or age, can have radon concerns if radon is generated in the underlying soil.

Elevated radon has been found in all types of homes regardless of their construction types or age. Perhaps the only types of houses that will likely not have a radon problem would be a houseboat or a tree house.

2.2.7 Radon Distribution in Buildings

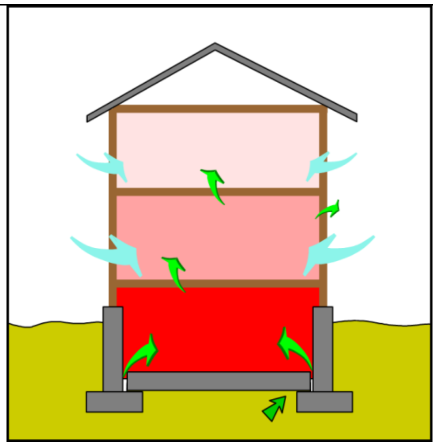
2.2.7.1 Radon Distribution in Homes - Based Upon Level of Home

The majority of radon found in homes enters from the soil beneath the building foundation. After entering the home, it moves upward where it is diluted with outdoor air that leaks through the upper shell of the building. This results in radon levels tending to be the highest in the lowest portion of the building.

- Radon primarily enters from the soil beneath the building.
- Radon tends to be the highest in the lowest portion of the structure.
  - This is because that is where it first enters.
  - It is not because radon is heavier than air.
- If a test is conducted in the lowest portion of the building and its results are less than 4 pCi/L, one can assume with reasonable assurance that radon levels on upper floors are also less than 4.0 pCi/L.
  - An exception can be multi-floor apartment buildings where vertical chases can provide unique pathways. (See Section 2.2.8)

Figure 14 shows radon distribution in a home, with the highest exposures typically occurring in the lowest level.

Figure 14: Radon Distribution in a Home



- Radon is typically the highest in the lowest portion of the building in contact with the radon-producing soil.
- A test result in the lowest level of the home is typically higher than results of tests in upper floors.
- This is why most "radon screening" tests are conducted in the lowest level of the structure.

2.2.7.2 Radon Variation on a Given Floor

2.2.7.2.1 Homes:

Studies have shown that for the most part radon levels do not vary significantly between occupied rooms on the same floor. Radon levels change from one floor to the next but not within the same floor. One only need to test one room within the floor selected to be tested (typically the lowest floor).

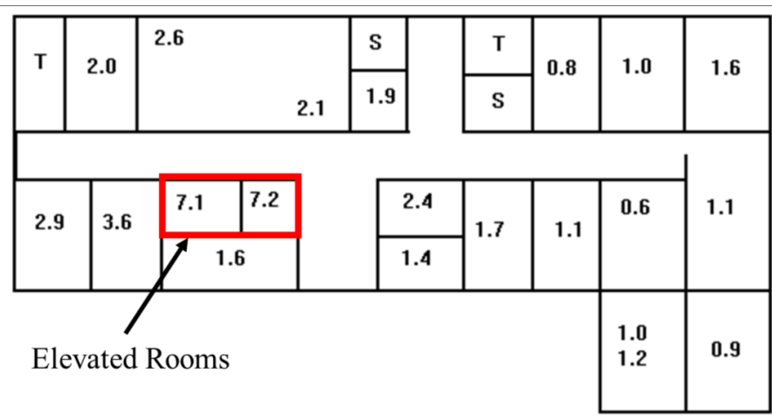
> ***Radon levels in <u>single-family homes</u> do not vary significantly from one room to the next on the same floor.***

2.2.7.2.2 Large Buildings

Due to the presence of much larger HVAC systems there can be significant variations from room to room on any given floor. Consequently, all ground-floor rooms should be tested concurrently.

> ***Radon levels in large buildings can vary significantly from room to room or apartment to apartment.***

Figure 15: Variation of Radon on Same Floor of Large Building



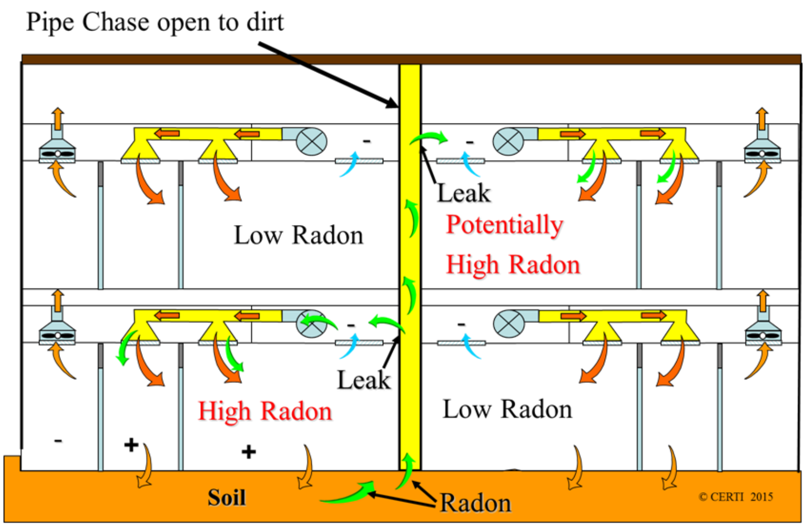
- Unbalanced HVAC systems can cause large, room-to-room differences in large buildings.
- 100 percent of ground-floor rooms should be tested.
- Random sampling is inappropriate and likely will miss localized concerns.

2.2.8 Upper Floor Pathways-Multi-Family Dwellings/Large Buildings

Apartment buildings and condominiums are typically separated by fire walls and fire ceilings. However, there are also common or demising walls between units that provide a vertical space through which utility pipes are routed. There can also be pipe chases reaching all the way from grade level that can be a pathway for radon movement to upper floors. For this reason, it is recommended that at least 10 percent of upper floor units be tested in addition to all ground-floor units.

- It is possible an upper-floor unit can have elevated radon when a unit beneath it is low in radon.
- The use of ceilings as return air plenums can exacerbate this concern.
    - Firewalls stop fire, but not gases like radon.
    - Ceilings under negative pressure can pull air from adjacent chases.
- 10 percent of upper floor units should be tested.
    - The upper units tested should be staggered so that upper-floor test locations are not aligned vertically.

Figure 16: Radon in Upper Floor Units in Multi-Family Dwellings



- Pipe chases and common demising walls can provide pathways for radon to enter upper units in apartments and condominiums.
- Ceilings as return air plenums exacerbate this effect.
- At least 10 percent of upper-floor units should be tested.

2.2.9 How the Variability of Radon Affects Measurement Strategies

There are two measurement strategy approaches: short-term and long-term.

2.2.9.1 Short-Term Measurements

The purpose of short-term measurements is to determine the radon potential of a home or a location within a building.

- Minimum sampling period is 48 hours.
  - Anything less than 48 hours is insufficient to determine the need for follow-up actions, including mitigation.
- Test in the lowest occupiable portion of the building where radon is likely to be the highest.
  - If the result is less than 4.0 pCi/L in lowest level, upper levels likely are also less than 4.0 pCi/L.
- Close all windows and doors except for normal entry and exit during a short-term test.
- The results of a short-term test are an indication of potential and not necessarily the levels to which the occupant is actually exposed over longer periods of time.

2.2.9.2 Long-Term Measurements

The purpose of long-term measurements is to determine actual exposure of radon to occupants in the manner in which they occupy and use the building.

- Long-term measurements provide a better representation of radon risk than short- term tests.
  - Long-term measurements are the basis of health studies and health advisories.
- The minimum sampling period for a long-term measurement is 91 days.
  - Testing for up to a year to encompass all four seasons is preferable.
- Deploy the test in the lowest portion of the building that is actually occupied.
  - Long-term testing determines health risk for the current occupant.
- Operate the building as normal during the test.
  - Open or close windows as usual.

2.2.9.3 Comparison of Short-Term and Long-Term Measurement Results

Because longer sampling times provide a better average of exposure, long-term measurement results take precedence over short-term measurement results. However, people often want a quick radon result, such as during the purchase of a home or a refinance/sale of a large building, creating the need for short-term radon testing.

Numerous short-term radon tests over different days can yield different results. Figure 17 provides consecutive short-term (two-day measurements) in the same home over a three-month period. As indicated, the results of any one short-term result could be above or below 4.0 pCi/L, while the long-term measurement result is below 4.0 pCi/L.

Figure 17: Comparison of Short-Term Measurements to Long-Term Averages

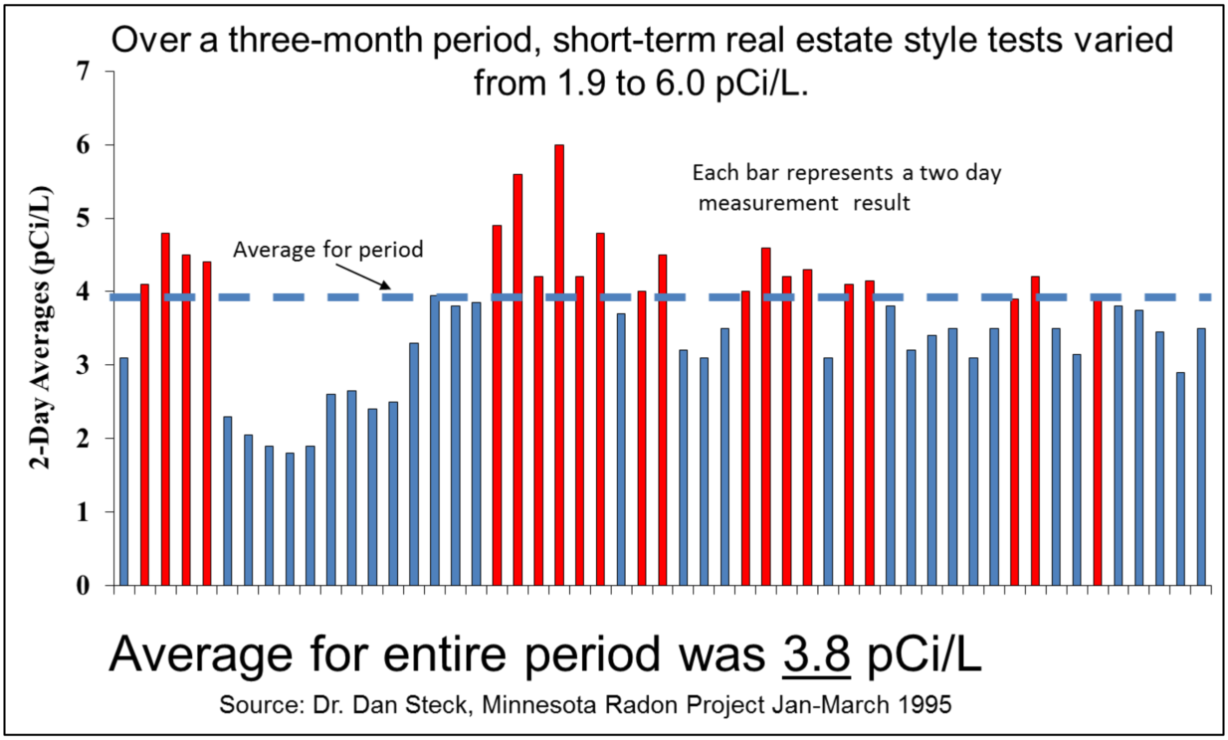


Figure 17 illustrates the variability of radon measurements even when carefully performed in the same house, the same location and under the same operating conditions. Historic measurement strategies have suggested:

- Perform initial short-term measurement.
- If the result of the initial short-term test is between 4 pCi/L and 8 pCi/L, retest with a long-term measurement device.
  - If the result of the long-term device is above 4 pCi/L, mitigate the building.
- If the result of the initial short-term test is above 8 pCi/L, retest with another short-term test device.
  - If the average of the initial and follow-up short-term test result is 4 pCi/L or higher, mitigate the building.

An exception to this process would be large buildings that are not occupied 24 hours/7 days a week, such as schools, office buildings and public administrative offices. In cases where the operation of HVAC systems is modified during unoccupied periods, short-term testing — especially using devices that discern radon levels during occupied versus unoccupied hours — provide a better representation of exposure levels.

3 MEASURING RADON IN SINGLE FAMILY HOMES, MULTI-FAMILY DWELLINGS, AND LARGE BUILDINGS IN COLORADO

Methods for Measuring Radon and Radon Decay Products in:

- Residential Buildings
- Multi-family Dwellings
- Schools and Office Buildings
- Child Care Facilities

3.1 Measurement Devices and How to Use Them

A common denominator to all types of buildings that should be tested is the use of an appropriate measurement device and where it is located within a selected room. This chapter should be used in conjunction with the testing approaches described in subsequent chapters specific to the type of building being tested.

3.1.1 Selecting Radon Measurement Devices

A number of radon and radon decay product (RDP) measurement devices are available for both professional and consumer use. Other than cost, the primary differences between them are the duration of measurement, what they measure, and who analyzes them. However, the one thing they should have in common is that they are "approved."

> ***Only measurement devices approved by the NRPP or NRSB should be utilized to determine the need for or the success of radon mitigation.***

An approved device is one that has been subjected to a series of tests that validate its ability to measure radon or radon decay products. One should always check the product literature to verify its status as "approved."

- Between 1989 and 1998, the EPA approved devices. Some devices still carry this designation on their packaging. Note: Prior approval does not mean the device is currently approved.
- After 1998, two organizations assumed EPA's operation of its radon device approval program. An approved device may now carry an approval from either one or both of the following organizations. Verification of approval can be found on their respective websites shown below:
  - The National Radon Proficiency Program (NRPP) (administered by the American Association of Radon Scientists and Technologists)
    - www.nrpp.info
  - The National Radon Safety Board (NRSB)
    - www.nrsb.org

The Colorado Department of Public Health and Environment (CDPHE) recommends the use of only approved measurement devices. Although radon test devices are available in hardware stores or online, users should verify that these devices are approved by the entities listed above.

3.1.2 Determining Where to Test

Determining which room or rooms to test depends on the type of building you are testing. The approaches will differ for a school versus a residential structure versus a multifamily dwelling or a condominium. The room selection criteria for these different buildings are provided in the specific chapters relating to those types of structures.

However, there are some common aspects to location selection:

- Tests are not conducted in unoccupiable areas, like crawlspaces or attics.

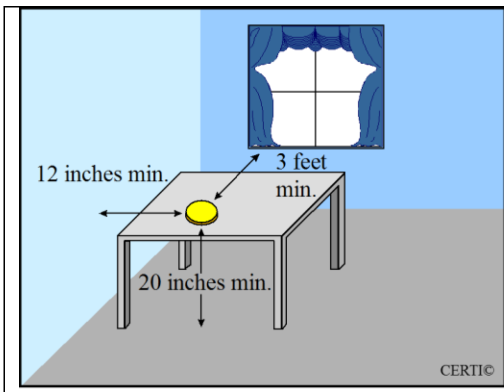
- Exceptions would be tests performed as part of a diagnostic investigation to identify mitigation approaches.
- Tests to determine a building's radon potential are conducted on the lowest occupiable level of the building where radon is likely to be the highest.
    - If the basement is unfinished, but could be finished and occupied, the test would be conducted in one or more rooms in the basement.
- Tests conducted to determine actual exposure are typically conducted on the lowest occupied portion of the building.
    - If the basement could be finished, but is not occupied (used for storage only) the test would be conducted in the level above the basement.
- Test devices are typically not located in rooms with high humidity such as bathrooms, kitchens, locker rooms, saunas, etc.

See subsequent chapters for building-specific criteria.

3.1.3 Location Criteria within a Room

Regardless of what rooms are tested and the type of building in which a test is conducted, use the criteria shown in Figure 18.

Figure 18: Test Device Location Criteria within a Room



- 20 inches or more above the floor
- 12 inches or more from an outside wall
- 36 inches or more from an opening to the outside
    - Windows (regardless if they can be opened)
    - Exterior doors
- 12 inches or more below the ceiling if device is suspended
- 4 inches or more of space around device
- Avoid areas where air from ceiling fans or air ducts will blow air directly onto the device

3.1.4 Short-Term Test Devices

Short-term measurement devices determine the radon potential of a home or a location within a larger building. Short-term device results are also referred to as "screening" measurements, as they provide a relatively quick determination if additional testing or follow-up is needed.

To identify radon potential, building conditions and test locations for short-term tests mimic a worst-case scenario to avoid missing a potential radon concern. Consequently, short-term tests are conducted as follows:

- Closed building conditions:
    - All exterior windows are closed;
    - All exterior doors are closed other than normal entry and exit;
    - Closed building conditions are established a minimum of 12 hours prior to the start of the test and maintained throughout the test period; and

- No changes to crawlspace vents or crawlspace dehumidification systems are made, other than to note their presence and status during the test.

- Test duration: Minimum of 48 hours
- Location:
  - **Minimum:** Lowest occupied or occupiable level of the building in contact with the soil.
    - The level selected is dependent upon if the test is being done by current homeowner or as part of a real estate sale inspection - See Table 4 in later Section 3.2
  - **Additional:** If the building has different foundation types it would be prudent to test in each distinct foundation area. For example if there is a basement and an adjacent crawlspace foundation, it would be a good idea to test the living space above the crawlspace in addition to the basement.

The results of the short-term test should be used to determine if additional testing or follow-up action would be warranted.

3.1.5 Long-Term Test Devices

Long-term devices determine overall radon averages in a specific location and under the conditions that the building is operated. Consequently, long-term measurements are generally viewed as confirmatory measurements after a short-term test has indicated a radon potential. In situations other than large buildings with HVAC systems that utilize energy management schemes for unoccupied periods, long-term measurement results are considered to be a better indication of radon exposure than short-term measurements. Here are aspects of their use:

- **Building Conditions**:
  - Operate building as normal
  - Closed building conditions are not required
- **Test Duration**: 91 days up to a year
  - A longer duration will better characterize the effects of different seasons
- **Location:** Same as initial short-term device that indicated a potential radon concern
  - Occupied areas

Figure 19: Long-Term Test Device

Example of Long-term Test Device Suspended from Ceiling

3.1.6 Advanced Measurements

Radon professional can use a number of devices to obtain additional information during a test or to assist in developing a radon mitigation strategy. A few examples are listed in the subsections below:

3.1.6.1 Radon Decay Product Measurement Devices

Radon decay product (RDP) measurement devices measure the particles that form when radon gas decays. The decay products of radon represent the primary health risk associated with the presence of radon gas (see section 2.1.3.2).

Figure 20: RDP Measurement Device

Example of Radon and Radon Decay Product Measurement Device Compliments of RadElec Inc.

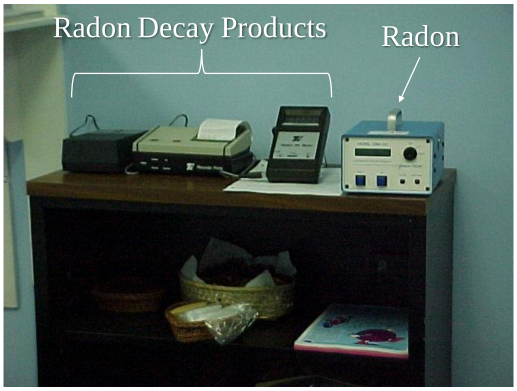
Radon decay product measurements are more complicated than radon measurements and are almost always performed after a radon gas measurement has identified a potential concern and also where building equipment exists that can affect the percentage of RDPs in the air relative to the radon gas. Examples of where radon decay product measurements are helpful would be where air cleaners or other special filters are used in an HVAC system, where high air circulation rates exist (as in a school or commercial building), where traditional mitigation approaches are not feasible and where it may be more practical to reduce RDPs rather than to reduce radon. Here are a few aspects of these types of measurements:

- To be conducted simultaneously with radon gas measurements.
- To be conducted by a trained and qualified technician.
- Typically short-term measurements requiring a minimum duration of sampling over 48 hours under closed-building conditions.
- Expressed in units of Working Levels and should be compared to the EPA Guidance of 0.020 WL (See section 2.1.4.2).

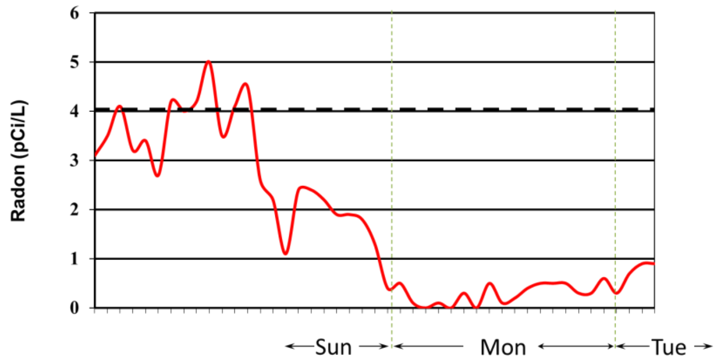
3.1.6.2 Continuous Monitors

Continuous Radon Monitors (CRM) or Continuous Working Level Monitors (CWLM) are devices that measure and report in hourly increments. The data obtained from these devices allow you to track radon or RDP levels as a function of time as building conditions and weather conditions change. This information can be very informative in assessing actual exposures — for example, determining exposures during occupied versus unoccupied hours in a large building.

Figure 21: Continuous Radon and Radon Decay Monitors



Continuous Radon and Radon Decay Product Monitors



Example of hourly measurements obtained from continuous monitors. Indicates significant change on Sunday night

Key things to know about Continuous Monitors:

- Require a trained operator.
- Should be approved devices calibrated within the last 12 months.
- Decisions regarding mitigation are based upon the average of measurements occurring over a minimum of 48 hours of sampling — not the highest or the lowest hourly reading.
- The averaged results are not considered to be any more accurate than other approved devices that simply provide an overall average.

3.1.6.3 Environmental Indicating Devices

Professional radon measurement providers may also have devices (or ancillary devices) that measure other factors than radon, which can assist them in identifying potential factors affecting their results. These could be effects caused by weather or indications that the building occupant tampered with the required building operating conditions. Examples of additional parameters that can be concurrently measured:

- Room temperature
- Barometric pressure
- Motion detector as an indication device has been moved

The ability to measure these additional variables does not mean that the radon results are any more accurate than those obtained from other devices.

These types of devices are often used when homes are tested at the time of resale when third-party test results are most beneficial.

3.1.6.4 Diagnostic Measurements

After a short-term or long-term test has identified and confirmed a radon concern, a radon mitigation professional may use specialized devices to develop a mitigation approach or to explain anomalies. Examples of diagnostic measurements include:

- Grab samples: Five-minute samples taken to identify unique radon entry points
- Radon in water samples
- Deployment of continuous monitors and operating the building in different manners

It is important to note that diagnostic measurements are for mitigation design purposes and are not to be used in determining the need for or the success of a mitigation effort.

Figure 22: Grab Sampler as Diagnostic Tool
Radon Technician taking a grab sample of air supplied to a room.

3.1.7 Interpretation of Measurements

How you interpret measurements depends on building type and the reason for taking measurements in the first place. Measurements to determine if mitigation is needed require different interpretation than do measurements to validate a mitigation system. Interpretation and follow-up action is addressed in the specific building-type sections that follow; however the following overall philosophies apply regardless of the situation:

- The minimum duration of a test to make any follow-up decisions is two days.
- The longer the duration of a measurement, the more confidence that is placed in the results.
- Results are compared to the EPA Action Level:
    - Radon: 4 pCi/L
    - Radon Decay Products: 0.020 WL
- The average of measurements is used to make a decision rather than the highest or lowest measurement observed.

3.2 Testing Single Family Homes

This section details the specific steps to take when testing a single family home. For more in-depth information about why these steps are taken refer to the earlier sections of this document.

Single-Family Homes are typically tested for two primary reasons:

- To determine potential health risk to the current occupants.
- To determine radon potential at the time of sale.

The only difference in the testing methodology under either of these circumstances is timing and the additional safeguards put in place in the case of a real estate transaction. The table below provides a summary of the approaches for consumer versus real estate testing.

Table 4: Consumer Testing vs. Testing at Time of Sale (Real Estate Testing)

	Consumer Testing	Real Estate Testing
Purpose	• Determine exposure of current occupants	• Determine radon potential of building
Test Location	• Lowest lived in level	• Lowest potentially occupied level
Minimum # of Test Locations	• One	• One
Number of test devices at location	• One	• **Two** - if Passive devices • **One** - if Continuous Monitor recording hourly
Minimum Duration of Test	• 48 hours	• 48 hours
Building Conditions for Short-Term Test	• Closed other than brief entry and exit	• Closed other than brief entry and exit
Identification of Test Tampering	• No	• Advised
Follow-up Action if Initial Test is Elevated	• Additional testing	• Additional testing or mitigation

3.2.1 Procedure for Testing Single Family Homes

Purpose:

Consumer Testing		Real Estate Testing
Determine radon exposure in the home as a function of how current occupant uses and lives within it.		Determine radon potential of home independent of current occupants' living patterns.

Step 1: Select level of home to be tested

Radon typically enters a building through its foundation and is at its highest concentration in the lower portions of the house. Consequently, initial tests are conducted in lower levels.

Consumer Testing		Real Estate Testing
Select lowest portion of the house in which you occupy or spend time, such as: • Finished basement • First floor of a slab-on-grade house If you have an unfinished basement you do not occupy, you may want to test here if it could be finished, as this would likely be the location tested if you sell your house in the future.		Select lowest portion of the house in which people could live. • Finished basement — If unfinished now but could be finished, test in this area. • First floor of a slab-on-grade home

Places <u>not</u> to test – regardless of the situation:

- Basement that could not easily be finished
    - Very low ceilings
    - Dug out basement – just for utilities, etc.
    - Root or wine cellar
- Crawlspaces under home
- Attics above homes
- Garages

Step 2: Select one room within the level of the home you have selected

After you have chosen the level of the home to test, select a frequently occupied room within that level. The selection criteria are the same for real estate and consumer testing situations. Here are some good examples. You only need to select <u>one</u> room.

- Bedroom
- Family room
- Workshop if that is the only room in that level
- If it is an open area, like a basement that has not been finished, select an area in the center of the large room.

*Rooms **<u>not</u>** to select due to possible test interference:*

- Laundry rooms
- Utility rooms that include your furnace
- Rooms with water drainage collection sumps
- Garages
- Root cellars

Step 3: Select the time to test

Your initial test will likely be a short-term test, where you will need to keep all exterior windows and doors closed. If possible, select a time of year when this will be most convenient for the minimum two-day test period.

In a test associated with a real estate transaction, you may not be able to test when closed-house conditions are convenient, but rather as a function of the timing of the sale.

Step 4: Prepare for test:

- Read instructions provided with the test device or instructions provided by a radon measurement professional conducting a real estate test.
- Close the building 12 hours prior to beginning the test.
    - This requirement does not artificially increase radon levels even if the house has been closed for several months. Radon comes into equilibrium with the interior of the building within 12 hours — but does not continue to build up.

Closed Building Conditions

Closed-building conditions allow you to estimate the radon potential of the house. You especially want to simulate these conditions during high heating or cooling periods.

- All exterior doors and windows must be closed for 12 hours before and throughout the duration of the test.
    - You may enter and exit the house, but do not leave doors or windows open.
    - Keep garage doors of attached garages closed other than for brief periods when bringing your vehicle in and out.
    - Treat doors from living spaces into attached garages as an exterior door and only open them long enough for entry and exit.
- If you test for longer than 48 hours, for example three to five days, closed-building conditions must exist throughout that period rather than just for the first 48 hours.

Mechanical Heating and Cooling Systems

A home's heating and/or cooling system should be operated as follows:

- **Evaporative coolers (swamp coolers) and whole house ventilation fans**
    - **Turned off 12 hours before as well as all during the test.**
        - This can be difficult when testing in the summer when these devices are needed for cooling, but it must be done; otherwise, the test has little value.
        - If swamp coolers or whole-house fans cannot be shut off, consider testing during a different season or deploying a long-term test for at least 91 days since closed-building conditions are not required for tests greater than 90 days.
- **Furnaces and Boilers**
    - **Can operate normally**
        - Thermostats set at normal indoor temperatures such as 68 degrees F.
- **Fireplaces**
    - **Should not be operated**
        - If your home is heated by a woodstove, operate the stove as normal.
- **Air to air heat exchangers or heat recovery ventilators**
    - **Can operate normally —** If a normal part of your mechanical system, but may affect your results.
- **Air Conditioning**
    - **Can operate normally**
        - Window units can operate if they are set to "Maximum Cool" to reduce introduction of outdoor air.
        - Forced air, air conditioning systems such as heat pumps or split A/C systems can operate normally.
- **Ceiling Fans**
    - **Can operate normally**

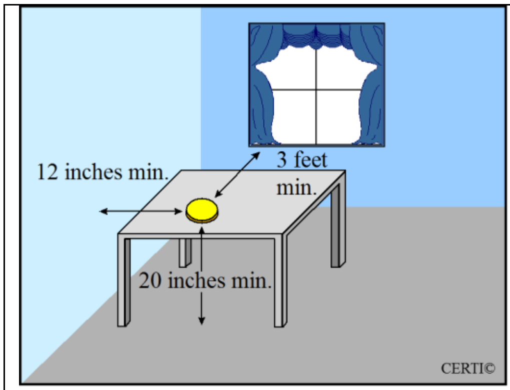
- Avoid deploying the device where the air from the fan directly hits the test device.

- **Air Cleaners**
  - **Can operate normally**
    - Whole-house or room units can operate provided air does not strike the measurement device.
    - Special precautions will be taken if a radon professional conducts a test for radon decay products in addition to a radon measurement.
- **Crawlspace Ventilation**
  - No special manipulation of crawlspace vents or operation of crawlspace dehumidification systems are made, other than to note their presence and status during the test.
- **Attic Ventilation**
  - Ventilation systems that only impact an attic space above and decoupled from the living space are operated as normal. This would include:
    - Ridge vents
    - Gable vents
    - Powered attic vent fans

Step 5: Deploy the test device

- Deploy the device in accordance with the instructions from the laboratory or radon professional.
  - If the test is being done as a part of a real estate transaction, the tester may ask you to sign an acknowledgement of acceptance of instructions for maintaining closed house conditions.
- Table 5 lists the location parameters to be followed:

Table 5: Test Device Location within a Room

	• 20 inches or more above the floor
	• 12 inches or more from an outside wall
	• 36 inches or more from an opening to the outside
	  ○ Windows (regardless if they can be opened)
	  ○ Exterior Doors
	• 12 inches or more below the ceiling if device is suspended
	• 4 inches or more of space around device
	• Avoid areas where air from ceiling fans or air ducts will impact the device

- After the test has been deployed, leave the device in place for the optimum test period recommended by the manufacturer.
- Do not move or disturb the test device after the test has been initiated.

Caution:
Once a test has been started, do not move or disturb the device until it is time to stop the test.

Step 6: Stopping the test

Consumer Testing (Non-Real Estate):

- At the end of the minimum 48 hours, or the duration recommended by the manufacturer, end the test in accordance with manufacturer's instructions.
- If device is to be shipped to a lab, it should be returned immediately so it arrives at the lab no later than three days after the conclusion of the test.
- Provide requested information:
  - Fill out forms and retain a copy with test device ID#
  - At a minimum provide:
    - Property address
    - Test location within house
    - Start date and time (a.m. or p.m. and time zone)
    - Stop date and time

Real Estate Testing

- The third-party tester will advise you as to how and when it will be retrieved.
- The radon professional will obtain all necessary information.

3.2.2 Interpreting Test Results

The results of an initial, short-term test conducted in the lower portions of a home and under closed-house conditions indicate the radon potential of the home for the conditions that existed when the home was tested.

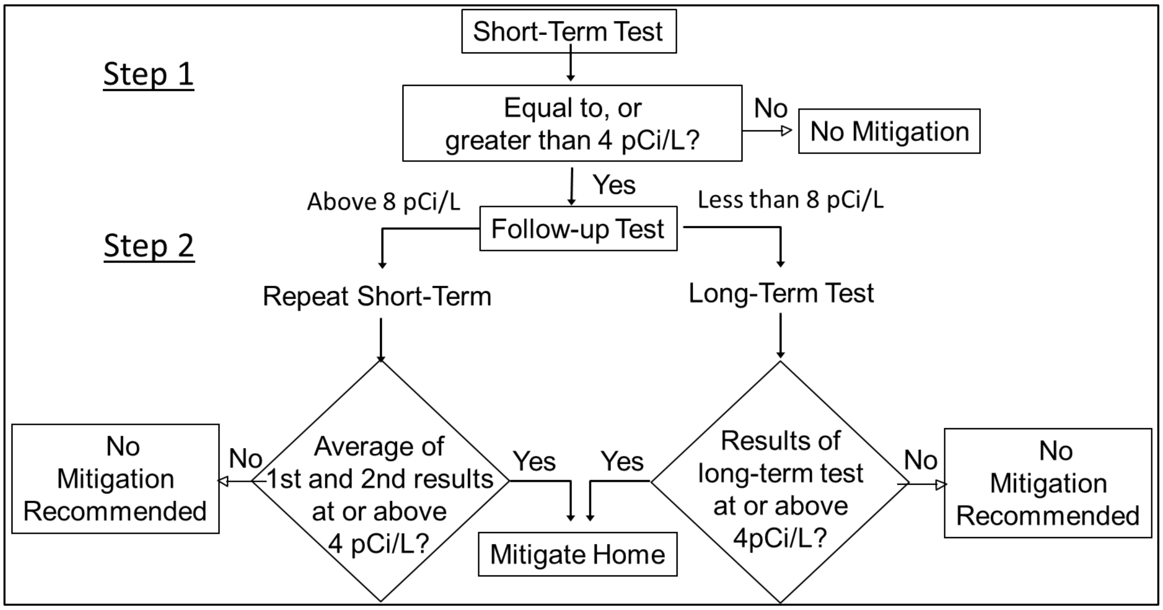
The results of a short-term test do not indicate what the radon levels will be under normal lived-in conditions and through varying seasons.

The results of a short-term test are designed to provide information that can guide follow-up action. This follow-up action can be repeated testing or mitigation, depending upon the occupant's preferences and why the test was performed.

3.2.2.1 Interpreting Consumer Results

Figure 23 below represents the EPA's recommendations for interpreting test results not associated with a real estate transaction and some key response actions:

Figure 23: Interpreting Measurements (Consumer Testing)



- If results are less than 4.0 pCi/L, no follow-up action is necessary.
  - Some risk can still exist and you may want a follow-up measurement to be certain.
  - If a follow-up action is taken, a long-term test would be a good choice.
- If the initial result is above 4.0 pCi/L, you should perform a second measurement in the same location as the first test.
  - **Initial test result above 8.0 pCi/L** (twice the action level): Perform another short-term test in the same location.
    - If the average of first and second result is above 4 pCi/L, you should mitigate the home.
  - **Initial test between 4 and 8 pCi/L -** A long-term test is recommended.
    - Long-term tests are conducted for a minimum of 91 days with no requirements for maintaining closed-house conditions.
    - The decision to mitigate a home should be made on the basis of the long-term test results, which are considered a better indication of exposure than is the short-term test result.
  - The diagram does not recommend mitigation after the initial test, but rather follow-up, confirmatory testing and, if confirmed, mitigation.

When conducting follow-up tests, expect your second result to be different, because radon entry can vary significantly as a function of weather. It is prudent to maintain the test results for disclosure when you sell your home in the future —especially any long-term test results.

3.2.2.2 Interpreting Results at the Time of Home Sale

Because time is of the essence during a real estate sale, negotiations typically use the results of an initial short-term test to determine the potential of the building rather than the exposure of its occupants. Presumably, such a test would have been performed by a radon measurement professional who would have added additional safeguards to increase confidence in the measurement to prevent tampering. The tester should have used one of the three strategies below:

Figure 24: Simultaneous Passive Measurements

Real Estate Testing Example
Two side by side test devices

Table 6: Testing Approaches at Time of Home Sale (Real Estate Testing)

Approach	Decision Basis
Two passive devices located four inches apart	Average of the two results
One Continuous Radon or Radon Decay Product Measurement Device measuring hourly levels	Average of minimum 48 hours of contiguous data
Two consecutive, two-day, short-term tests using passive detectors – in the same location	Average of the two results

The approaches listed above do not include repeating tests until you get a preferred result. In fact, if repeat tests are performed and they are all valid and conducted in the same location, average the results of multiple tests together. Of course, if a test or test conditions are tampered with, the result is invalid and should not be included in any averaging.

Actions for Elevated Results at the Time of Sale:

The action taken due to an elevated result is likely to depend on the details of the purchase contract and negotiations between the buyer and seller. Typically, the house would be mitigated and retested to verify acceptable radon levels prior to closing. However, there are other options. All homes can be fixed equally before or after the sale!

- Obtain bids from certified radon mitigation contractors who will guarantee results to at least below 4 pCi/L. Also be sure to review warranty for equipment, as well as continued radon reduction and how it will be verified.
- Possible approaches include:
  - Have the work performed and retested prior to closing;
  - Escrow funds for mitigation and have the work performed after closing;
  - Negotiate costs and have the work performed after closing; and
  - Use normal real estate negotiation procedures to negotiate costs of radon mitigation as one would with any other noted defect.
- Perform a long-term test after closing (minimum 91 days)
  - Escrowed funds from bids can be released based on the results of the long-term tests and the provisions of the escrow agreement.
- Do nothing at all and fix it after you move in.

When contemplating mitigation there are a few additional items that may be considered:

- Use a qualified radon mitigation contractor who guarantees results and will follow recognized procedures:
    - Obtains necessary permits;
    - Follows EPA or AARST protocols; and
    - Provides written contract with guarantees and warranties that are transferrable to new owners.
- Retest the building after the work has been completed.
    - This can occur as soon as 24 hours after completion.
    - Repeat the short-term test in the same location as the original test.
    - Use a certified radon measurement professional to conduct the test rather than the contractor themselves.
- Have input on how or where the system will be installed:
    - All homes can be fixed, but there are aesthetically different approaches.
    - Fixes can be very apparent or hidden.
    - Additional work can be done to improve performance as well as aesthetics.
- Even after the performance of the mitigation system has been verified with a short-term test, retest the home at least every two years.

After a home has been successfully mitigated, test at least every two years.

3.2.2.3 Long-Term Testing

Should you decide to conduct a long-term test as a follow-up measurement in either a real estate or non-real estate situation you should:

- Deploy it in the same location as the initial test.
    - Additional locations could be tested for better characterization of locations where you spend the majority of your time.
- Deploy in accordance with the instructions that come with the device.
- Deploy for a minimum 91 days up to a full year.
    - The longer it is deployed the closer the result will be to your long-term exposure.
- There is no requirement for maintaining closed-building conditions for tests lasting 91 days or longer.

Figure 25: Long-Term Test Example
Long-term test device suspended from ceiling

3.3 Testing Multi-Family Dwellings

This section details the specific steps to be taken when testing multi-family dwellings. For more in-depth information, refer to the earlier sections of this document.

This section provides a building owner with the basis by which radon testing would be conducted by a radon professional. Although a building owner or property manager may be allowed to test their own facility, it is recommended that the testing be conducted by a certified radon measurement professional adequately trained in multi-family testing. There are many complexities involved with performing such a survey.

Radon tests on multi-family dwellings such as apartment buildings or condominium complexes are performed for a variety of reasons:

- Refinancing or sale of the complex;
- Individual tenants' concerns about radon;
- As a proactive measure by the owner or property manager to improve tenant relations or avoid potential future liabilities and/or complications in future sales/refinancing; and
- Testing performed on an individual condominium unit as part of a real estate transaction.

How the test is conducted can depend on why it is being done, as well as the type of air-handling systems that exist for Heating, Ventilation, and Air Conditioning (HVAC) to the units. Typically, units have their own self-contained air-handling systems and airflows are not mixed from unit to unit. However, in some older buildings and other facilities air within the units is circulated back to central air handlers where it is conditioned and returned to the units. If the facility, or a portion of the facility (such as a clubhouse or common area), has a central air handler, then the test should be performed as described in the next section. See Section 3.4.

Use the table below to determine which section is applicable to your facility.

Table 7: Navigating the Multi-Family Measurement Section

Situation	HVAC Type	Section
Testing entire building	Each unit has its own independent ventilation system	This section
Testing entire building	Units served by radiant heating systems from a common boiler	This section
Testing entire building	Units served by a common air handler	Section 3.4
Testing entire building	Units served by radiant heating systems from a common boiler, but have centralized air conditioning system for cooling	Section 3.4
Testing Individual unit within complex (Individual condo sale)	No criteria for HVAC type	Section 3.2
Testing common area buildings e.g. clubhouses	Building served by a common air-handling system	Section 3.4

3.3.1 Unique Aspects of Radon Entry in Large Multi-Family Dwellings

All of the elements affecting radon entry occur equally in multi-family dwellings as they do in single-family residences; however, the effects can be more dramatic and certainly more complex in these large structures. Primary examples of these effects are:

- Unit to unit variation in foundation types
  - Example: Units over crawlspaces and other units over slabs
  - Exterior grade and location relative to prevailing winds
- Variable radon potential beneath the footprint of a large building due to different cut and fill approaches and/or materials.
- Pathways from soil to upper floor units that can cause upper floor units to have elevated radon levels even if the unit directly below it is not elevated.
  - Utility chases
  - Spaces between demising walls
- Tenant cooperation with closed-building conditions is needed for short-term (two-three days) measurement surveys
- Buildings constructed primarily with concrete can have elevated radium content in the concrete, which if low ventilation rates exist, can cause elevated indoor radon levels.
  - Single family construction utilizing lumber is less apt to have this concern, compared to much larger structures constructed with steel-reinforced concrete.

These situations lead to the following key elements of a multi-family radon survey:

- All tests should be conducted simultaneously to allow for unit to unit comparisons
- Test 100 percent of the units in contact with the ground
  - Slab-on-grade
  - Over crawlspace
  - Dirt berm on side of unit
- Test 10 percent of upper floor units with staggered test locations

3.3.2 Caution on Random Testing

Prior to the institution of multi-family testing protocols there was a tendency to do a random sampling (10 percent or 15 percent) of units with the idea that elevated readings were found, additional radon testing would be conducted.

To properly test a multi-unit building one is to sample:

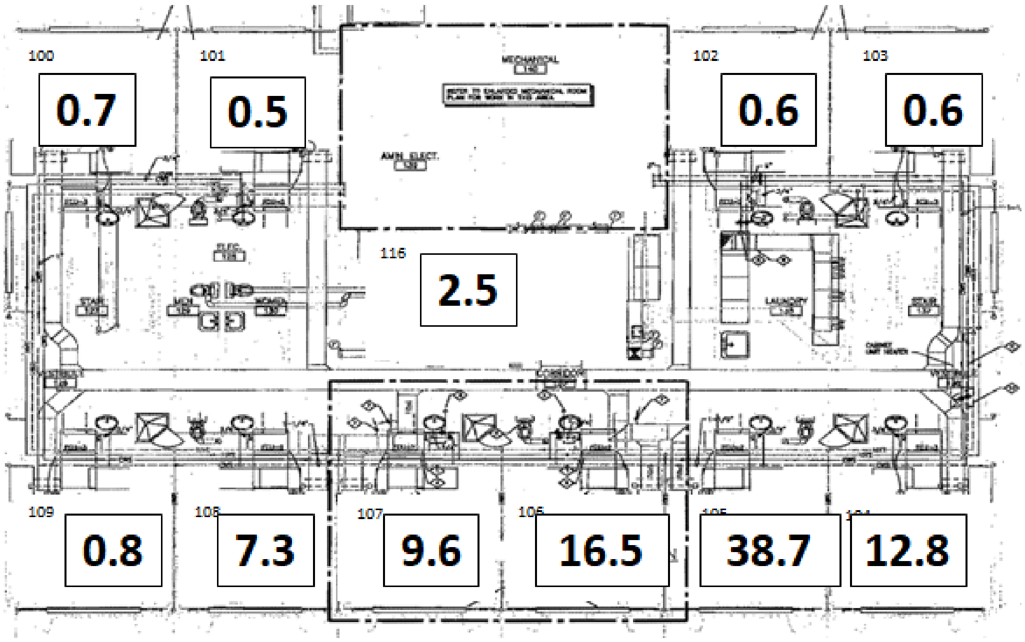
- ***100% of ground floor units***
- ***10% of upper floor units***

The problem with random samplings is the variability of radon entry due to the factors described above. A random sampling, especially one as low as 10 percent, is likely to miss units that have radon concerns.

Figure 26 shows an example of a radon survey conducted simultaneously within 11 apartment units in the same building. The results varied from a low of 0.5 pCi/L to a high of 38.7 pCi/L. If only 10 percent of the units had been tested (i.e. only one unit tested), it is highly likely the elevated units would not have been identified.

Figure 26: Example Variability of Radon in Multi-Family Building

Numbers shown in boxes are results of simultaneous short-term tests (pCi/L)
Compare to EPA Guidance of 4.0 pCi/L



3.3.3 Closed Building Conditions-Short-term Tests

Short-term tests are often utilized at the time of sale or refinancing. As described in more detail in Section 2 of this document, short-term tests determine the radon potential rather than actual exposure.

When conducting a short-term radon test, all exterior doors and windows throughout the building are to be kept closed other than momentary entry and exit.

ALL doors and windows should be closed, because their position can affect radon entry, not only in a given unit but other units within the building as well. This includes keeping doors and windows closed on upper floor units that have not been selected as part of the 10 percent upper-floor requirement. Maintaining these conditions during a building survey is perhaps one of the most challenging aspects for a property manager and radon professional. It requires good communication and vigilance.

3.3.4 Quality Assurance and Quality Control

Multi-family surveys are typically expensive and involve a large number of test locations. For this reason, it is necessary to incorporate quality assurance and control measures to ensure confidence in the results. Some of these measures will require additional measurement devices and outside services that add cost to the project. Table 8 details these additional requirements.

Table 8: Quality Control and Quality Assurances Means and Interpretation

Type	Description	Frequency	General Criteria for Acceptability
Duplicates	Side by side devices (4 inches apart)	10 percent — 1 for each 10 locations	Aggregate average of Relative Percent Difference for those pairs deployed in environments greater than 4.0 pCi/L should be less than 25 percent
Blanks	Blanks deployed but not exposed to room air.	5 percent — 1 for each 20 locations	Lab results should be at or near the Lower Level of Detection of the lab (typically less than 1 pCi/L)
Blind spikes	Devices sent to a radon chamber for exposure to a known radon level.	3 percent — 3 for each 100 locations	Results from lab should be within 25 percent of the radon level the device was exposed to in the third-party chamber. (Typical results are within 10 percent)

It should be noted that different protocols will treat QA/QC a little differently depending upon the size and purpose of the survey. The table above provides a common thread to these protocols. It is critical that QA/QC specific protocols be followed and response actions be taken if acceptable parameters are not achieved. Building owners should insist that QA/QC be included in survey proposals.

3.3.5 Strategies for Testing Multi-Family Dwellings

There are two basic testing methodologies, or a combination thereof, that are available when conducting a full-building radon survey. The two methodologies are summarized in the table below. Note: If testing a single unit, refer to the procedures described in the Section 3.2.

Table 9: Multi-Family Testing Time Frames and Conditions

Type	Typical Duration	Purpose	Building Conditions During Test
Short-term	Two-three days	Determine radon potential	Closed building
Long-term	91 days up to a full year	Determine normal exposure	Normal lived in

The methodology chosen depends on the reason for the radon survey. If time is of the essence, such as in a sale or refinance, the short-term methodology will be utilized. Short-term testing has the advantage of getting quick results, but can be a challenge, because closed-building conditions will be required of all tenants.

If time is not of the essence, long-term testing can relieve the difficulties of maintaining closed-building conditions. On the other hand, results may not be available for several months based upon the duration of the test (minimum 91 days).

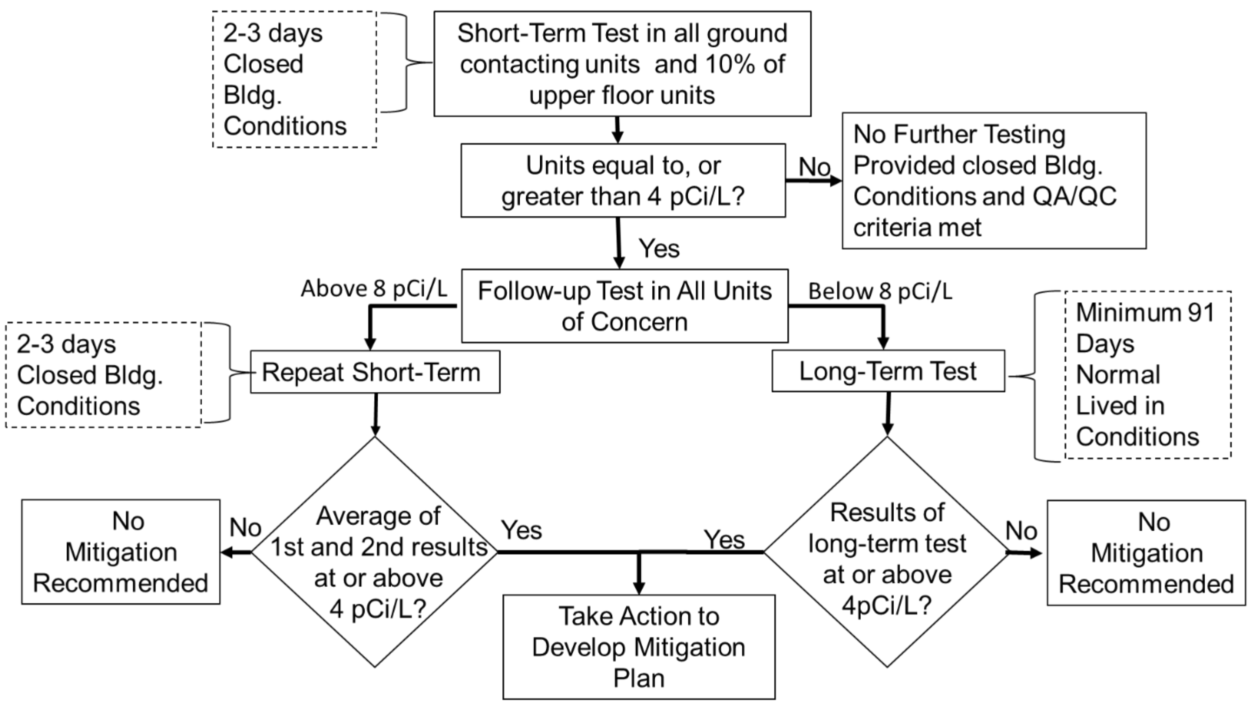
The following subsections describe options that a building owner can discuss with the radon professional depending upon timing and needs. In reviewing these, remember that in all options:

- Minimum testing period is two days
- 100 percent of units in contact with the ground and at least 10 percent of upper floor units are to be tested
- Follow-up action should occur when radon levels are found to be at or above 4 pCi/L
- QA/QC measures to be in place during the survey
- Communication with occupants is critical

3.3.5.1 Option 1: Initial Survey: Short-Term to Long-Term

This approach involves doing an initial survey to identify potential concerns and then following up with long-term tests to determine actual exposure, with long-term results determining the need for mitigation efforts. This approach is similar to that suggested for testing single-family residence, except the scope of test locations is much larger. This method, if initial results are found to be elevated, could take approximately four to seven months to complete.

Figure 27: Multi-Family Testing Short-Term to Long-Term Testing



In this approach, preference is given to long-term testing under normal lived-in conditions. However, short-term test results should be scrutinized closely if changes to the HVAC system are contemplated that would make closed-building conditions more prevalent. An example would be adding air conditioning to a building where windows and doors would most likely be closed in the future.

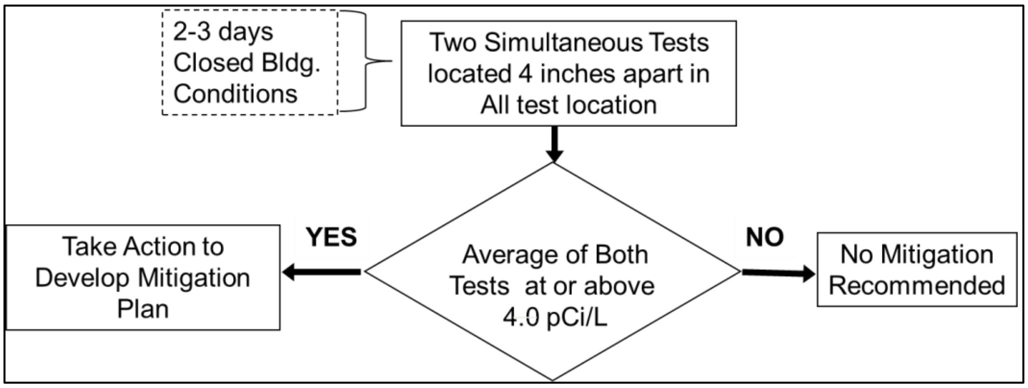
If elevated short-term results are obtained, yet long-term results are low, the building site has the potential for elevated levels and retesting in the future is recommended.

3.3.5.2 Option 2: Initial Survey: All Short-Term Tests

This approach is appropriate when time is critical and there is no ability to conduct long-term follow-up assessments.

Because this approach does not include long-term testing, radon professionals may place duplicate tests in all locations, rather than just the 10 percent as required for QA/QC requirements — in other words, 100 percent duplicates. This approach is similar to the testing protocols for single-family residents at the time of sale.

Figure 28: Multi-Family Testing All Short-Term Tests



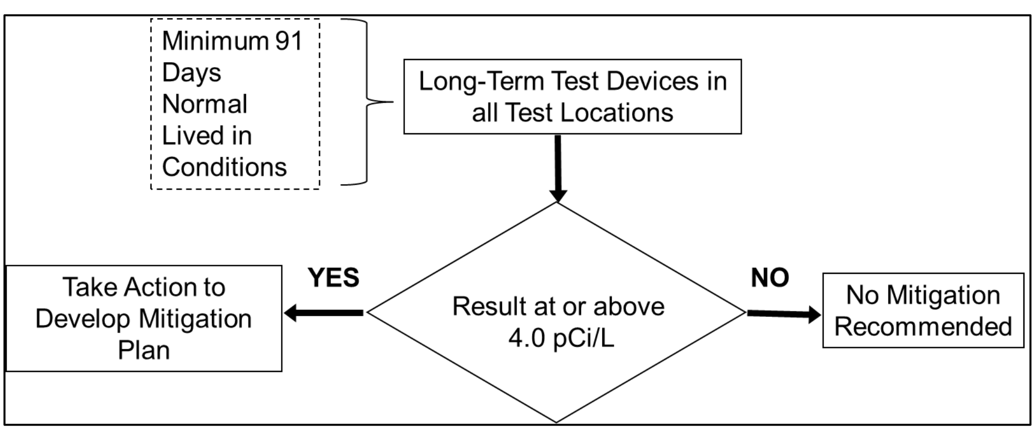
The advantage of this approach is that quick results are obtained. One disadvantage is that units that tested low may have tested low because the occupants did not maintain closed-building conditions and possibly should be mitigated. Another disadvantage is that some units might be mitigated unnecessarily if a long-term test had been conducted.

3.3.5.3 Option 3: Initial Survey: All Long-Term Tests

Another option is to conduct all long-term tests initially. This approach is appropriate where time is not of the essence and a real estate transaction is not in process. Examples of this situation include closely held housing complexes such as:

- University housing
- Military housing
- Detention facilities

Figure 29: Multi-Family Testing All Long-Term Tests



One advantage of the long-term-only approach is that occupants need not maintain closed-building conditions.

Greater confidence is also given to long-term results because the result encompasses more weather conditions. However, there can still be a weather bias if the minimum 91-day test period was in the summer versus the winter. Many radon professionals will use this approach and suggest extending the test period to six months if not a full year in order to avoid seasonal bias.

3.3.6 Communication Plans

When conducting surveys in multi-family dwellings, communication is critical. Tenants must be educated about the purpose of the testing, the device and the importance of following test protocols, such as closed windows.

Communication to occupants should occur at least one to two weeks before testing is initiated and repeated the day before testing begins. The radon professional should provide the following information to the property manager, who should then distribute it to occupants:

- Indicate radon is being tested for and provide links to state and federal websites for further information
    - Hiding what is being tested can be problematic
    - Most people know what radon is and are not overly concerned
- Test start and stop dates
- Description of test device
    - Photo of device to be deployed
    - Not a listening device or hidden video camera
    - Poses no risk to occupant
    - Only a few minutes needed within the unit to deploy and later retrieve
- What will happen to results
    - Available for tenant review?
    - Hiding results can cause problems
    - Make available in office for review
- Why survey is being done
    - If there is a known problem, or
    - Part of a normal survey process
- What the occupant needs to do
    - Closed-building conditions if short-term test is being performed
    - Do not disturb or remove the device
- Who to contact if they have questions or if the device falls
    - This should be a person the occupant is familiar with such as the facility maintenance person or facility manager

3.3.7 Mitigation/Follow-up Actions

If a survey identifies units where radon levels need to be reduced, a radon professional should be brought in to assess the situation and develop a mitigation plan.

Fixing multi-family buildings can be very complex but can also be fairly innovative. The following items can assist with designing an effective and cost-effective solution.

- Retesting with more sophisticated devices
- Testing other locations
- Evaluating non soil gas sources, such as water supply and building materials
- Evaluate alternative approaches, such as HVAC adjustments and reducing radon decay products
    - Beneficial when dealing with high-rise structures
- Performing diagnostics that simulate active soil depressurization systems
    - Identifies coverage areas for soil depressurization systems
    - Can reduce the number of systems required

Radon professionals experienced in large buildings, working with building maintenance personnel, mechanical contractors, etc. can save the building owner money, not only in immediate capital cost, but also operation, and maintenance costs in the future.

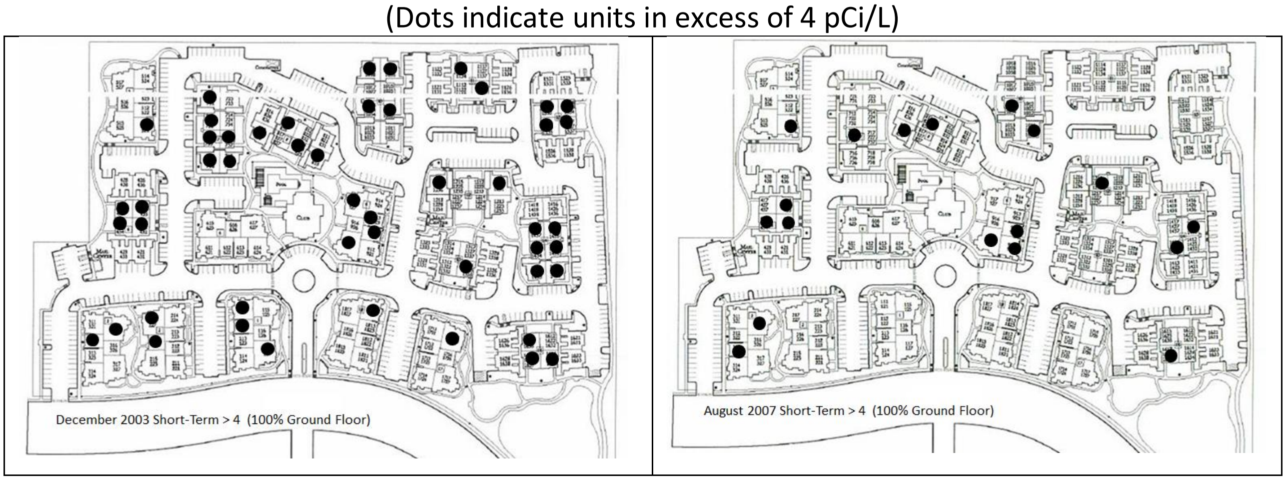
3.3.8 Retesting in Future

It is recommended that multi-family buildings located in high radon potential areas, such as the state of Colorado, should be tested at least once every five years and at the time of refinance or sale.

The retesting should follow the aforementioned protocols. Figure 30 illustrates how radon levels can change within an apartment complex. The dark dots in the two diagrams indicate short-term results above 4 pCi/L from identical surveys taken four years apart.

Figure 30: Comparison of Short-Term Results – Four Years Apart

(Dots indicate units in excess of 4 pCi/L)

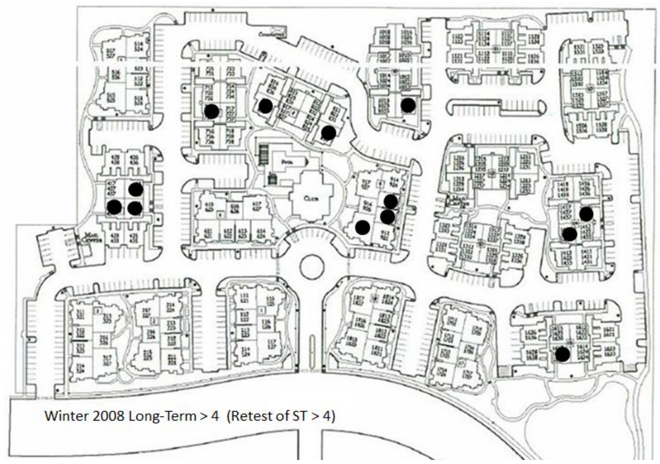


Certainly, the radon source potential of the underlying soil did not change over four years and there were no major modifications to HVAC systems. So the difference could be attributable to three things:

- Occupants did not adhere to closed-building conditions.
- New tenants may have different living habits.
- The time of the year the tests were conducted was different i.e., December versus August.

The illustration also points out the need to do 100 percent retesting.

In comparison, long-term tests were also conducted in the same complex. The results are depicted on the right and indicate fewer locations that were confirmed to require mitigation than were indicated in either of the short-term surveys.



Long-term test results for same complex.

3.3.9 Retesting after Mitigation

Once a building is mitigated, the mitigated units should be tested at a minimum of once every two years with either a short-term or long-term test devices.

- Note that some financial institutions require annual retesting

Other units that were not mitigated should be included in post-mitigation surveys to ensure that radon levels have not increased.

3.4 Testing Schools and Commercial Buildings

This section details the specific steps to be taken when testing schools and commercial buildings. Should a reader want more in-depth information, refer to the earlier sections of this document.

This section provides a building owner with the basis by which radon testing would be conducted by a radon professional. Although a building owner or property manager may be allowed to test their own facility, it is recommended the survey be conducted by a certified radon measurement professional adequately trained in large building radon surveys.

3.4.1 To What Types of Buildings Does this Section Apply?

The primary criteria for utilizing the approaches described in this section is the effect that large, central forced-air heating and air conditioning systems can have on radon entry and indoor radon levels. Due to high occupancy, fresh air make-up is typically forced into the building to control indoor air pollutants and to reduce the build-up of bio effluents such as carbon dioxide.

Furthermore, the types of buildings discussed in this section are typically not occupied around the clock or on weekends. Consequently, where energy management practices are utilized that reduce the addition of outdoor air during unoccupied periods (such as nights and weekends), radon levels can vary significantly during a given day.

Finally, because the impact of the building's air-handling system can be so dramatic, the maintenance of these systems, including room-to-room balancing of delivered and exhausted air flows, is critical to the control of indoor radon levels.

The approaches within this section apply to any building that:

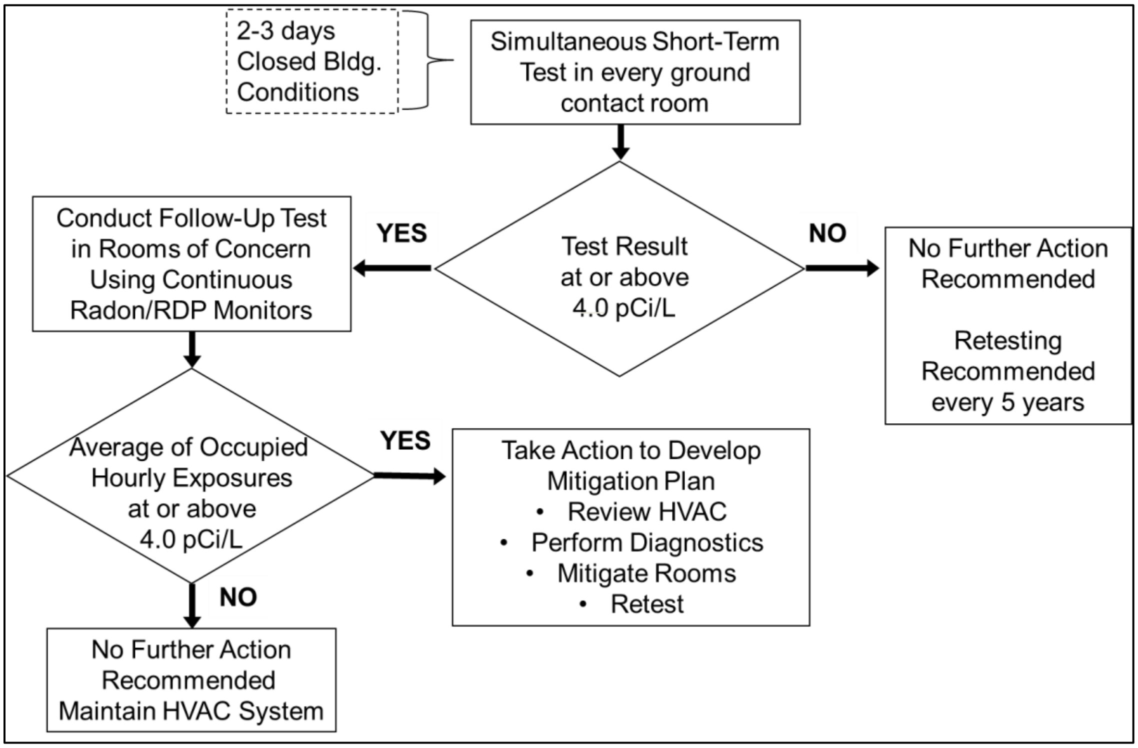
- Has a large, centralized forced-air heating and cooling system
- Has an energy management plan that differentiates between occupied and unoccupied periods
- Is not likely to be occupied 100 percent of the time

3.4.2 Strategy for Testing Schools and Commercial Buildings

- Short-term measurements are deployed during the work/school week with follow-up testing to track radon levels during occupied vs. unoccupied times
- 100 percent of frequently occupied rooms in contact with the ground are tested
  - The effect of unbalanced HVAC systems is so pronounced that every occupied, ground contacting room is to be tested

Figure 31 illustrates the first step, to conduct a two- to three-day test during the school/work week to identify potentially elevated rooms. As a follow-up, to determine actual occupant exposure, a measurement device can be used to record hourly radon levels. These results can be used to determine occupied and non-occupied exposure levels.

Figure 31: Testing Buildings with Centralized HVAC Systems with Energy Mgmt. Plans



It is common for survey results to reveal that a small percentage of rooms are elevated. This is typically due to an unbalanced HVAC system that often can be corrected by building maintenance personnel or mechanical subcontractors.

3.4.3 When to Test

Tests should be conducted during periods that best reflect when the building is occupied. Use the following parameters to schedule the survey:

- When the building will be occupied
  - Typically during school/work week
  - Do not test on weekends or holidays when the HVAC system would be in set-back mode
  - Select a two- to three-day period such as Monday to Thursday or Tuesday to Friday
- When closed-building conditions can be met — all exterior doors and windows closed other than normal entry and exit
- When economizers that supply 100 percent outdoor air to the building are not operational

Tests should be conducted in November and or December (excluding holiday breaks) or January through March (excluding spring break).

Do not test over summer break, even if the building may be operating normally.

If HVAC or building modifications are planned, it would be prudent to conduct the test after these are completed.

3.4.4 What Rooms to Test

Initial short-term measurements should be conducted in ALL frequently occupied rooms that are in contact with the soil or directly above the soil (e.g. over crawlspaces) or have soil bermed onto a side.

- A room is defined as an area having floor-to-ceiling walls
  - Effects of HVAC can be isolated to individual rooms
  - Office cubicles divided by partitions that do not extend to the ceiling are not considered to be separate rooms and therefore do not need to be individually tested
- An occupied room is one that is either occupied or could be occupied
  - If a room has been converted to storage, but could be occupied, test it.
  - If a room can be occupied, it should be tested, regardless of how often it is used.
  - It is not necessary to test hallways.
    - They are not frequently occupied
    - HVAC systems can cause hallways to be under high negative pressure, causing high readings
- Rooms with high humidity are not tested due to potential interference with test devices. These rooms would include bathrooms, locker rooms, saunas and kitchens.

The table below provides some guidance:

Table 10: Ground Contact Rooms to Test and Not Test in Large Buildings

Room	Test	No Test
Classroom	X	
Individual offices with floor to ceiling walls	X	
Individual/partition offices within larger open areas where office walls do not extend to ceiling (However the general open area would be tested at a rate of one test location/2,000 square feet)		X
Hallways		X
Kitchen area (food prep, dishwashing, freezers)		X
Kitchen office	X	
Music practice rooms	X	
Boiler room		X
Boiler room used as an office	X	
Cleaning supply closet (unless used as an office by janitor)		X
Storage only rooms (not convertible to occupied space)		X
Electrical vaults		X
IT server rooms (not occupied)		X
Security offices	X	
Conference rooms	X	
Break rooms / Teacher prep rooms	X	
Bathrooms		X
Cafeteria / Gymnasium	X	
Library/Media center	X	
Auditorium	X	
Athletic director office	X	
Athletic equipment storage		X
Maintenance facility	X	
Temporary buildings/classrooms that are or could be occupied	X	

Special Consideration for Large Open Areas

In rooms larger than 2,000 square feet such as auditoriums, libraries and gymnasiums, additional test devices should be deployed at a rate of one per 2,000 square feet. These additional devices should be distributed around the room (such as opposite ends). Large rooms with small office cubicles should follow the same one per 2,000 square feet rule.

3.4.5 Test Devices

Given the large number of devices that will typically be deployed, passive radon measurement devices will likely be used. These devices would have the following characteristics:

- From a laboratory certified by the National Radon Proficiency Program or the National Radon Safety Board
- Small unobtrusive devices that are hung from ceiling or can sit upon a cabinet
- Shipped to an independent lab for analysis

Figure 32: Examples of Common Radon Measurement Devices

		
Activated charcoal device hanging from ceiling	Electret ion chamber setting on cabinet where it will not be disturbed	Activated charcoal canister deployed on desk

3.4.6 Quality Assurance and Quality Control

Schools and commercial building surveys typically involve a large number of test kits and locations. For this reason, quality assurance and quality control (QA/QC) measures must be put in place. This requirement may result in additional measurement devices and outside services that will add cost to the project, but are justifiable and common in other types of environmental sampling programs.

Table 11: QA/QC Requirements and Interpretation for Schools/Commercial Buildings

Type	Description	Frequency	General Criteria for Acceptability
Duplicates	Side by side devices (four inches apart)	10 percent — one for each 10 locations	Aggregate average of relative percent difference for those pairs deployed in environments greater than 4.0 pCi/L should be less than 25 percent
Blanks	Blanks deployed but not exposed to room air.	5 percent — one for each 20 locations	Lab results should be at or near the lower level of detection of the lab (typically less than 1 pCi/L)
Blind Spikes	Devices sent to a radon chamber for exposure to a known radon level.	3 percent — three for each 100 locations	Results from lab should be within 25 percent of the radon level the device was exposed to in the third party chamber. (Typical results are within 10 percent)

Different testing protocols may treat QA/QC a little differently as a function of the survey size and purpose. The table above provides a common thread to these protocols. It is critical when reviewing survey proposals that they include QA/QC, the specific protocols to be followed and response actions that will occur if parameters for acceptability are not achieved.

3.4.7 Communication Plans

When facilitating surveys in large buildings, communication is critical. Employees, staff members and parents can become highly concerned when any type of survey is done, especially one that has radiation associated with it.

Communication is recommended to occur at least one to two weeks before the test is initiated and repeated the day before the test begins. The following list of elements should be considered when developing the notice. The radon professional conducting the survey should provide this information to the client for distribution to impacted parties.

- Test start and stop dates
- Description of test device
    - Photo of device to be deployed
    - Not a listening device or hidden video camera
    - Poses no risk to occupant
    - Only a few minutes to deploy
- What will happen to results
    - Available for staff and parent review?
    - Hiding results can cause problems

    - Make available in office for review
- Why survey is being done
    - Part of a normal survey to protect students and staff
- Indicate it is radon being tested for and provide links to state and federal sites for further information
- What the students and/or staff need to do
    - Closed building conditions if short-term test is being performed
    - Do not disturb or remove device
- Who to contact if they have questions or if device falls
    - This should be a person who is familiar to staff and students such as the principal or maintenance person/janitor

3.4.8 Follow-up Actions

There are a few follow-up actions to consider prior to proceeding to mitigation.

3.4.8.1 Use of Continuous Monitors as Follow-Up Measurement

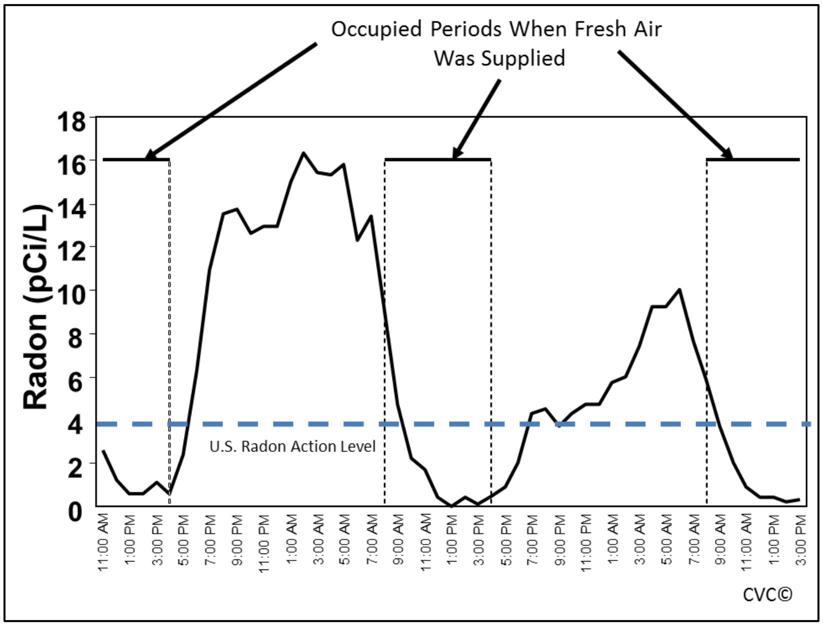
If a short-term test identifies rooms with elevated radon levels, it does not necessarily mean these are the levels to which the occupant is being exposed. Short-term tests provide an average exposure over its deployment period. They do not separate radon levels between occupied vs. non-occupied time.

Consequently, one follow-up action could be retaining a radon professional to deploy a continuous radon or radon decay product monitor that reports hourly levels to discriminate between occupied and unoccupied periods. To do this:

- Deploy continuous monitor in room or rooms of concern
- Deploy for a minimum of two days during the normal school/workweek
- Maintain building conditions as you did during the initial short-term test
- Identify occupied and unoccupied times of the building
    - Take into account after-hours staff and evening activities
- Determine occupied and unoccupied averages from hourly data and determine if follow-up action is required.

Figure 33 provides a comparison of occupied and unoccupied averages (This was explained in more detail within Section2.2.3)

Figure 33: Determining Occupied vs Unoccupied Exposures



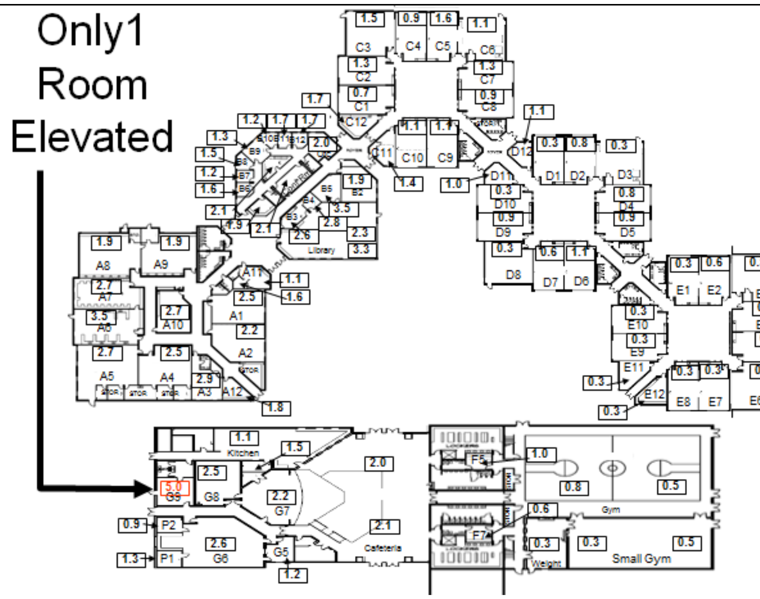
Radon levels dropped significantly when fresh air is supplied to the building.

HVAC Repairs as a Follow-Up Action

After the initial results are obtained, it is helpful to transfer them to a building diagram that can point out trends or perhaps elevated readings associated with a specific zone of the HVAC system. A review of these HVAC systems by maintenance personnel can often identify a readily fixable situation and then verify with a retest of that location.

Figure 34 provides an example of a school where all rooms but one had low radon levels. Investigation by maintenance personnel revealed the belt on the air handler had broken. This was easily fixed, but also points out the importance of HVAC maintenance as well as the need for retesting in the future.

Figure 34: Example of HVAC Caused Problem



Measurements in all rooms except 1 were well below 4.0 pCi/L

- Broken belt on air handler caused problem in one room
- HVAC needs to be maintained
- Radon levels can point out HVAC problems

A number of things can cause radon concerns, which can be reviewed without a radon professional:

- Closed outdoor air dampers
  - Boarded over
  - Freeze protection switches broken causing outdoor air dampers to be closed
  - Dirty outdoor air filters
  - Dirty dehumidification coils
- Energy management system timing is off
  - Reprogram
- Unbalanced air flows
  - Room split with return on one side of partition and supply on other side
  - Balancing dampers are not correctly adjusted
  - Fusible link fire dampers have failed
- Exhaust fans without outdoor air to provide make up air

Oftentimes, solving these problems will also solve other indoor air quality issues.

Correction of these issues is often required before normal active soil depressurization mitigation approaches are feasible. A review of the HVAC system makes good sense as a follow-up measure; but always retest to verify. If it doesn't work, then call in the radon mitigation professional who may work in tandem with the building's HVAC contractor to develop a complete solution.

Fixing buildings can be complex, but can also be fairly innovative if you allow for an investigation and design phase. This can include but not be limited to the following items that not only help identify the source but also help develop a cost-effective solution.

- Retesting with more sophisticated devices
- Testing other locations
- Evaluating non-soil-gas sources such as water supply and building materials
- Evaluate alternative approaches such as ventilation or radon decay product reduction as opposed to the normal active soil depressurization systems
- Performing diagnostics that simulate active soil depressurization systems
    - Identifies coverage areas for soil depressurization systems
    - Can reduce the number of systems required

The bottom line is a radon professional experienced in large buildings, working with building maintenance personnel; mechanical contractors etc. can save the owner money, not only in immediate capital costs, but also operation and maintenance costs in the future.

3.4.9 Retesting in Future

It is recommended that schools and large buildings located in high radon potential areas, such as the entire state of Colorado, are tested at least once every five years and at the time of refinance or sale.

It is also recommended they be retested after major HVAC or building modifications.

When retesting a building that previously had elevated levels, one should test all ground contact rooms, not just the rooms that were previously elevated.

When mitigation or HVAC adjustment efforts have been needed, it is critical to understand the elevated radon measurements shown to occur in only a few rooms indicates the potential of the entire building. Yes, in 2017, the problem may be in Room 102 due to an unbalanced HVAC, but in 2021 the problem could move to Room 110 that previously tested low solely due to a malfunction in the HVAC system. Consequently, when performing resurveys, you should test all of the rooms tested in the original survey, rather than just those that were previously of concern.

Buildings that have been mitigated should be retested after major HVAC or building modifications but no longer than the following frequency:

Table 12: Frequency of Retesting Schools & Commercial Buildings after Mitigation

Building Type	Frequency
Schools	Once per year
Non-School Buildings (commercial usage)	Once every five years

3.5 Testing Child Care Facilities

Child care facilities are also locations of radon exposure and in many states including Colorado; radon testing of licensed child care facilities has been mandated by statute.

Some child care facilities are essentially like residential building and in the past, some owners have tested them as though they were single family homes. However, due to the potential variations in room to room exposure levels and concern for the safety of children occupying these different rooms, all occupied, ground contact rooms are to be tested, rather than a single location on the lowest level. In other words, child care facilities are to be tested using the same protocols as are used for schools as described in Section 3.4.

When testing a child care facility, simultaneously test all occupied rooms in contact with the soil. Test like a school.

As is the case with schools, a communication plan for staff and parents is critical to avoid undue concern. The communication plan suggested for schools provides a good outline to follow. See section 3.4.7

The use of a radon professional to at least oversee the survey including the requisite Quality Assurance and Quality Control is advised.

For additional guidance and training opportunities for facility operators, visit:

www.colorado.gov/cdphe/child-care

4 TECHNICAL GUIDANCE DOCUMENT: INSTALLING RADON MITIGATION SYSTEMS IN SINGLE FAMILY HOMES, MULTI-FAMILY DWELLINGS, AND LARGE BUILDINGS

Methods for Mitigating Radon in:

- Existing Residential Buildings
- Existing Schools and Commercial Buildings
- New Homes
- New Large Multi-Family Dwellings and Commercial Structures

4.1 Overview of Radon Mitigation Techniques

4.1.1 Definition and Objectives of Radon Mitigation Systems

Radon reduction systems are referred to as "mitigation" systems. They control radon, rather than removing the radon source, as would be the case with the removal of asbestos or contaminated soils. The source of radon gas is the underlying geology beneath structures. Mitigation systems reduce the entry of radon from beneath the building or dilute radon after it has entered the building. Radon systems must be operated continuously and must be maintained like any other mechanical system (e.g., a furnace or a water heater).

There are several objectives that should be met when installing a radon mitigation system:

- Designed as an integral part of the building
- Durable and easily repairable
- Easy and inexpensive to operate
- Easy to maintain
- Quiet and unobtrusive
- Reduce radon decay product (RDP) exposure by either:
    - Reducing radon gas (most common), or
    - Reducing airborne radon decay products
- Decrease long-term indoor exposures to less than 4.0 pCi/L of radon gas and/or 0.020 WL of radon decay products
- Have a method to indicate when system components fail
- Have a program of retesting established to ensure continued functionality
    - Retesting after mitigation system installation or occupation
    - Retesting of mitigated schools annually
    - Retesting of mitigated residences every two years

4.1.2 Overview of Radon Mitigation Approaches

The methods used to reduce radon risks address the factors that cause radon to enter a building. To learn more about those factors, see Section 2.

4.1.2.1 Reducing Radon Entry

The vast majority of radon entering buildings come from the movement of radon-laden soil gases through a building's foundation. These soil gases enter a building either by interior vacuums that pull soil gases in (due to stack effect or exhaust fans) or are pushed into the building when the underlying soil is pressurized (e.g. wind striking hillsides). Systems that alter the pressure differential between the interior of the building and the subgrade effectively reduce radon entry. These systems typically utilize fans to create sub-grade negative pressure and are referred to as Active Soil Depressurization (ASD) systems.

Due to the pervasive nature of radon and the fact that these are individual atoms, caulking and sealing alone is NOT an effective technique for mitigation. However, caulking and sealing is utilized to make active soil depressurization work more effectively and prevent the loss of interior conditioned air.

Caulking and sealing foundation openings alone does not prevent radon entry. It is however used to make proper mitigation systems work better.

Soil gas entry can also be reduced by pressurizing the interior of the building, thereby reducing the flow of radon in through the foundation. This is not a very practical method in residential buildings due to the amount of air that would need to be forced into the interior. However, the introduction of fresh outdoor air into schools and commercial buildings is an integral part of their air quality program, and if designed and operated properly, can reduce radon entry and dilute interior radon levels. The outside air must be conditioned — the expense of which is already planned in large buildings, but could be cost-prohibitive in residential structures.

Active Soil Depressurization is the primary, initial method used in mitigating indoor radon.

Systems that draw radon out from beneath the foundation before it enters the building are referred to as Active Soil Depressurization systems (ASD). ASD is the most successful (and relatively inexpensive) in reducing elevated indoor radon levels, especially when extreme radon levels are encountered. There are situations when the source of radon may not be totally from the underlying soil. In these cases, alternate approaches can be used as trim techniques to fully reduce the radon.

4.1.2.2 Reducing Radon Risks From Within the Building

There are situations where it is necessary to address the radon concern from inside the building. Although ASD systems work very well, there are cases where radon is coming from internal building materials or diffusing through the slab and the reduction of radon from the soil via ASD will provide no benefit. For example:

- When ASD systems cannot fully reduce radon and additional reductions are needed;
- When radon emanates from interior walls of the building, such as from concrete with elevated levels of radium;
- When radon passes directly through a concrete slab (very rare and would require a radon professional to diagnose);
- When radon levels are only slightly elevated and other indoor air quality concerns exist that can be addressed with alternate techniques; or
- When radon is conveyed into a building via well water.

The table below provides some guidance and applicability to common and alternate techniques for radon reduction.

Table 13: Summary of Radon Mitigation Approaches and Application

Approach	Description	Application	Source: Soil Gas	Emanation[3]	Diffusion[4]	Radon in Water[5]
Active Soil Depressurization	• Draws radon laden soil gases from underlying soil	Applicable up to very high radon levels	X			
Increased Ventilation	• Dilutes radon by adding outdoor air • A common practice in large buildings • Can be done in residential buildings via heat recovery ventilators to reduce energy impact	Radon less than 8 pCi/L	X	X	X	
Radon Decay Product Reduction	• Reduces decay products of radon by circulating air through higher efficiency filters in whole house or central air handling systems. • Reduces RDPs – not radon gas	Radon less than 8 pCi/L and where airborne particulate reduction is beneficial	X	X	X	
Removal of Radon from Water	• Treats all water used in home other than that used for irrigation. • Employs aeration and disinfectant system, or runs water through large whole house charcoal filter	Only applicable for radon from water supply				X

[3] Where radon is released from the surface of interior building materials (like high radium-containing rock or concrete).
[4] Where radon can pass through an uncracked slab due to high concentration in radon beneath the slab.
[5] Where high levels of radon gas are dissolved in a building's potable water supply — as water is brought directly into a building (without being stored in an exterior, vented storage tank such as a cistern), the radon will degas from the water and enter the indoor air adding an additional amount of airborne radon above and beyond that which comes from the underlying soil. This is rare, but has been found to present a problem in mountainous communities where well water goes directly into a pressure storage tank within the home prior to distribution.

4.1.3 Prescriptive Standards vs Performance Based Approaches

There are several documents that provide a prescriptive approach as to how radon systems are to be installed without a performance requirement that post-mitigation levels are below 4.0 pCi/l.

Radon technology has advanced to the point where radon professionals are willing to provide performance-based guarantees to reduce levels to less than 4.0 pCi/L-even when all elements of the prescriptive guidance levels are not met. An example of this would be where a basement area has been finished and access to floor-to-wall joints for prescribed sealing would be impractical-and in most cases not necessary to reduce indoor radon to less than 4.0 pCi/L.

One of the goals of this guidance is to provide a technical basis by which a performance-based approach can be taken in lieu of a totally prescriptive path provided that:

- All building codes are followed
- Safety aspects of the prescribed codes/guidance levels are met, such as:
    - Safe location for discharged radon
    - System monitoring features provided
    - No back drafting of combustion appliances
- Durable installation
- Post-mitigation testing to verify performance guarantee is met
    - Short-term test and
    - Long-term testing

4.2 Soil Depressurization Techniques (New and Existing Buildings)

Soil depressurization reverses air flow direction. Air goes DOWN rather than UP through foundation.

Soil depressurization is the most widely used and successful approach for reducing radon in buildings. It creates a negative pressure under the foundation that reverses the direction of soil gas flow. Prior to mitigation, radon-laden soil gases can flow up and into the building through the smallest of openings. After mitigation, the direction of airflow is from within the house down into the soil, retarding radon entry.

In essence, the radon system creates a vacuum under the building stronger than the vacuum being applied to the soil by the building itself. It draws out radon-laden soil gases with a continuously operating fan and exhausts it to the outside of the building at a location where it will not re-enter through windows and other openings.

The success of these systems depends on the ability to create a suction area under the building. The larger the area of influence, the more successful the reduction will be and can be enhanced by:

- Having permeable fill under a slab;
- Having installed a length or loop of perforated pipe under the slab during construction;
- Adding an additional suction point to increase the area of impact; and
- Maximizing sub-grade suction by caulking and sealing foundation leak points, such as perimeter floor to wall joints.

Soil depressurization is accomplished by creating a suction point below the slab and connecting to it a piping/vent system that either uses a fan to create the vacuum (active soil depressurization) or routing the vent piping up through a heated, interior space to allow the pipe to act like a chimney and create a slight vacuum due to stack effect (passive soil depressurization). The two approaches are described in the table below:

Table 14: Definition and Application of Active vs. Passive Mitigation Systems

Type	Description	Application
Active	• Uses a continuously operating, inline fan to forcibly draw radon out from the soil • Typical power consumption: 60-100 watts	• Existing buildings where allowance has not been made to facilitate subgrade radon collection. • Augment passive systems that do not adequately reduce radon (see below). • New construction of large buildings to maximize collection area and minimize number of systems.
Passive	• A pipe routed from the subgrade, up through the house and extending through the roof. Thermal draw on pipe creates slight negative pressure on soil	• Used exclusivity in new home construction where permeable aggregate or a soil gas collection system has been installed in the subgrade during construction to make radon gas collection easier

4.2.1 Three Types of Depressurization Methods

The method by which soil depressurization is accomplished is a function of the foundation type or the existence of a surface water drainage system.

The complexity, and hence cost, is not a function of the indoor radon levels but rather a function of the building's foundation. This approach is very effective with extremely elevated radon levels.

The mitigation system complexity and cost is a function of the building's foundation and not the indoor radon levels.

There are three basic approaches (or combination of approaches) for capturing radon-laden soil gases via a soil depressurization system. These are illustrated in Figure 35 with additional details below.

Figure 35: Diagrams of Three Primary Soil Depressurization Approaches

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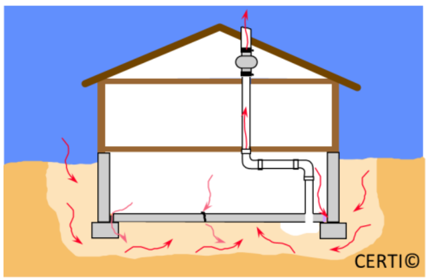
<td>
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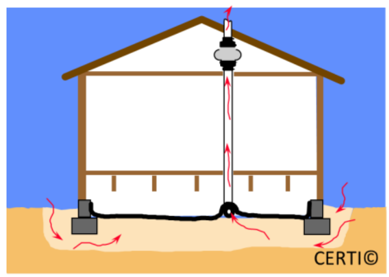
<td>
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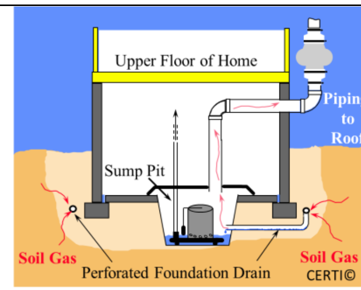
<td>
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<tr>
<td>Sub-Slab Depressurization (SSD)</td>
<td>Sub-Membrane Depressurization (SMD)</td>
<td>Drain Tile Depressurization (DTD)</td>
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4.2.1.1 Sub-Slab Depressurization

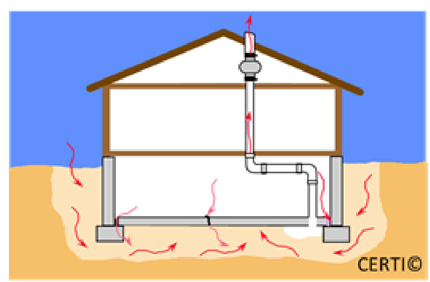


Figure 36 Sub-slab depressurization

- Utilized where a concrete slab is in direct contact with the soil or base fill.
- Existing Homes:
  - Hole is cored near perimeter of slab.
    - Typically, one core is sufficient.
    - Additional core/connection points are needed if footings or bearing walls separate slab areas.
  - Suction points are dug out beneath slab to form a small void space.
    - Typically dug by hand, removing five to 10 gallons of earth
    - Facilitates soil gas collection
- New Homes
  - Loop of perforated pipe or soil gas collection mat under slab connected to radon vent pipe, or
  - Four inches of clean aggregate completely under slab with assurances that pathways are created between grade beams and intermediate foundations
- Vent Piping System

- Collection points are connected to vent piping system where collected soil gases can be exhausted safely to atmosphere.
    - Optimal four-inch (minimum three-inch), schedule 40 PVC or ABS pipe
    - Existing homes almost always require an active fan to pull radon gases from beneath the slab.
- Caulking and Sealing Slab joints
    - Minimizes loss of conditioned interior air and maximizes sub-slab vacuums and radon collection efficiency.
        - Existing buildings
            - Where accessible
            - Those nearest suction point are the most beneficial to seal
        - New Homes
            - All perimeter, cold joints, expansion joints, control joints and utility penetrations

4.2.1.2 Sub-Membrane Depressurization

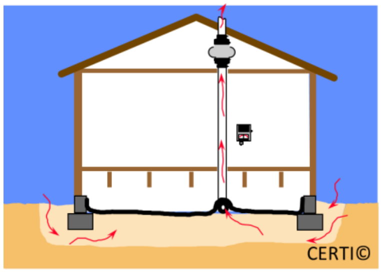


Figure 37 Sub-membrane depressurization

- Utilized where earthen areas are within the structure, such as a crawlspace beneath occupied floors.
    - Even if crawlspace is below the conditioned space, it is a large radon contributor.
    - Crawlspace vents are not effective radon control systems.
    - Dehumidification systems in crawlspaces do not run continuously and therefore are not acceptable radon mitigation solutions. However, radon mitigation systems can reduce humidity as well as control radon.
- High-density polyethylene (six-mil or three-mil cross-laminated) is laid on dirt of crawlspace and sealed to sidewalls, around penetrations, and piers and at seams.
- Perforated pipe is inserted under poly sheeting and connected to the radon vent pipe.
    - Minimum 10-foot length.
    - Three- to four-inch perforated and corrugated pipe.
- When activated with a radon fan the system draws radon from the soil underneath the poly sheeting and exhausts it outdoors.
    - Also effective for moisture reduction and other noxious soil gases

4.2.1.3 Drain-Tile Depressurization

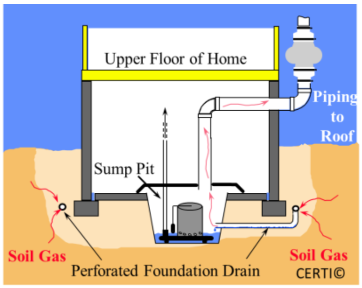


Figure 38 Drain tile depressurization

- Radon system is connected to a surface drain collection system
  - Interior or exterior drainage systems can be used
  - For both new and existing homes
- Drainage system acts as radon soil gas collector
- Radon vent pipe is connected to drainage system
  - Via sump lid, or
  - To actual drain tile (provided sump is covered and sealed)
- Openings to be controlled or identified as potential concerns:
  - Daylight soakaways fitted with full flow back water valves
  - Sump lids covered, gasketed, and mechanically sealed
  - Floor drains to sumps fitted with water traps
  - Downspouts connected to drain may need to be disconnected and diverted
  - Window well drains connected directly to perimeter foundation drain

Note: Openings such as downspouts or window well drains connected to foundation drain may not be controllable without impacting their primary intended use; an alternate approach such as sub-slab depressurization would likely be the better choice.

4.2.1.4 Combination Systems and Collateral Area Impact

Many buildings feature more than one foundation type. It is also common in older structures to have additions put on the building — each with an intervening foundation wall. Fortunately, a separate system is not always needed for each individual foundation and they can be connected to a common radon vent system if routing allows.

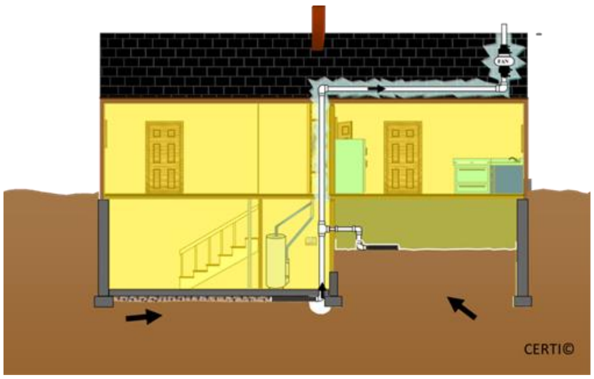


Figure 39: Combination foundation systems

Example of a single mitigation system treating both a crawlspace and a basement slab

Multiple foundations can be handled by one mitigation system if strategically placed.

If the vacuum created on the soil is strong enough and there are subgrade pathways, such as through bedding around buried utility lines, applying the vacuum to one foundation area can also treat an adjacent area. This is useful when treating large buildings such as schools or apartments where one strategically placed suction point can correct problems in several classrooms or units at once. The proper placement of suction points to achieve this benefit can typically only be obtained through pre-mitigation diagnostics by a trained radon professional.

4.2.2 Sub Slab Depressurization

This section addresses how radon gas collection can be applied to slab foundations regardless of size whether done before or after construction.

Goal One: Draw Air Laterally across Bottom of Slab to a Collection Point

The objective for a sub-slab depressurization system (SSD) is to draw radon-laden air laterally across the underside of the slab to a collection point. This can be very easy if the aggregate directly beneath the slab is porous and unobstructed by barriers to lateral flow such as grade beams or intermediate foundations.

In the case of new construction, this can be controlled by insuring there is unimpeded horizontal airflow by installing subgrade openings in grade beams that allow lateral air flow. Properly designed, a single suction point can treat thousands of square feet.

In the case of existing slabs, a number of lateral airflow barriers can exist, making it difficult to predict the area of influence without proper diagnostics. When obstructions under the slab exist, multiple suction points for even small areas may be necessary.

Goal Two: Draw Sufficient Air from Subgrade to Create Vacuum

Another goal of SSD is to extract air from beneath the slab faster than air is supplied to the subgrade. By doing so, a negative pressure is created beneath the slab that will capture the radon-laden soil gas prior to its entry into the structure. The air that has to be extracted comes from three sources, only one of which can be controlled in existing buildings:

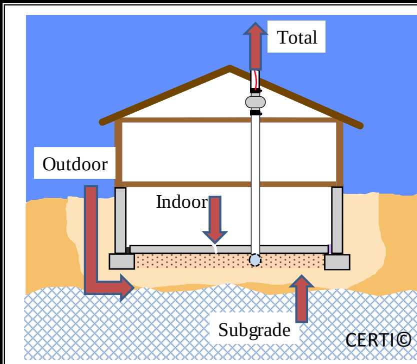


Figure 40: Air sources to mitigation system

Air handled by system comes from three sources; only indoor air can be controlled.

- Indoor air
  - This can be reduced by sealing – provided slab joints and other slab openings are accessible.
- Subgrade Air (See Figure 40)
  - Fractures in geology can provide huge air sources.
  - Wind against hillsides can force air into underlying geology, especially if it is porous (e.g. decomposed granite).
- Outdoor air (i.e., air coming from above grade down, along the side of the foundation and into the area beneath the slab)
  - Window wells provide an easy outdoor air pathway -especially if there is a window well drain connected to the sub-grade.
  - Roof downspouts connected directly to the foundation drains also provide an easy pathway to the sub-grade.
    - These direct connections to outdoor air can reduce the amount of vacuum that can be applied to the sub-grade. One should exercise caution in disconnecting these systems, as they have a specific purpose in the home design. Consider rerouting downspouts or providing an alternate drainage point for these systems, or employ a different radon

reduction approach (e.g. sub-slab depressurization that is not directly connected to potential leak points).

There is no standardized footprint area that a single suction point can treat.

Because of the variability of these factors from building to building, there is no standardized area that a single suction point can treat — especially in existing buildings that may have sub-grade obstructions like grade beams that cannot readily be observed. However, much greater control can be exercised when designing a system to be installed during construction.

4.2.2.1 Existing Slabs

4.2.2.1.1 Single Suction Points

It is impractical to remove the slab and install a system as you could when building a new house. A suction point must be created where radon-laden soil gas can be drawn towards it with a radon fan. In cases where airflow is restricted by fill material, subgrade obstacles or distance, additional suction points will likely be needed. These suction points should have the following attributes (See Figure 41):

- Installed in locations where the vent pipe will not interfere with the use of the building
    - Typically closets or utility rooms
- Installed near foundation walls
    - Installation near a footing allows the suction point to communicate with a void space that often exists near foundation walls. This allows for the system to communicate with a much larger portion of the slab
    - Should be located sufficiently away from wall to avoid drilling down into the footing.
- Installed near subgrade plumbing lines so the vacuum can be extended by pulling air through the loose fill on the outside of the buried utility line
    - Core near plumbing line and hand excavate toward utility line
- Slab Core
    - Typically four to six inches in diameter
    - Precautions
        - Do not cut tendons in post-tension slabs (x-ray first)
        - Do not damage in-floor and sub grade heating pipes (Use infrared detectors to locate)
        - Do not cut subgrade plumbing (difficult to detect if PVC – cut carefully)
        - Avoid cutting conduit cast in concrete or directly beneath slab
    - Pit Excavation
        - Remove five to 10 gallons of soil.
        - The tighter or less porous the soil, the more that needs to be excavated
        - There is no need to backfill the pit, as the slab can bridge over the void space. Backfilling the void can diminish effectiveness of the suction point.
        - In cases of very tight soils and clays a much larger pit may be needed. When making a larger pit:
            - Saw cut concrete

    - Dig out pit, going deep and wide
    - Re-pour damaged slab utilizing new rebar keyed into sides of pit
    - Maintain structural integrity of the floor system
- Connect the vent pipe to the cored hole, sealing around the pipe-to-floor joint with polyurethane caulk
- Seal accessible floor to wall joints and penetrations that are accessible with caulk. Give higher priority to those closest to the suction point
- Verify pressure field extension after the vent system is connected to suction point:
    - Use a non-thermal smoke bottle to determine the airflow direction at uncaulked floor-to-wall joints or via 3/8-inch holes drilled through slab.
    - If only a portion of the slab is treated, consider adding an additional suction point, or if time allows, conduct a short-term radon test to verify the need for an additional suction point.

Figure 41: Illustration of One Method for Creating Suction Pit

 • Draw an outline of the fitting on floor.	 • Be sure the hole is far enough from the wall to avoid a below-floor footing.	 • Drill small holes along the outline, going fully through the slab. • Avoid going deeper than the bottom of slab to avoid below-slab plumbing lines.
 • Chisel out the concrete plug.	 • Hand dig dirt. • Remove about 10 gallons of dirt — the harder to dig, the more that should be removed (wear gloves).	 • Use a shop vacuum to help remove loosened dirt.
 • Apply polyurethane caulk around the fitting.	 • Place the fitting in the hole.	 • Apply additional polyurethane caulk between the slab and fitting.

4.2.2.1.2 Multiple Suction Points

If pressure field extension is not adequate due to discontinuities, such as mixed fill or grade beams, additional suction points may be necessary. These can be connected to a common vent pipe if routing of the vent pipe allows it.

- Each suction point is installed as described previously
- Route piping to ensure that moisture inside the pipe can drain back to either suction point
- Homes: Typically one, occasionally two, suction points are adequate in single family dwellings
- Large Buildings: Multiple suction points are often needed, especially where post-tension slabs are used and multiple grade beams form a waffle-like pattern. Figure 43 provides an example of the number of grade beams that can be under a post-tension slab.
- Locating suction points near buried utility lines can reduce the number of suction points required.

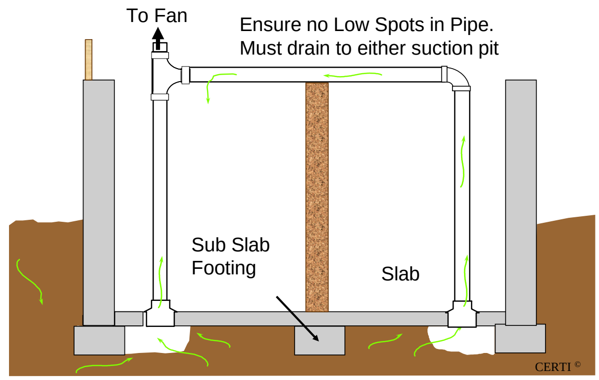
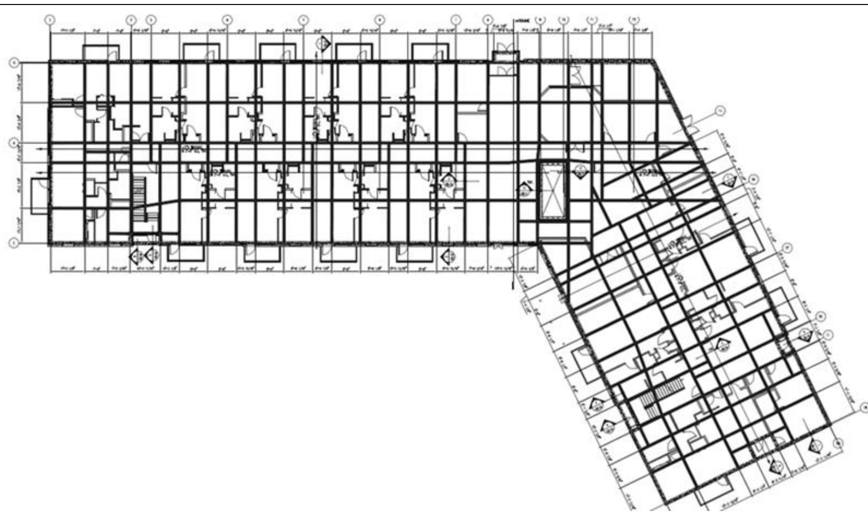


Figure 42: Multiple suction points

Multiple suction points to jumper over sub-grade obstacles.

Figure 43: Grade Beams under Slabs



Foundation plan of multi-family dwelling
Dark lines indicate grade beams under a post-tension slab which can impede soil gas collection

Grade beams or intermediate foundations can interfere with lateral air movement requiring multiple cells of foundation to be treated.

4.2.2.1.3 Side Core Suction Points

Radon suction points can also be placed horizontally through an exterior foundation wall below the bottom of the slab (if soil depth allows). This can be helpful in several situations:

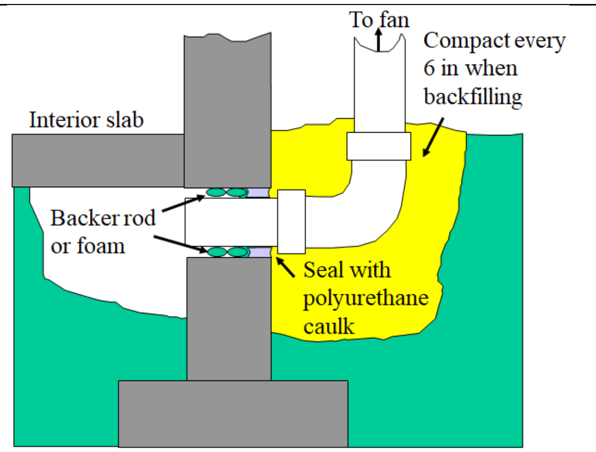
- Avoiding tendons within post tension slabs
- Avoiding in-floor heating systems
- Avoiding loss of interior space
    - Helpful for slab on grade construction

Ensure that the foundation wall is not compromised and treat any damaged rebar.

Dig the pit by hand through the foundation hole or cut the interior slab for a large pit and re-pour the concrete floor.

Figure 44: Suction Point through Exterior Foundation Wall

Horizontal core below bottom of slab



Suction point installed externally

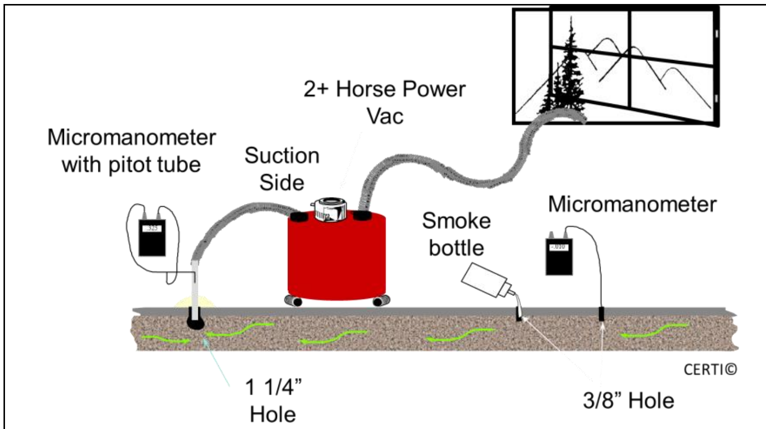
4.2.2.1.4 Slab Diagnostics

There can be a number of challenges to obtaining good lateral air flow beneath a slab toward the suction point. In the case of small residential-sized slabs, it is often most cost-effective to install an initial, expandable system and see how it performs.

However, in larger buildings, such as multi-family structures where multiple systems will likely be needed, it is prudent to conduct a more thorough investigation. Researching the building and conducting diagnostics will assist in determining how many systems will be needed and where they should be strategically placed. It is best for a radon professional to conduct this investigation.

Diagnostics involves simulating a radon collection system without installing it. This is done by selecting a location for the preferred suction point, drilling a 1 ¼-inch hole through the slab and attaching a large shop vacuum to it. Small 3/8 inch test holes are also drilled down through the slab at varying distances from the suction point hole. The shop vacuum is then turned on and off and a determination is made if air is being drawn down at the test holes. This determination can be made using a non-thermal smoke bottle or utilizing sensitive differential pressure measurement devices. The following figure illustrates the approach:

Figure 45: Slab Diagnostics



Hole drilled at preferred suction point and vacuum temporarily applied

Impact is measured at various locations of slab.

<u>Diagnostic Approach:</u>

- Test holes initially drilled at opposite ends of a slab.
    - If there is communication, a single suction point will work.
- Test holes can also be drilled on a slab located on the other side of a grade beam.
    - Communication to opposite side of grade beams indicates a single suction point will work.
- Airflow measurements of the vacuum are also made to assist in sizing the radon fan.
- The HVAC system should also be turned on and off to determine its effect on subgrade pressures.
    - This is critical when dealing with large buildings with central air handlers
        - Sub-slab pressure measurements can indicate a severe negative pressure situation caused by the HVAC system where a soil depressurization system would not be able to overcome without significant HVAC modifications.
    - Air handlers in single-family homes should also be turned on and off during diagnostics to identify significant challenges such as buried return ducts or forced-air plenums communicating with subgrade. This can identify when alternate approaches may be needed.

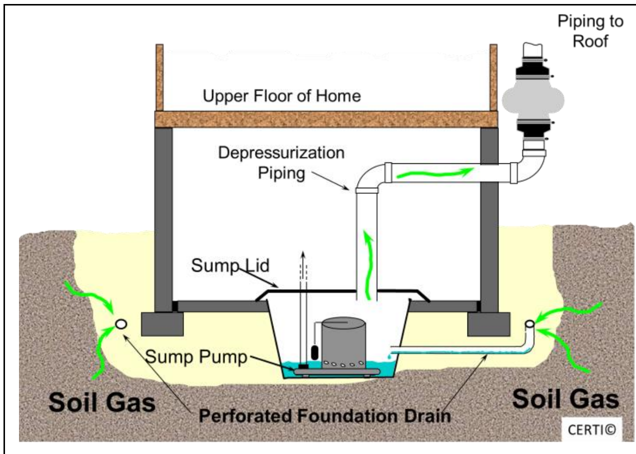
Conducting pre system installation diagnostics in single-family homes and especially large buildings is extremely beneficial. A well-placed suction point can increase system efficiency and significantly reduce the number of systems required to cover a large footprint.

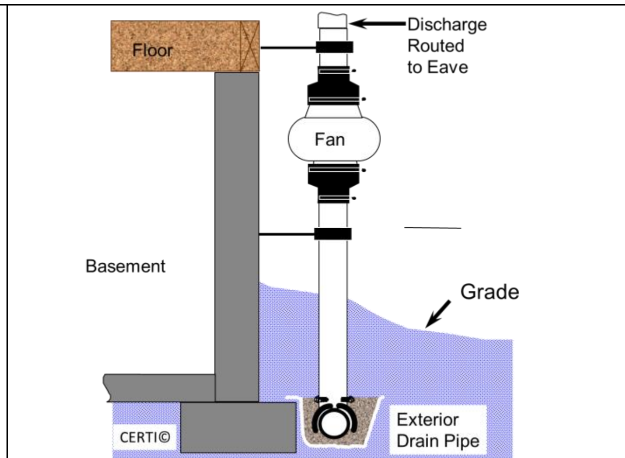
4.2.2.1.5 Using Drainage Systems as Radon Collector (DTD)

Surface water drainage systems can double as soil gas and drainage water collectors, provided their primary purpose of collecting water is not compromised. These systems are typically referred to as perimeter drains, and are common throughout the state of Colorado and elsewhere. Their use as a radon-collection system works regardless if they are located inside or outside of the footer.

If a drainage system exists on a home or a large building, drawing a vacuum on the buried pipe can significantly increase the capture area for a radon system. This can be extremely helpful when treating a large building with a myriad of internal grade beams.

Figure 46: Drainage Systems as Soil Gas Collectors





Radon system connected to sump	Radon system connected to exterior drain

In considering this approach for either new or existing buildings, there are some key considerations:

- Sumps must be covered with a lid that is sealed to the floor with an airtight gasket and mechanical fasteners. This prevents significant air leakage while allowing for future access to sump pump.
- The water control level within the sump must be lower than the drainpipe coming into sump.
    - If incoming pipes are below the water line, the radon system will not be able to extract soil gases from the subgrade.
- Soakaways on surface water systems that drain by gravity to a hillside must be fitted with a full flow backwater valve.
    - Allows water drainage
    - Prevents outdoor air from entering radon system and making it less effective
- Downspouts should not be connected to the perimeter drain.
    - If so, they could drastically reduce the effectiveness of the radon system.
    - Disconnect downspouts and drain to another location (or consider a different radon-reduction approach)
- Drains from window wells that are directly tied into perimeter drain may render this approach ineffective.

- In new construction avoid direct connection or employ a soil gas collection system that is independent of the water drainage system.
- Floor and laundry drains in older homes may be connected to sumps. If you were to pull air from the sump, a lot of interior air could also be extracted, causing an energy penalty or a combustion appliance backdraft concern. If this is the case, seal the sump with a lid and employ a sub slab depressurization system independent of the sump.

Figure 47: Sealing Drainage Features without Compromising Them

 Soakaways on gravity drained systems to be fitted with full throat check valve. Referred to as Backwater Valves.	 Lids on sumps to which a radon system is connected can leak significant amounts of air. This should be gasketed and bolted.
 Pump Discharge and radon vent pipe.	 Manufactured cover with holes for radon pipe, pump discharge and view port.

4.2.2.2 New Construction Slabs

The approaches described in this section apply to both small and large buildings. When installing a radon system during the construction of a building, one has the opportunity to address items that can challenge the installation of a system after construction. These opportunities are:

- Ensuring air can easily move laterally from all portions of the sub grade area without impedance from grade beams.
- Reducing air leakage through the slab by being able to access and seal all joints and slab penetrations.
- Being able to incorporate the vent pipe system into the building such that it is unobtrusive.
- Being able to route the vent pipe through a conditioned portion of the building where a thermal stack effect on the pipe can exert a slight negative pressure and possibly eliminate the need for a radon fan (i.e. a passive system).
    - Even though a passive system may be planned, the design should be based upon or at least allow for upgrading it to an active system with fan.
    - If post construction testing indicates elevated radon levels, the owner and/or the builder should activate the system by installing a fan.

4.2.2.2.1 Soil Gas Collectors for New Construction

There are three soil gas collection systems that have worked well in Colorado construction. All of the systems are effective; which one you choose depends on the building design and cost of materials and labor. Table 16 summarizes the approaches with additional details in subsequent sections.

Table 15: Subgrade Options in New Construction

Soil Gas Collection	Brief Description	Comments
Aggregate under slab	• Four-inch layer of ¼-inch or larger clean aggregate under slab • Penetrations to be made in grade beam to allow lateral air movement	**PROS:** • Ensures air flow completely under slab **CONS:** • Can be expensive, as clean aggregate is not readily available in many areas • May require higher air flow fans to achieve negative pressure Other documents have stated rock must be ¾ inch or larger. Experience in Fort Collins, CO has indicated that smaller aggregate e.g. clean pea gravel is more than adequate
Native soil with perforated pipe trenched around perimeter	• Three- to four-inch diameter perforated pipe in a loop around perimeter crossing grade beams and interior footings. • Pipe in 18 x 12 inch trench filled with ¾ inch rock.	Similar to interior perimeter drain. It can also serve as the interior drain **PROS:** • Less clean aggregate must be imported. • Reduces over-dig requirements **CONS:** • Requires soil gas collection pipe to pass through or around interferences • Trench can be labor intensive, especially if sub grade is compacted or frozen
Soil Gas Mat	• One-inch tall by 12-inch wide mat encircled with geotechnical fabric. Laid around perimeter	Sits on top of the compacted subgrade directly beneath the vapor barrier. No need for a trench. **PROS:** • Can be installed immediately prior to slab pour • Does not require trenching or importation of aggregate **CONS:** • Higher material cost • Requires mat to pass through intermediate grade beams and other interferences • May need to pour thicker slab to maintain slab thickness.

4.2.2.2.1.1 Aggregate Option

In this option, communication for lateral movement of radon gas consists of a four-inch layer of aggregate. The following description is borrowed from the Fort Collins Residential Code:

A uniform layer of clean aggregate, a minimum of 4 inches (102 mm) thick. The aggregate shall consist of material that will pass through a 2-inch (51 mm) sieve and be retained by a 1/4 -inch (6.4 mm) sieve. In buildings where interior footings or other barriers separate sub-grade areas, penetrations through the interior footing or barrier equal to a minimum of 12 square inches (0.094 m^2) per 10 feet (3.048 m) of barrier length shall be provided. A minimum of two penetrations shall be provided per separation and be evenly spaced along the separation.

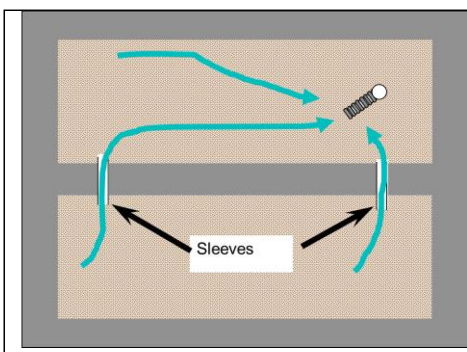
Rock aggregate being installed prior to slab pour

Aggregate that is a little larger than a quarter inch will work, provided:

- It is clean (low fines).
- Provisions are made to allow air to travel across grade beams.
    - Holes made through grade beams should be just below bottom of concrete.
    - Openings through grade beams or intermediate, below-slab footings should provide 12 square inches of cross sectional area for lateral air flow per every 10 feet of footing/grade beam

Figure 48 shows how these crossovers allow for a single collection point as well as an example of how it was done in two large building projects.

Figure 48: Crossovers for Poured walls and Grade Beams



Cross-over pathways for soil air to move towards single collection point

Foam between form boards prior to pour, knocked out later to form subgrade crossovers

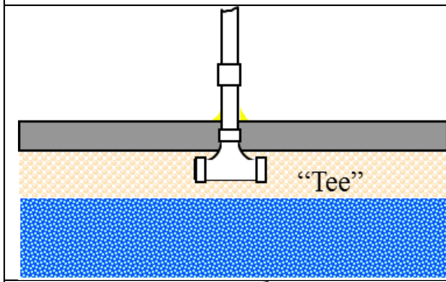
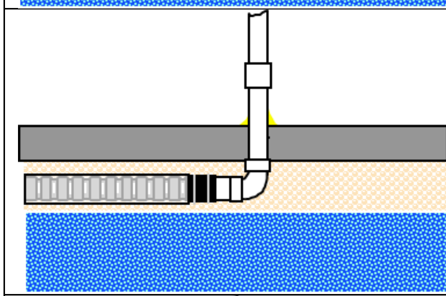
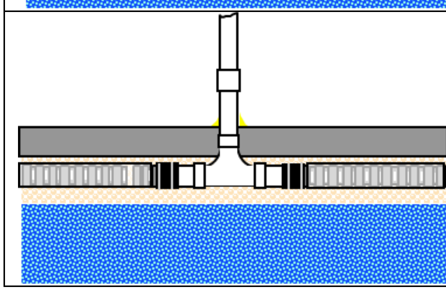
Concrete blocks laid on side to allow air to pass through wall

Other guidance such as ASTM 1465 recommends larger rock such as ASTM C33 # 4-6, when a contiguous four-inch deep layer aggregate is used. Larger rock such as this is acceptable but may be more expensive and likely to increase the amount of air that is drawn from the outside of the building perimeter, thereby increasing fan requirements. If an aggregate option is used, experience in Colorado suggests smaller, quarter-inch and bigger aggregate is acceptable.

Radon Gas Connection for Aggregate Option

The following table illustrates methods for connecting the soil collection layer to the vent riser.

Table 16: Soil Gas Riser Options in New Construction

Method	Comments
	**Tee in aggregate** • Shown in older guidance • **<u>Not recommended</u>** because gravel can easily fill the tee and choke off airflow
	**Elbow with 20-foot length of perforated pipe** • Four-inch corrugated and perforated pipe in aggregate • No need to cap end of perforated pipe
	**Tee with two 10-foot lengths of perforated pipe** • Three-inch corrugated and perforated pipe on either side of tee • Pulls air from both sides for better soil gas collection

The following considerations apply when utilizing aggregate:

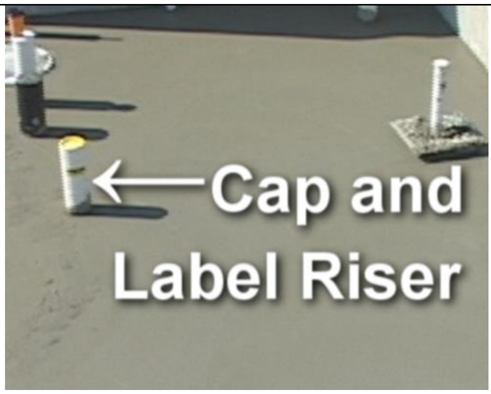
- Ensure concrete does not seep down into the four-inch layer and reduce air flow.
  - Add an additional two inches of aggregate; or
  - Lay vapor barrier over aggregate prior to pour.
- Pipe used under the slab must be perforated.
  - If rigid pipe is used, orient the pipe so one set of drain holes faces downward to allow condensed water in the system to drain into the subgrade.
  - If corrugated and perforated pipe is used, use pipe with perforations all around its perimeter for proper drainage that also is wrapped with a geotechnical cloth.
- Collection piping must be at an elevation above the sump water control level.
  - Do not bury pipe where it will be below standing water.
  - Keep pipe up close to the bottom of the slab.
- For Colorado conditions, it is recommended that the vent riser be a minimum three inches with four inches being optimal, schedule 40 PVC, or ABS pipe.

One of the most common installation errors is getting concrete or other debris down into the riser connection. Be sure the riser is visible and capped during and after the pour.

The transition from perforated pipe to PVC must occur BELOW the slab to avoid air leakage (Figure 49).

Figure 49: Protecting Soil Gas Riser During Construction

Do not run perforated pipe above slab. Use four- inch, Schedule 40 PVC or ABS



Put temporary pipe plug in riser and label to avoid:

- Debris getting in during construction
- Confusion about which pipe is the radon pipe

Radon Gas Collector for Large Buildings Using Aggregate Option

Using a full loop of perforated pipe under the slab is preferred for large footprint areas. However, it is also possible to collect soil gases from a single point over a large area (Figure 50) provided:

- Several crossovers are made at grade beams and intermediate foundations.
- A very large suction pit and vent pipe is used.

Figure 50: Large Suction Pit Option During New Building Construction

Suction pit box with expanded metal on four sides

Aggregate spread around box prior to vapor barrier and slab pour.

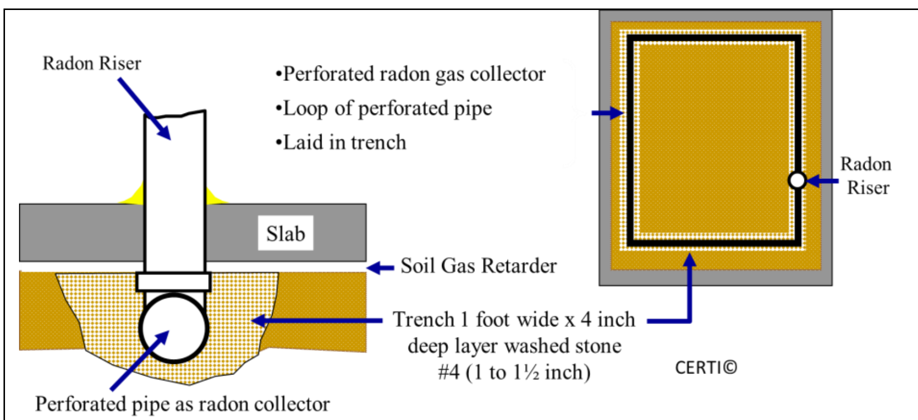
This approach is typically more costly due to the need for multiple crossovers on grade beams and large vent pipes (typically eight-inch diameter) are needed to handle the volume of air collected. The larger vent pipe is also difficult to route and requires specialized mechanical fire dampers, rather than pipe collars, when going through fire-rated walls or ceilings.

4.2.2.2.1.2 Loop of Perforated Pipe Option

A perimeter loop of perforated pipe acting as a radon collector is installed much like an interior perimeter drain. In fact, it can work as both a radon collector and a perimeter drain (provided the water control level of the sump is below the level of the perforated pipe). Aspects of this approach are:

- The perforated pipe will cross over grade beams, negating the need for any special crossovers.
- Radon gas has a shorter distance to travel through subgrade to the perforated pipe rather than across the entire subgrade to a single suction point.
- No special fill is needed under the slab.
    - Larger clean aggregate should be in the trench surrounding pipe — approximately 18 inches wide and 12 inches deep.
    - Install normal subgrade materials as called out by engineer.
- Can also be the perimeter drain
- Can be installed by the drainage subcontractor
- Use corrugated or rigid perforated pipe.
    - Three-inch for areas of 2,000 square feet
        - Join ends of loop in Tee connected to a four-inch riser.
    - Four-inch for areas from 2,000 to 4,000 square feet
        - Join ends of loop in Tee connected to Six-inch riser.
    - Multiple loops for slabs greater than 2,000 square feet (section 4.2.2.2.2)
- Bring open ends of pipe together at a “tee” for single connection.
- If using corrugated pipe with perforations completely around the pipe, the pipe can change elevation and back up to avoid other subgrade utility lines.

Figure 51: Perforated Pipe Loop Option for New Construction



- Loop of perforated pipe routed around perimeter acts as soil gas collector.
- Install like perimeter drain. Can also function as perimeter drain.

Install pipe like a perimeter drain

Fill trench with clean aggregate

Cover with geotech cloth

4.2.2.2.1.3 Soil Gas Mat

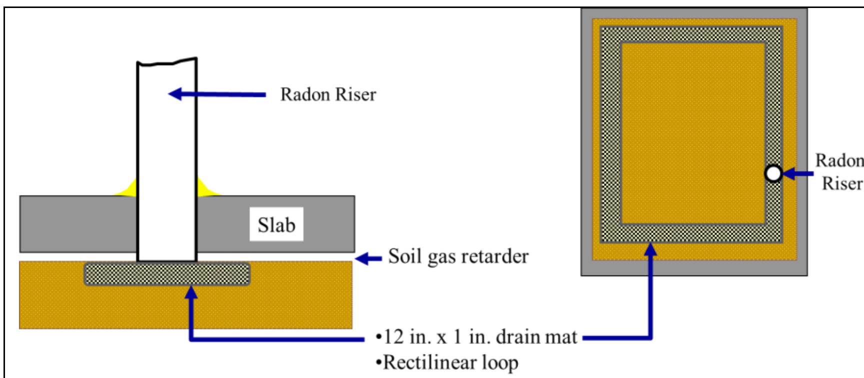
Soil gas mats function the same as a perforated pipe loop design, except a trench is not needed. The mat lies flat on top of the compacted subgrade, beneath the vapor barrier/slab. It is routed around the perimeter.

Figure 52: Soil Gas Mat

Soil gas mat laid out prior to slab pour on multi-family apartment building with a post tension slab.

- It can be laid after the subgrade is compacted and minutes before the slab is poured.
- It takes less labor to install but may be more expensive to purchase than a perforated pipe
- It can be laid over the top of grade beams prior to the slab pour.
  - Very efficient for large post-tension slab slabs
  - Fits between hairpins of grade beams
- It connects to special tee for connect to riser.
- No special fittings are needed for corners and joining sections together.

Figure 53: Soil Gas Mat Installation



Mat is laid around perimeter between sub grade and vapor barrier.

Mat has plastic matrix inside to allow airflow.
Fully wrapped with geotech fabric.

Mat rolls out on compacted sub grade

Corners spliced

Mat under tendons or rebar

Opposite ends of loop connected to special Tee for riser connection

The decision to use a soil gas mat versus a perforated pipe loop is simply a function of time and money.

4.2.2.2.2 Addressing Very Large Slabs-During New Construction

The approaches used for collecting soil gases in small-footprint structures (homes) are essentially the same for large slabs. The primary distinction is the larger amount of soil air that will need to be extracted to achieve the desired depressurization. As the volume of air that needs to be extracted increases, more resistance to air flow is encountered in both the radon gas collector as well as the vent pipe. This situation can be addressed by:

- Increasing radon gas collector and vent pipe sizes, or
- Installing multiple systems of a normal size

Which option is followed depends on the design of the building and an analysis weighing costs of large systems versus more numerous smaller systems.

The benefits and/or costs to be considered appear in Table 18.

Table 17: Large vs. Multiple Small Systems - New Construction Large Buildings

Consideration	Large System(s)	Multiple Small Systems
Ease of routing vent pipe	More difficult due to size of vent pipes May require separate or enlarged chase	Easier Smaller pipe can be routed up within walls or chases similar to plumbing vent routing
Number of vent pipes	Fewer	More
Number of roof penetrations	Fewer	More
Number of fans and electrical circuits	Fewer	More
Fan size	Larger May cause space issues and localized noise concerns	Smaller
Redundancy	If a single large fan is used and it fails, the entire building is not being treated.	If a single fan fails, the other operating systems can continue to have collateral benefit on adjacent slab areas.

4.2.2.2.2.1 Design Assumptions for Slabs 2,000 Square Feet or Larger

When designing a radon system the radon professional and/or engineer will determine the best approach to mitigation. Choosing the best approach will depend on the size of the slab, how it is to be constructed and the type of fill materials planned.

Excess Air Flow:

When a radon vent system is activated, it will draw in external air in addition to air directly beneath the slab. The more external air that is available to the radon system, the more air volume it will have to remove to obtain the desired sub-slab vacuum. The external air can come from the exterior perimeter or from the geology below the slab. From studies facilitated by a Colorado builder, air flows and slab pressure differentials were measured under two different conditions:

Condition 1:

- Native fills compacted under slab
- Loop of three-inch perforated pipe in a 18-inch wide trench filled ¾ inch clean aggregate as a radon collector

Condition 2:

- Four-inch deep layer of large clean aggregate completely under the slab
- Loop of three-inch perforated pipe as a radon collector

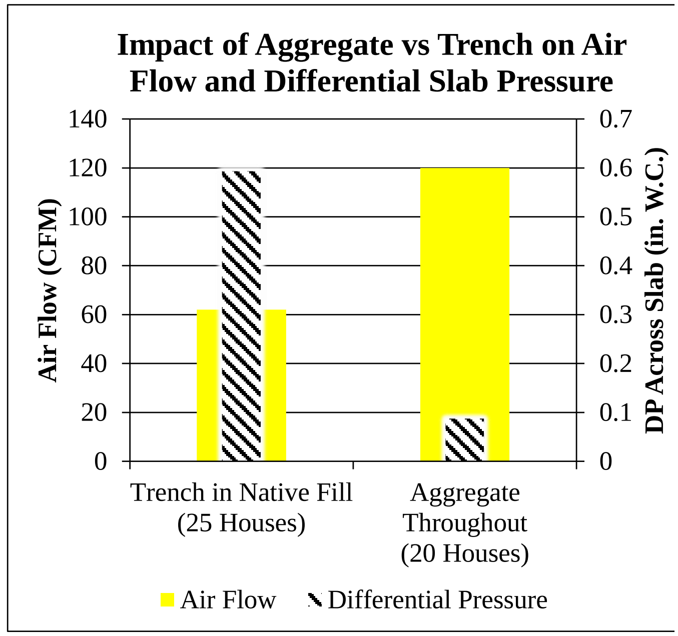


Figure 54: Comparison of aggregate to trench methods-New Construction

Study of 45 homes newly constructed with active radon fans.

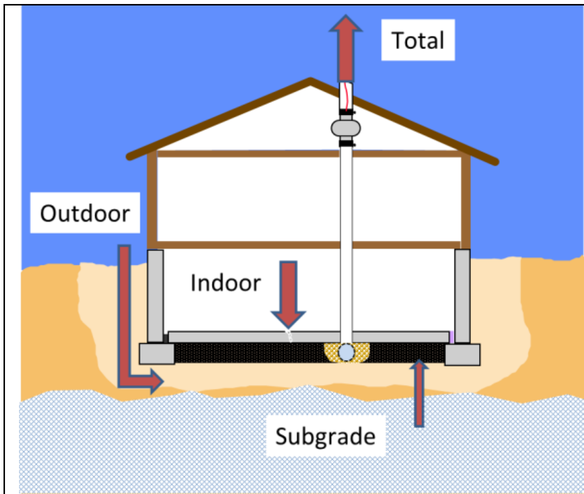
- Twenty-five with compacted fill and soil collector in gravel filled trench.
- Twenty with a four-inch layer of aggregate throughout

Compacted fill provided tenfold greater vacuum with half the air extracted.

Figure 55 compares the air flow as well as the pressure differential created across slab when a radon fan was installed. In the case of native fills with a gravel filled trench (Condition 1), much higher sub-slab vacuums could be achieved (better radon control) with less air having to be extracted (smaller radon fan).

The higher sub-slab vacuums are due to the resistance to excess air entry from the building perimeter and the underlying geology imposed by the compacted and less-permeable native fills. Furthermore, the location of the perforated radon gas collector just beneath the slab situated in a trench surrounded by compacted fill also causes the suction of the system to be focused on the smaller interstitial area between the bottom of concrete and the top of the aggregate rather than the entire slab as would be the case with aggregate completely under the slab (Condition 2) Figure 55 illustrates the difference between the two approaches with the size of the arrows indicating the amount of air flow from each source.

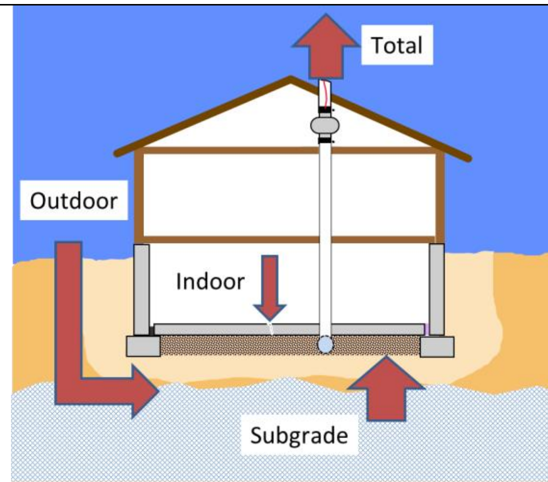
Figure 55: Air Flow Full Aggregate versus Compacted Fill and Trench



Condition 1

Slab with compacted fill beneath with radon system consisting of perforated pipe in trench or soil gas mat.

- System vacuum is applied to small gap between vapor barrier and subgrade.
- Compacted fill represents an airflow barrier at perimeter edge.
- Compacted fill provides resistance to air pathways from underlying geology.



Condition 2

Slab with four inches of clean aggregate throughout.

- System vacuum applied to the entire four-inch deep aggregate area.
- External air can more easily be drawn down through the outside grade.
- Deep geologic air can be easily drawn up through the aggregate.

Although the data presented above was obtained from residential buildings, it also applies to large slabs where air volume reduction is important in reducing radon vent piping size.

Subgrade specifications should be established in relation to the primary structural needs of the building and the radon system should be designed around that specification. Recognize that air flow volumes needed for the radon system will be a function of what fill is specified, with compacted fill requiring lower air flows.

Design Assumptions and Parameters

Radon system design for large-footprint buildings is a developing area and additional engineering guidance will undoubtedly become available in the future. The following represents assumptions that have been used in Colorado, subject to future refinement.

These assumptions apply to slabs that are larger than 2,000 square feet. Smaller footprints, such as for single-family homes, are treated as described previously.

Air Flow:

- Clean aggregate throughout slab:
  - 0.025 CFM per square foot of footprint
- Compacted fill with loop of perforated pipe in trench or soil gas mat:
  - 0.015 CFM per square foot of footprint

Maximum air flow in a given riser:

- 800 feet per minute
- Higher velocities will result in:
  - Higher pressure drop in piping
  - Air noise in pipes, possibly leading to occupant noise complaints

Pressure drop:

- Calculate as you normally would for ductwork
- Smooth wall, plastic pipe
- Turbulent flow

Fan sizing:

- Able to generate 0.75 to 1.00 inches of water column at suction point at calculated airflow rate and after radon vent pipe pressure losses

Soil gas collector:

- Cross sectional area of connection of soil gas collector to be equal to or greater than radon vent riser. This is accomplished by connecting opposite ends of a loop of perforated pipe or soil gas mat to a tee, which is connected to the single-pipe radon vent riser.
- Number of independent systems dictated by airflow calculated above and pipe sizes assumed during calculation.

4.2.2.2.3 Soil Gas Retarders-Vapor Barriers-Slab Sealing

The following discussion applies to both single-family homes as well as large slab-on-grade structures.

Sealing the interface between the subgrade and the interior portion of the building is a critical element of a radon system. This is true for both new and existing homes. In the case of an existing building with a slab, the only means to do that is to caulk and seal the slab in those areas that are reasonably accessible. However, in new construction there are greater opportunities for sealing when the slab can be accessed at different points during the construction process.

In addition to sealing the slab at construction joints, some guidance documents have suggested that a well-sealed membrane be installed directly under the concrete slab. The rationale is that it would provide a better seal initially, as well as bridge over cracks that may develop in the concrete over time. Casting concrete slabs over tightly sealed membranes can be problematic, especially in dry climates such as Colorado. The slab can curl and crack when it cannot adequately dewater downward during the curing process unless additional water and plasticizers are used (this can also add labor costs during finishing).

For a radon system to work efficiently, a barrier between the sub-grade and the interior of the building is needed. The question is whether the membrane under the slab should be a vapor barrier or an air barrier.

A *vapor barrier* is loosely laid on the subgrade with seams and edges unsealed, often with holes punched in it to aid in the dewatering/curing process. The purpose of a vapor barrier is to reduce the ability for soil moisture to diffuse through the concrete affecting floor finishes such as tile. It is not designed to stop airflow around joints such as floor-to-wall joints.

An *air barrier* is a means by which convective airflow is stopped and entails extensive sealing at edges.

In the case of a radon system, an air barrier is needed. There are two ways this can be done:

Option 1: Poly as air barrier

- Install a high density (10 mil) poly sheet under the slab, overlap and seal seams, edges and plumbing penetrations, or

Option 2: Slab as air barrier

- Install vapor barrier as needed for moisture control (without exhaustively sealing poly)
- Caulk and seal all floor to wall joints and penetrations at the slab level.

Figure 56: Option 1: Membrane as Air Barrier

			
• Bring poly sheet to wall and seal • Apply expansion boards over poly	• Tape seams and penetrations	• Install rebar/rewire • Take care not to damage membrane	• Pour concrete • Do not puncture membrane with spreading tools and rakes

Figure 57: Option 2: Slab as Air Barrier

			
• Slab poured as normal over vapor barrier	• Floor-to-wall joints caulked	• Control Joints Caulked	• Slab penetrations caulked

Option 2 (slab as air barrier) has several advantages that have been learned by Colorado home builders.

- Slabs can be more effectively caulked and sealed versus attempting to maintain the integrity of a poly barrier prior to a concrete pour.
- Slab caulking and sealing can be inspected, whereas a polysheet beneath a concrete slab cannot be inspected after the slab is in place.
- Slabs can be poured normally without the need for special additives and additional labor.

The experience of Colorado builders indicates that no statistically significant advantage has been found by installing a well-sealed air barrier under the slab versus sealing the slab itself with no barrier. The approach of sealing the concrete slab as an air barrier rather than exhaustively sealing the vapor barrier is also a fundamental element of ASTM 1465-08 Standard Practice for Radon Control Options for the Design and Construction of New Low-Rise Residential Buildings.

4.2.3 Treating Old or New Crawlspaces with Soil Depressurization

Dealing with earthen floor crawlspaces is the same regardless of whether the building is being constructed or is an existing structure. The approach is also the same regardless of the size of the crawlspace. The primary issue is whether one can get into the crawlspace to work or if it is an older home with an inaccessible crawlspace where clearance is minimal.

4.2.3.1 Sub-Membrane Depressurization

Sub membrane depressurization is the preferred method for addressing earthen crawlspaces.

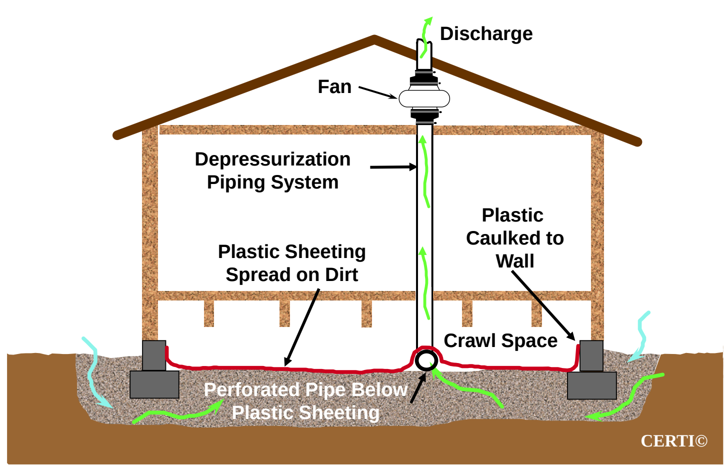


Figure 58: Submembrane Depressurization

A length of perforated and corrugated pipe is laid on the earthen floor of the crawlspace; a polysheet is laid on top of it and is sealed to the walls and at the seams. A fan (outside of the crawlspace) and a vent riser are attached to the perforated pipe. When the fan is turned on, the poly is drawn down like vacuum packaging. By covering the entire earthen area, these systems reduce radon effectively. They also have the added benefit of reducing other soil contaminants (as well as moisture) that may be entering the building via the crawlspace.

4.2.3.1.1 Considerations:

- The membrane should be a durable polyethylene sheet. Typically, three-to-four--mil high-density or a reinforced poly sheeting.
    - Standard six-mil poly, as is commonly used as a vapor barrier in crawlspaces, can be used. However it can easily be damaged. Special precautions are advisable,

    - such as laying down an additional protective layer in higher-traffic areas or near appliances that may be in the crawlspace. To avoid adding additional layers, heavier sheeting is recommended.
    - The sub-membrane system also functions as a vapor barrier.
- The membrane should be laid on the earthen floor rather than trying to attach it to the floor joists above.
- It is best to seal the poly to the foundation walls, which:
    - Reduces air leakage
    - Keeps it in place
- A perfect seal is neither practical nor necessary.
    - Some leakage can be tolerated, but leaks will increase the quantity of air that has to be handled, as well as loss of interior, conditioned air.
    - Rough rock walls can be difficult to seal.
    - When the crawlspace becomes inaccessible due to low height, push the edge of the polysheet as close to the wall as possible and locate the soil gas collector away from this open edge
- Merely installing the barrier is insufficient; a depressurization fan is necessary.
    - Without a depressurization system, radon will still enter the building.
    - A well-sealed membrane with no fan will balloon up against the floor joists and leak at the seams.
- Multiple soil gas collectors may be needed if multiple crawlspaces exist.
- If installed during new construction, it may be advisable to wait until after the subflooring above the crawlspace has been installed to reduce potential damage to the membrane.
- Instead of installing a polyethylene membrane, a thin, two-inch slab could be poured in the crawlspace to make it more amenable to storage. In this case, address the slab as you would with slab depressurization.
- If plumbing cleanouts or sumps exist in the crawlspace, ensure poly sheeting is below the cleanout or below the sealed lid to allow access to these items.

4.2.3.1.2 Installation Procedure

- Identify and address safety hazards.
    - If friable asbestos is found in the crawlspace, a depressurization system should not be installed until this hazard is assessed and properly addressed.
    - Be cautious of stored hazardous materials, insects or recent applications of pesticides and other critters that may live in the crawlspace.
- Remove major debris.
    - Broken glass and other sharp objects should be removed.
    - There is no need to rake the surface of floor unless it will make it more useable.
- Protect poly in areas where traffic may occur
    - Put 30# roofing felt or equivalent under the poly sheeting in high traffic areas.
        - Crawlspace access
        - Routes to mechanical equipment.
    - If there is an existing vapor barrier, the poly can be laid over the top of it, provided the soil gas collector is inserted beneath both.

- Lay a length or loop of corrugated and perforated pipe on floor of crawlspace
    - Typically three to four inches in diameter
    - Sizing would be identical to sizing consideration provided in Section 4.2.3.2.1 for slabs
    - Minimum 20-foot length of perforated pipe
- Install high-density polyethylene sheeting material over the top of the soil gas collector
    - Comply with local codes if fire-resistant poly is required.
        - If installed in an area where equipment is also located, a Flame Spread 25 rating is typically required.
    - Minimum six- mil or three- mil reinforced polyethylene.
- Seal to walls
    - Clean area of wall for attachment with a wire brush.
    - Apply a continuous bead of polyurethane caulk onto the wall.
    - Bring plastic up onto concrete wall approximately 12 inches and press into caulk.
        - It can be less than 12 inches as long as it is secure.
        - Do not attach to wooden member such as the rim joist.
    - In large crawlspaces, furring strips (termination bars) should also be used to secure the poly to the wall.
        - Furring strips (termination bars) do not provide an air seal, but rather mechanically hold the poly in place. Consequently, they do not need to be continuous around the entire perimeter.
        - The caulk between the poly and the wall provides the air seal.
- Overlap seams nominally 12 inches and seal with polyurethane caulk or specialty tape as recommended by the poly manufacturer.
- Seal poly to plumbing penetrations.
- Seal poly to pads under mechanical equipment.
    - If there are no pads under the equipment, temporarily suspend the equipment and slide the poly under it or seal as best as possible.
        - Avoid proximity to hot sources such as gas pilot lights.
- Connect the radon vent riser to the perforated pipe under the poly.
    - Perforated pipe should not extend above the poly.
    - Seal poly around the PVC pipe penetration.
    - Riser pipe is typically four inches in diameter for Colorado conditions, but may be larger in the mountains where porous geology exists and high winds can pressurize the area beneath the structure.
        - Although some guidance/codes allow for three-inch pipe, airflow requirements often found in crawlspaces in Colorado are best served by the use of four-inch diameter vent pipes.
- Identify leaks after system is turned on
    - Leaks can often be heard
    - Use a smoke stick and flashlight to identify or verify leaks

Figure 59: Sub-Membrane Installation Pictures

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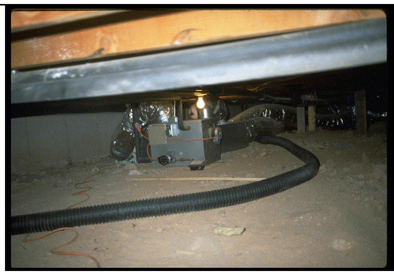
<tr>
<td>
Clean floor
Run minimum 20-foot length of corrugated and perforated pipe</td>
<td>
Brush attachment surface</td>
<td>
Apply ~1/2-inch-wide bead of caulk to wall</td>
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<tr>
<td>
Press membrane into place</td>
<td>
Attach termination bars to hold poly in large buildings</td>
<td>
Caulk and overlap seams ~ 12 inches</td>
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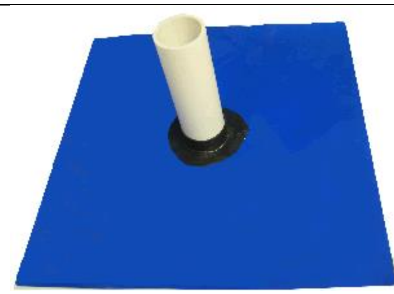
<tr>
<td>
Tape seams to secure them</td>
<td>
Attach radon vent pipe to soil gas collector
Option 1:
Roof jacks above and below membrane sealed to poly with radon pipe passing through grommet of roof jack</td>
<td>
Attach radon vent pipe to soil gas collector
Option 2:
Premade pieces of poly with grommet for passage of pipe through membrane. Seal edges to main membrane</td>
</tr>
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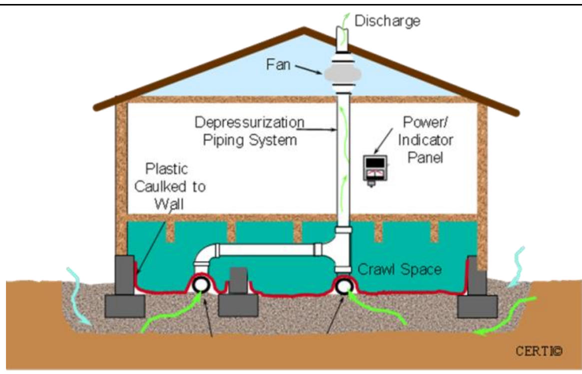
4.2.3.1.2.1 Multiple Crawlspaces

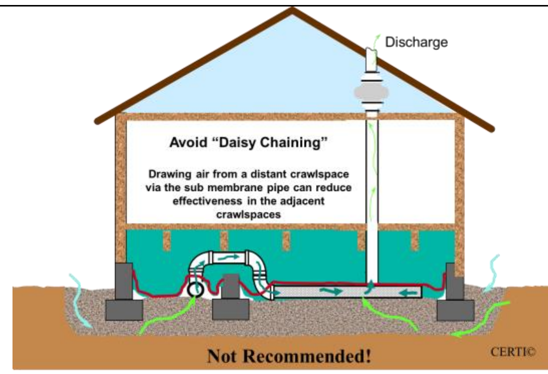
Multiple crawlspaces can exist, especially in large structures such as apartments and even in single-family homes. In this case:

- Each crawlspace area should have its own individual membrane.
- The radon vent pipe should be routed horizontally over the top of the crawlspaces with a separate drop going to each crawlspace.
- Do not daisy-chain the radon vent pipe from crawlspace to crawlspace. This will restrict air collection at the furthest crawlspace.
- In large buildings, install dampers on the individual header drops to allow for balancing of desired airflows.

Figure 60: Multiple Crawlspaces



Multiple crawlspaces should have individual air barriers with radon collection via header.
Dampers for distribution of air collection recommended when more than two crawlspaces are connected to the same header.



Avoid daisy chaining gas collection pipe. This reduces the amount of air that can be drawn from the distant crawlspaces. An overhead header with drops to each area is preferred.

4.2.3.2 Crawlspace Depressurization

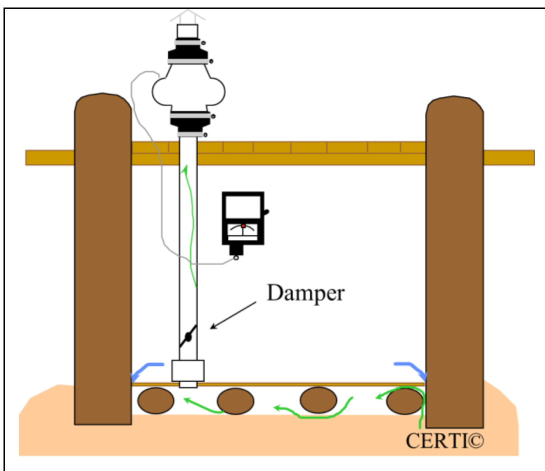
Although sub-membrane depressurization is the preferred method, there may be instances where it is difficult or very costly. In those cases, crawlspace depressurization can be considered. In this approach, the floor above the crawlspace serves as the air barrier, with air being extracted from the crawlspace itself. Applications for this approach include:

- Inaccessible crawlspace
- Very large crawlspaces with easily sealed floors above (e.g. structural floors)
    - Examples include large schools or commercial buildings where the floor above the crawlspace is concrete
- Tunnels that interconnect above grade structures
    - Examples include utility tunnels where steam and water lines are routed from a main boiler area to individual housing units, passage ways under airports, etc.

Crawlspace depressurization **should not** be contemplated in the following situations:

- Where combustion appliances are located in the crawlspace
    - Creating a negative pressure in the same area as these appliances can cause them to draft improperly
- Where the upper floor cannot be sealed well
    - Due to large openings or gaps in the floor under cabinets, showers tubs, etc.
- Where the crawlspace is used as a plenum for air ducts
    - This is rare but not unheard-of in older buildings

Figure 61: Crawlspace Depressurization



Crawlspace Depressurization

- Used infrequently and where sub-membrane depressurization is not practical and the floor can be well sealed
- Air is extracted from crawlspace
- Floor openings are sealed to minimize interior air loss
- Air flow rate is reduced to just where negative pressure is achieved across floor
- Access points to crawlspace are sealed and labeled to reduce inadvertent opening and loss of interior air

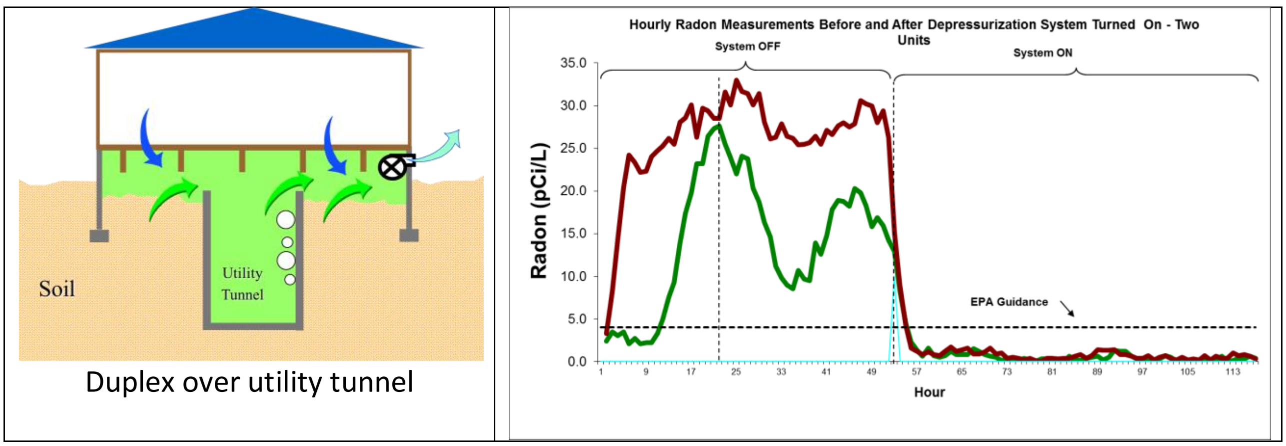
This technique should be approached with caution. It has the potential of extracting a large amount of interior air from the building, which can increase heating/cooling costs, as well as cause combustion appliances to backdraft. When applying this technique, one should only extract enough air to create a slight negative pressure in the crawlspace relative to the interior. Measures should also be added to avoid accidental loss of air by leaving crawlspace access open. At a minimum, these doors should be labeled with a warning to turn depressurization fan off before opening.

Procedure

- Install fan and short stub of PVC/ABS piping with damper in crawlspace.
- Turn on system and use smoke bottle to find leaks in floor. Seal with an appropriate material consistent with floor finish.
- Find or make a hole in the floor at a distant location from the suction point. Adjust damper to position that just allows smoke to be drawn down distant hole.
    - Use micro-manometer to adjust flow to approximately 0.010 inches of water column negative pressure in the crawlspace relative to the upper occupied space.
- Fix damper handle in place.
- Label any crawl accesses that could be opened.
- A carbon monoxide monitor should be installed as an additional precaution against back drafting combustion appliances.
- Include advice in instructions against leaving crawlspace access doors open as well concerns that could arise during future remodels.

Figure 62 illustrates a crawlspace depressurization performed on two units of a duplex over a common utility tunnel. The results show the rapid reduction in indoor radon levels in the occupied space of each unit when the crawlspace was depressurized.

Figure 62: Crawlspace Depressurization



4.2.4 Depressurization Fan and Venting Systems

Regardless of the soil depression method used, there needs to be a venting system that will draw the collected radon gas and convey it to a proper location outside of the building. There are several key factors that are to be observed when designing a venting system.

4.2.4.1 Radon Vent Design Parameters

4.2.4.1.1 Air Flow

The system needs to be able move air faster than air is supplied to the sub-grade area. The amount of soil air removal required can vary, especially where wind will blow against hillsides in areas of high soil permeability. Therefore, additional air-handling capability (pipe size and fan size) is prudent.

Guidelines for estimating airflow rates for large new construction buildings are provided in Section 4.2.2.2.2.1 but typically for Colorado conditions, the systems need to be able to move:

- Residential: 60-100 CFM
- New home construction: 20-60 CFM
- Individual systems for multi-family: 60-100 CFM, depending upon fill used

In the case of existing buildings, especially large footprint structures like apartment buildings, field diagnostics are highly recommended to estimate this crucial variable.

4.2.4.1.2 Control of Condensed Soil Moisture

4.2.4.1.2.1 Condensation on inside of vent pipe

In addition to radon, humid air is extracted from the subgrade as the mitigation system operates. In locations where the vent pipe passes through a cold environment, such as an attic or outdoors, moisture in the conveyed air will condense on the inside of the vent pipe. This condensed water will drain by gravity to the lowest point in the system. One study in Colorado measured as much as three quarts of condensation a day refluxing down a radon mitigation system. To avoid problems with moisture accumulation and system blockage do the following:

- All vent piping, from its termination down, must have a positive slope back to the suction point.
    - Some guidance documents suggest a slope of 1/8 inch per foot in horizontal runs.
    - As long as the pipe has a slight slope backwards to the suction point, the condensed water will not be retained.
    - Perforated piping beneath a slab or a crawlspace membrane is not an issue, because water will drain into the subgrade
- Above a slab or membrane, piping should never be trapped where moisture can accumulate.
    - If there is an obstruction where a trap would be necessary, use an alternative routing.

4.2.4.1.2.2 Condensation on the Outside of the Vent Pipe:

The air inside the vent pipe can often be at a lower temperature than air in the space it is passing through. If the air in that space is also humid, water can condense on the outside surface of the pipe and drip onto other building materials. This occurs because the soil air being extracted is at the mean annual temperature, which would be lower than room air or outdoor air during the summer. It can also occur if a large amount of interior air is leaking down through the foundation openings from an air conditioned room. If the pipe passes through an area of high humidity (like an unconditioned attic or storage area) condensation can occur.

In an arid environment such as Colorado, this is not necessarily a concern unless the pipe is routed through a potentially humid area such as a pipe chase or a locker room in larger buildings. If this is the case, the outside of the pipe should be insulated with an insulation that has a vapor barrier or alternatively a closed cell, foam insulation. Pipe insulation can also reduce the noise of air movement through the pipe, which could be annoying if the pipe is routed through a bedroom, for example.

4.2.4.1.3 Type of Pipe

Due to the large amount of moisture draining back through these systems, the venting should be routed similar to a sewer drain however; it does not need to be pressure rated.

Preferred material:

- Schedule 40 PVC or ABS rated as Drain Waste and Vent (DWV).
    - ASTM D1785, D 2446 or D2665
- Prime and glue (i.e. solvent weld) joints as would be typical for PVC or ABS piping.

Downspout for exterior routings:

- Oversized commercial grade downspout can also be used but <u>only</u> for portions of the vent piping that is outdoors
- 4 x 3 inch galvanized
- Only on discharge of fan and only outdoors
- Where multiple lengths are utilized, the upper section should fit down into the lower section to allow water to drain down towards suction point.
    - Install like normal downspout
- Joints should be sealed
- Prime and paint
- Use specialty round-to-rectangular adapters to convert from fan discharge to downspout.

Figure 63: Adapting exterior pipe to downspout

Adapter connecting round discharge pipe from fan to exterior-mounted downspout as radon vent. Caulk and seal downspout into adapter. Note this is NOT an existing downspout or one to be connected to the gutter!

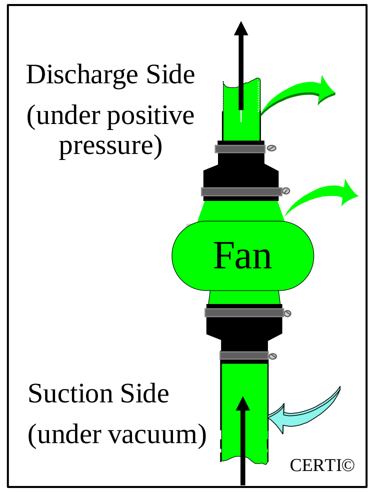
Do not Use:

- HVAC system ductwork as water will leak at seams
    - Sheet metal is unacceptable.
    - Insulated flex duct is unacceptable.
- Flexible dryer vent pipe is unacceptable
- SDR or schedule 20 plastic piping is easily broken

4.2.4.1.4 Fan Location and Discharge Piping

Radon concentrations inside of the vent pipe and fan can be extremely high. For this reason, radon fans and discharge piping should NEVER be in living spaces. Should a leak occur in the system, indoor radon levels could spike without the occupant knowing it. Most radon standards state:

- The radon fan or its discharge piping shall NOT be routed through conditioned spaces of the home
- The fan and its discharge piping shall NOT be located or routed through a basement or crawlspace beneath the living space of the building
- The fan and its discharge piping shall NOT be routed through a garage that has living space above it



Locate fan and discharge piping such that if leaks occur, radon will not be pumped into occupied spaces

Figure 64: Fan Leaks

The only acceptable locations for the radon fan are as follows:

- Attic space above home
  - Vent through roof, or
  - Vent out gable end and turned up above the eave
- Outdoors
  - Must be an outdoor-rated fan
- In a garage that does not have living space above it

In buildings that do not have attics, (e.g., vaulted ceilings or roofs immediately above dropped ceilings) the following options apply (Figure 65)

- Locate fan outdoors
  - Mount system on outside of structure, or
  - Install fan on roof
    - Hide behind parapet of flat roof
    - Use a low-profile roof fan (similar to an attic ventilator)
    - Enclose fan in a roof-mounted enclosure such as a cupola

If a passive system is being designed for a new building, a proper space for the potential installation of a radon fan that meets the above criteria needs to be designed into the construction of the building.

Figure 65: Fan Locations

Radon Fan in attic	Fan located outside	Roof-mounted fan

4.2.4.1.5 System Discharge Point

The radon gas discharge point should be carefully located to ensure discharged radon does not re-enter a building through an opening, such as a window or a mechanical air intake. The following is an excerpt from the EPA Radon Mitigation Standards that provides guidance for locating discharge points.

> ***EPA Radon Mitigation Standards. Section 14.2.8***
>
> *To prevent re-entrainment of radon, the point of discharge from vents of fan-powered soil depressurization and block wall depressurization systems shall meet <u>all</u> of the following requirements:*
>
> *(1) above the eave of the roof,*
>
> *(2) ten feet or more above ground level,*
>
> *(3) ten feet or more from any window, door, or other opening into conditioned spaces of the structure that is less than two feet below the exhaust point, AND*
>
> *(4) ten feet or more from any opening into an adjacent building. The total required distance (ten feet) from the point of discharge to openings in the structure may be measured either directly between the two points or be the sum of measurements made around intervening obstacles. Whenever possible, the exhaust point should be positioned above the highest eave of the building and as close to the roof ridge line as possible.*

The reason for having the discharge point at or above the eave is to prevent radon from re-entering the building through an opening or even through siding.

To comply with this requirement, the vent pipe is routed either up through the building or up alongside the exterior of the building. When routed through the interior of the structure the vent pipe would meet this standard if it penetrates the roof, provided it is separated from an operable skylight and at least 30 feet from or three feet above a mechanical air intake such as a roof top air handler or a swamp cooler[6].

When routed up the outside of the house, the pipe should elbow around the eave of the roof so the discharge point is above the gutter and pointed straight up or at a 45-degree angle away from the structure. It should NOT terminate below the soffit. The moist air can damage the soffit and other portions of the building, causing mildew, mold and ice problems.

There are other standards that suggest the discharge point be at least 12 inches above the eave. This is appropriate when penetrating the roof. However, when systems are routed up alongside the exterior of a building it can cause problems when snow builds up on the roof. In these situations, terminating just above the eave is adequate (Figure 66)

Figure 66: Proper Discharge Points

		
Discharge through roof. Good separation and also puts fan in attic.	Exterior fan and routing with discharge above eave.	Exterior fan and routing with discharge above rake edge of roof.

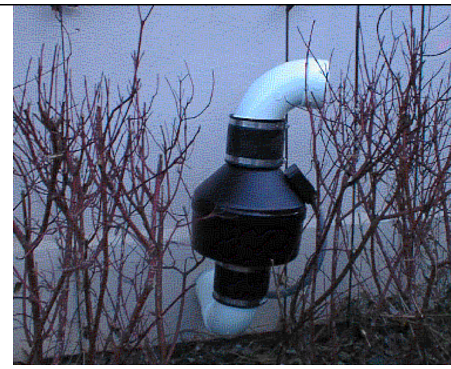
[6] ANSI/AARST RMS-LB, Radon Mitigation Standards for Schools and Large Buildings, 2014

Figure 67 provides examples of what should not be done.

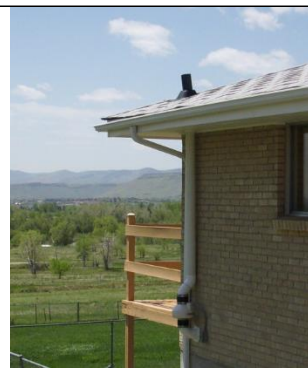
Figure 67: Improper Discharge Points

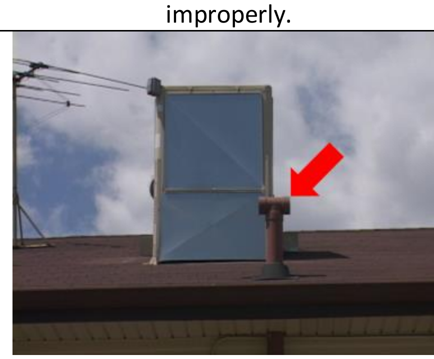

Exterior routing with the discharge impinging on soffit causing mold, mildew and damage to overhang.


Discharge is too low.


Discharge at grade level not to mention not being supported and wired improperly.


Through low roof and discharged near window of upper story.


Discharge is above roof, but penetrates the overhang, which can cause ice dams and leaks.


Discharge located near intake to roof-mounted swamp cooler.

4.2.4.1.5.1 Vent Termination

Installing a rain cap on the end of the vent pipe is **NOT** recommended. Rain caps can cause problems such as:

- Moist air from the system can ice up under the cap, causing an obstruction to proper airflow. This ice can also break off and fall into the fan, causing damage.
- Some caps can force the radon back down towards openings in the structure.

If the system piping is properly installed, moisture pulled from the subgrade will go back down the pipe to where it originated. The amount of rainfall that will enter the pipe is negligible.

The air coming out of the discharge is warm and attractive to birds and squirrels. For this reason, a “critter” screen on the end discharge pipe is required. Screens must:

- Be mounted on the very end of the vent pipe
- Be of a large mesh size (3/4 –inch to one inch) to allow for good airflow and prevent frost build up during cold weather

Figure 68: Protecting Discharge End from Varmints

Ice can form on discharge end. Rain caps exacerbate this problem.

Canadian Mitigation Guide

Remnants of red squirrel that entered vent pipe and fan.

Install large mesh screen on end that keeps out varmints, lets moist air pass easily and minimizes frost buildup.

4.2.4.1.6 Performance Indicators

After an active radon system is installed, the building must be tested to ensure safe levels. There must also be some type of failure indicator on the system to alert the occupant or building owner if the system stops working.

Typically, this is a vacuum indicator that shows the fan is still creating a vacuum on the soil and presumably drawing radon out of the soil. A change from the initial vacuum level would indicate that something has changed in the system and service is required. These U-Tube manometers have the following attributes:

- One port open to indoor air and the other port connected via a small tube to the interior of the suction piping of the radon system
- The device should be in a location that is easily visible to the occupant
    - Typically the U-tube is mounted directly on the radon vent piping
    - If the pipe is hidden behind walls, a tube can be connected to the pipe and the U-tube can be mounted on an interior wall nearby, such as in a laundry room
- Do not run tubing inside of radon vent pipe
- Tubing should not be run through a cold space where moisture could condense inside the tubing, such as being routed through an attic space
- U-tubes should measure a vacuum range of 0-four inches of water column

Alternatively, there are electric indicators that measure the electrical current to the fan. When there is a change in the electrical current the system is drawing, it indicates a problem with the system. These devices are useful because they are integral to the wiring for the fan and do not require additional wires or tubes to be run. This is especially applicable when:

- The system is totally outdoors, where low temperatures can cause problems with U-tube oil consistency or its sensing tube being obstructed with condensation and ice
- When a fan may be installed at a later date, as would be the case if a passive system was installed during construction and post-construction testing dictated a need for installing a fan

Another approach is the use of a consumer-grade radon measurement device that will indicate changes in radon levels. These should only be used **in addition** to the pressure or electrical current style indicators. Consumer grade radon indicators may not be "approved" devices, but they can show changes in radon levels that can alert the consumer if there is a problem. If a significant change in radon is indicated, it should be verified with an approved device before major repairs are made. NOTE: the Colorado Department of Public Health and Environment does not recommend the use of non-approved devices for determining the need for, or the success of, a radon mitigation system.

Figure 69: Example of ASD System Performance Indicators

U-Tube manometer connected to suction piping with label indicating initial installation

Electrical current style indicator. in line with wiring to fan

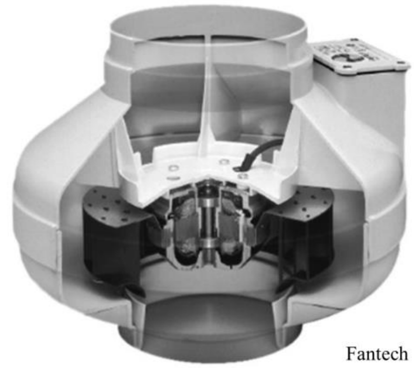
Consumer grade radon indicator can sense changes in indoor radon

NOT An "approved" device for determining the need for or success of mitigation

Regardless of the type of indicator used, clear labeling should be posted near the device with advice about how to interpret readings.

4.2.4.1.7 Radon Vent Fans and Installation

Radon vent fans come in many sizes and capacities, but they have one thing in common-they are manufactured specifically for use in radon systems. The use of other HVAC types of fans and blowers (e.g., squirrel cage fans) are unable to deal with the moisture conditions presented with radon systems. In particular, radon fans have the following attributes:



- Inline installation
- Internal motors and impellers
- Casing design that when mounted vertically allow condensed water in the discharge piping to flow around the inside of the casing to the suction side of the fan where it can drain by gravity to the suction point
- Rated for outdoor installation
- Sealed bearings requiring no maintenance
- Rated for continuous service
- Sealed and gasketed electrical connection box
- Thermal overload protection (self-resetting)

The proper fan size will be determined by the amount of air that will need to be extracted while being able to overcome the pressure drop caused by the piping system and still maintain between ¾ inch and 1 inch of water column at the suction point.

4.2.4.1.7.1 Fan Mounting

Fans must be installed as follows:

- Oriented vertically to allow water drainage
- Installed outside the envelope of the building (see section 4.2.4.1.4)
- Secured to pipe with flexible couplings
  - o Allows for future replacement
  - o Reduces vibration back into structure
- Piping above and below fan should be braced such that fan can be removed without moving piping.

Radon Fan

Fan installation

- Fan installed vertically
- Flexible couplings above and below fan
- Piping is secured to allow for fan removal
- Electrical disconnect within eyesight of fan

Figure 70: Fan installation

4.2.4.1.7.2 Electrical for Radon Fan

Most radon fans draw less than one amp even on startup — meaning they can typically be connected to a shared circuit (unless the current circuit is overloaded). Not only is a dedicated circuit unnecessary, it can be detrimental because occupants may not realize the circuit breaker that solely serves the fan has tripped.

Although electrical and mechanical codes may not require an electrical disconnect, radon mitigation standards do require disconnects as an added precaution, regardless of their horsepower or power draws. The following electrical requirements have been extracted from the *US EPA Radon Mitigation Standards:*

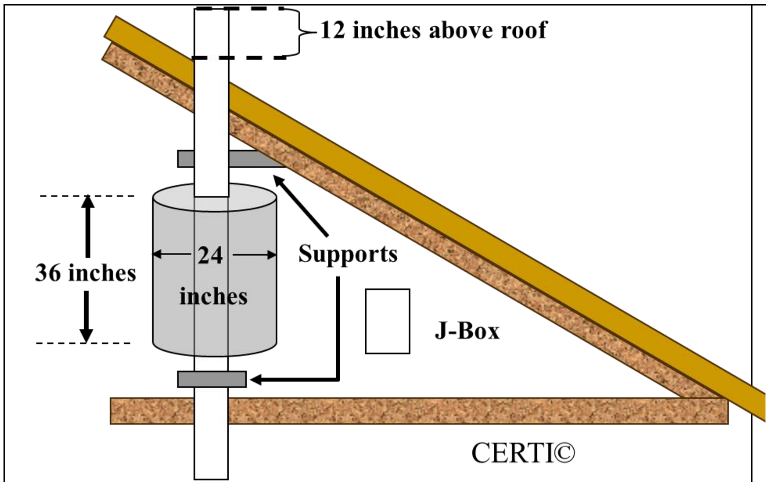
> ***14.6.1** Wiring for all active radon mitigation systems shall conform to provisions of the National Electric Code and any additional local regulations*
>
> ***14.6.2** Wiring may not be located in or chased through the mitigation installation ducting or any other heating or cooling ductwork*
>
> ***14.6.3** Any plugged cord used to supply power to a radon vent fan shall be no more than 6 feet in length*
>
> ***14.6.4** No plugged cord may penetrate a wall or be concealed within a wall*
>
> ***14.6.5** Radon mitigation fans installed on the exterior of buildings shall be hard-wired into an electrical circuit. Plugged fans shall not be used outdoors*
>
> ***14.6.6** If the rated electricity requirements of a radon mitigation system fan exceed 50 percent of the circuit capacity into which it will be connected, or if the total connected load on the circuit (including the radon vent fan) exceeds 80 percent of the circuit's rated capacity, a separate, dedicated circuit shall be installed to power the fan*
>
> ***14.6.7** An electrical disconnect switch or circuit breaker shall be installed in radon mitigation system fan circuits to permit deactivation of the fan for maintenance or repair by the building owner or servicing contractor (Disconnect switches are not required with plugged fans)*

4.2.4.1.7.3 Planning for a Future Fan – Passive to Active – New Construction

If a passive system (no fan) is installed during new construction, with the potential of the fan being installed later as a function of post-construction radon testing; accommodations need to be made to allow for the fan to be installed per the parameters cited above.

The most notable aspect is providing adequate space for the fan. A vent pipe routed up an outside wall and through the roof not only reduces the effectiveness of the passive system due to lack of natural thermal stack effect, it also does not allow for room for the fan other than mounting it on the roof, which is not aesthetically pleasing. See Figure 71 for space requirements.

Figure 71: Planning for Future Fan Installation – New Construction



4.2.4.1.7.4 Penetrating Occupancy Separations and Plenums

Figure 72: Fire Collars

Fire collars placed around pipe when passing through a fire-rated wall

When routing radon vent pipe, care should be taken to maintain the integrity of occupancy separations (i.e. fire walls). Examples are:

- Passing from a living space into an adjacent garage
- Passing up through a garage ceiling if the ceiling is fire-rated
- Passing through fire-rated ceilings/floors separating apartments or condominium units

A fire collar that encases the plastic pipe at the penetration should be used. Mechanical dampers with fusible links are not recommended due to corrosion that can occur due to high humidity airflow. Also, fire caulks applied around the outside surface are unacceptable for large plastic pipes as used in radon systems (three- to four-inch diameter).

Another concern when routing radon vent pipes in schools and commercial buildings is if the ceiling is being used as a return air plenum. Most building codes prohibit the routing of plastic pipe through plenums where noxious fumes from a burning plastic pipe could be spread throughout the building. In this case, the routing should be changed to avoid the plenum ceiling or use steel pipe instead of PVC.

4.2.4.1.7.5 Ice Protection Exterior Systems

Systems that are installed on the exterior of buildings are subject to freezing temperatures. When this occurs, the high moisture content of the exhausted gases will not only condense but ice can also form. Since the air in the pipe is warm, the ice will eventually thaw, causing ice chunks to fall down into the fan, damaging it.

Hose-style systems that route condensed water from the discharge of the fan to its suction piping can be problematic due to the potential for water freezing in the by-pass hose. Devices that protect ice from falling into fan or drain condensate onto the ground have proven effective in cold climates like Colorado.

There are two ways in which ice can be precluded from entering the fan housing:

Criss-Cross

Install two lengths of stainless all thread (3/8 inch) in the pipe immediately above fan.

- Drill pipe from outside with holes at 12, 3, 6, and 9 o'clock positions.
- Insert all thread in and secure with washers and nuts.
- Caulk penetrations.
- This cross pattern will stop large chunks from falling into the impeller without significantly impairing airflow.

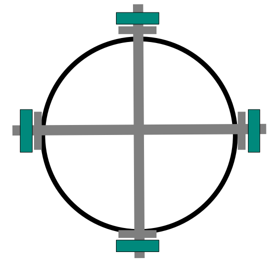


Figure 73: Criss-Cross Ice Guard

Handmade with short lengths of all-thread inside of pipe just above fan

Hydro-Sep Water Diverter

- A Hydro-Sep water diverter can also protect the fan from ice because it has a nozzle within it that will stop large ice chunks from falling into the fan housing.
    - It also allows water to drain out on the area around fan.
    - Do not use a Hydro-Sep on a fan located in attic or garage. Only use this type of device when fan is outdoors and where dripping water will not cause damage.

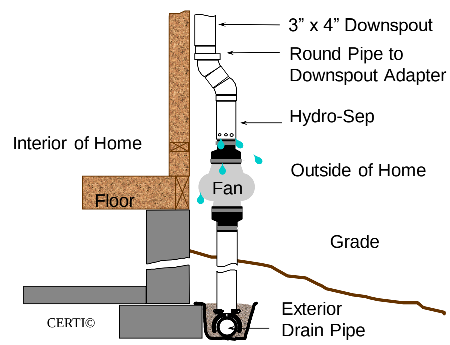


Figure 74: Hydro-Sep Ice Guard and Water Drain

Only use in outdoor fan locations

4.2.5 Caulking and Sealing

A well installed soil depressurization system reverses the airflow through the foundation to where interior air moves down into the subgrade, retarding the entry of radon-laden soil gases. Because of this reversal, it is not imperative the foundation be perfectly sealed. However, sealing the openings in slabs, drainage systems, and sub-membrane sheeting systems will increase the radon capture rate and reduce the loss of conditioned air within the structure.

In existing homes, sealing is performed where foundation openings can be accessed. When radon systems are incorporated during the construction of a new building, openings are more accessible and therefore sealing can be more rigorous.

4.2.5.1 Sealing Slab Openings

- Caulking materials should be a flexible, elastomeric caulk that is suitable for adhesion to concrete.

    - Polyurethane caulk is typically used. Floor adhesives and glues are typically not flexible enough to prevent cracking when the slab shifts. Silicone caulks typically contain acetic acid, which can cause the bond to deteriorate. However, they are suitable when sealing items that are mechanically attached such as sump covers and inspection plates.
    - Read MSA sheets to ensure that caulk or solvents will not harm workers or occupants.
    - Proper ventilation should be employed when utilizing caulks, sealants as well as glues.
- Floor-to-wall joints, whether they are expansion joints or cold joints, should be caulked.
    - Joints should be brushed and adequately caulked to ensure a bond from floor to wall.
- Plumbing block-outs
    - Fill block-out with thin layer of non-shrink grout, or
    - Fit small piece of durable polyethylene sheeting into block out and seal edges to inside of block-out.
    - Large block-outs such as under tubs and also behind protective walls can be sealed with expanding foam.
- Plumbing and conduit penetrations
    - Cut expansive wrap around pipe flush to floor then apply polyurethane caulk around the pipe where it penetrates the floor.
- Slab control joints
    - Remove debris.
    - Caulk with gun-grade or flowable polyurethane caulk up to level of floor.
- Floor cracks are typically not major leak points due to the shape of the crack and accumulation of dust and debris that serves to close off these pathways. However, where slab reinforcing is not utilized (uncommon in newer construction), these cracks can be large leak points.
    - If floor cracks are to be caulked, then they should be ground out, cleaned and then caulked.
    - Alternatively, floor tile or linoleum will seal these minor pathways.
- Floor drains that drain directly into the soil or to a sump should be retrofitted with “P” traps or cupped traps and be filled periodically with water.

4.2.5.2 Drainage Systems

- Interior sumps, regardless of whether they serve as the soil-gas collector or not, are to be covered with an appropriate lid and mechanically fastened to the floor.
- Sump covers should be sealed to basket or floor with a gasket or silicone caulking.
    - Do not use a caulk such as polyurethane that could make access to the sump pump difficult due to its adhesive strength.
- Exterior sumps used as a soil-gas collector should be fitted with a mechanically bolted and gasketed cover.
- Foundation drains that are part of soil gas collection system that also have a soakaway termination should be fitted with a backflow check valve.

4.2.5.3 Sub-membrane Systems

Polyethylene sheeting used as part of a crawlspace treatment system should be sealed where possible with a polyurethane caulk or tape recommended by the membrane manufacturer. The following leak points should be addressed:

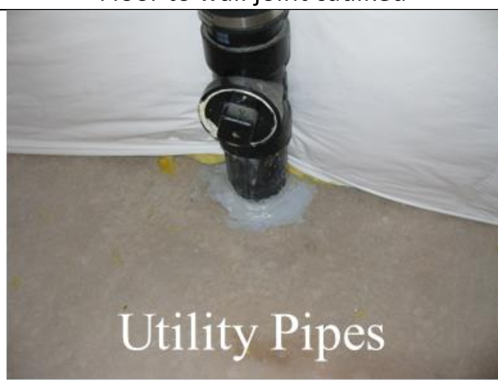
- Where edges meet foundation walls
- Seams
- Membrane penetrations
    - Utility lines
    - Support piers
    - Equipment pads
    - Sump baskets (sumps themselves should also be sealed
- Poly around soil vent riser

Figure 75 provides some examples of sealing.

Figure 75: Slab Caulking and Sealing Examples

Floor to wall joint caulked

Caulked control joint



Plumbing penetrations

Block-outs around support posts

Plumbing block-outs

Membrane sealed in plumbing block out
Also accomplished if vapor barrier is installed under slab

4.2.6 Finishing Touches

In addition to the actual installation, there are some finishing touches that address the goal of making radon systems integral parts of a building.

4.2.6.1 Labeling

To avoid confusion for future owners or maintenance personnel, the system should be clearly labeled as to what it is and what special precautions should be taken. There are several locations that are to be labeled:

Table 18: Radon System Labeling

Label Type	Location	Detail Summary
System label	• In a prominent location such as on radon vent pipe or if system is hidden, near electrical panel	• Only one label is necessary • Advises owner that a radon system exists • Installer's name and contact info • Date of Installation • Advice to retest • Where to shut fan off at (disconnect and breaker number) • If a passive system, advise to test and who to call to activate it • Contact info for Colorado Department of Public Health and Environment
Vent pipe label	• On vent pipe and at each floor of building • Pipes behind walls should also be labeled for future maintenance purposes. • Interior and exterior systems although portion penetrating roof is not typically labeled	• Identify pipe as *Radon Vent Pipe*
Sump Lid	• On top of sump lid	• Advises occupant not to remove lid without turning off fan (and how) • Advice that lid should be replaced after sump pump servicing, resealed, and fan turned back on.
Membrane	• On surface of sub-membrane poly sheeting • One label typically near access door	• Advises the need to maintain integrity of membrane • If cut or removed, fan to be turned off after service work, poly should be repaired/replaced and fan turned on
Performance Indicator	• On or near performance indicator	• How to interpret device readings • Indication of reading after installation • Action to take if changes occur • Who to call for service work
Breaker Label	• On circuit breaker panel • On circuit that powers fan	• Typically hand written in with indelible marker (Radon Fan)

4.2.6.2 Combustion Appliance Draft Checks

A radon system will extract some interior air out of the house. If openings in the foundation are not properly sealed, the radon system could cause combustion appliances to backdraft, causing exhaust gases to enter the home. This could have serious consequences. Radon mitigation contractors should conduct a backdraft test at the conclusion of their work to verify the appliances are still properly functioning.

Other issues that may cause backdrafting include:

- Lids being pulled off sumps, without turning off radon fan
- Polysheeting of sub-membrane systems being removed or cut without turning off radon fan
- Pipes being broken
    - This should not be an issue if the recommended Schedule 40 pipe is used

These situations can occur without anyone knowing. For this reason, it is recommended that all homes, and especially where occupants may sleep, be equipped with carbon monoxide detectors with audible alarms. It would be prudent to verify the existence and proper operation of these devices when a radon system is installed.

4.2.6.3 Aesthetics

Aesthetics of the system can be very important, especially since these systems will become an integral part of the building. Some considerations:

- Pipe routing can be interior or exterior
    - Interior routing conceals system
    - Interior routing is much easier to do when system is installed during construction
- Exterior vent piping can be primed and painted to match trim colors
- Alternate pipe routings may look better although they may cost more
- Exterior fans can be located within enclosures
    - Not necessary since fans are rated for outdoor installation
    - Improves appearance (e.g. paint to match exterior colors)

Figure 76: Improving Aesthetics

Downspout painted to blend with other architectural features of home

System located near other mechanical components

Fan located in shroud

Downspout on exhaust painted to match trim colors

Interior routing hides system routed up through closets

Concealed within framing when installed
while building is constructed

Concealed in attic when installed during construction

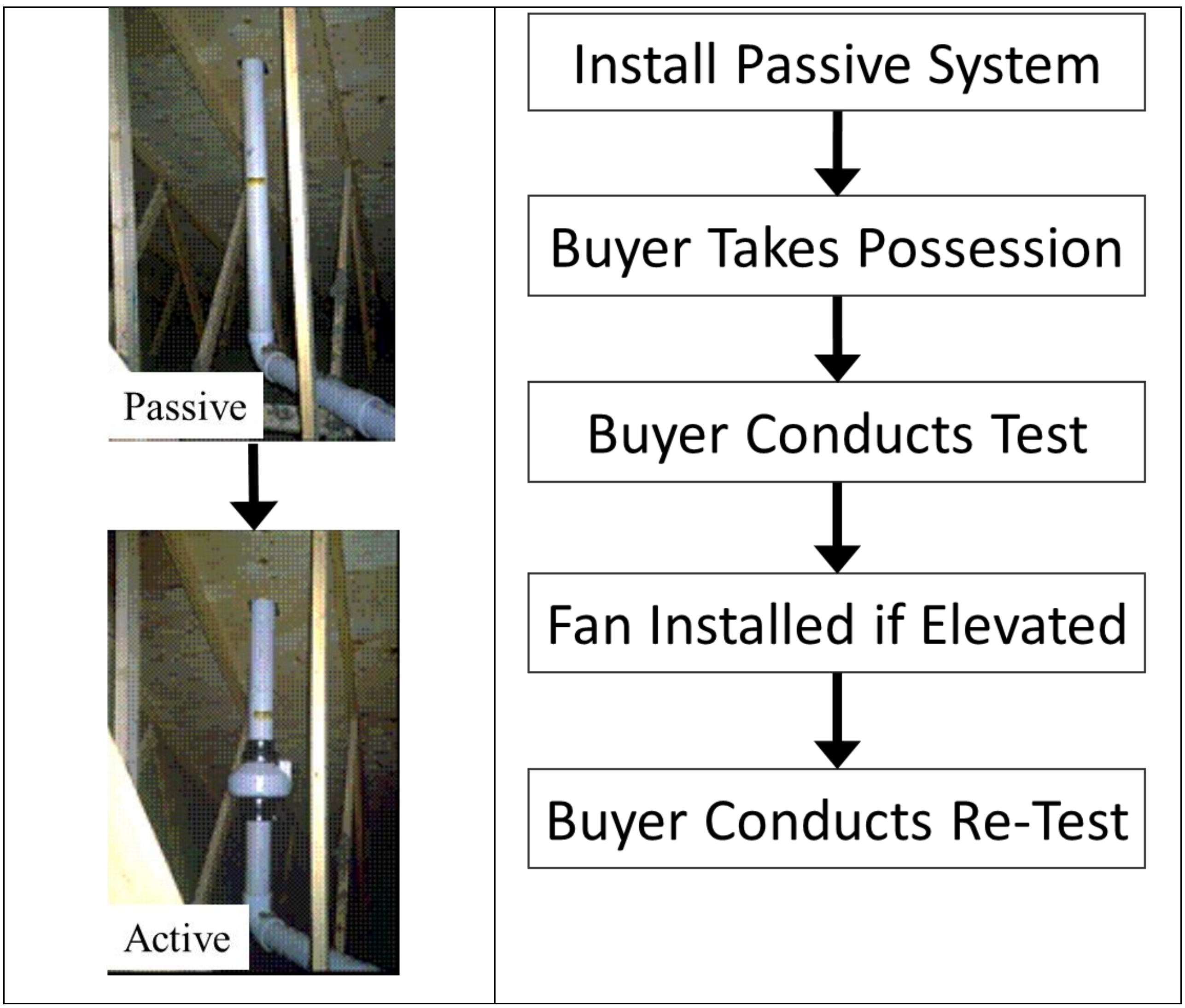
4.2.7 Installing Soil Depressurization Systems during New Building Construction

Previous sections of this document discuss in detail how radon control systems are designed and installed. However, there are a few additional items worthy of consideration when installing a radon system during construction.

4.2.7.1 Passive to Active Approach

Appendix F of the International Residential Code details an approach for installing a passive radon system where certain elements included during construction would allow a radon system to reduce indoor radon levels to where a constantly operating fan may not be necessary. This is referred to as Radon Resistant New Construction (RRNC) and assumes that the effectiveness of a passive system would be verified with a radon test after the house is constructed and if necessary a radon fan could be easily added. The process is illustrated in Figure 77.

Figure 77: Passive to Active Fan Concept



A passive radon system may adequately reduce indoor radon levels. A study in Ft Collins, CO showed an approximately 50 percent reduction in radon levels with a passive system (Figure 78 and Figure 79). There is also the added benefit of reduced electrical costs. However, the home MUST be tested after occupancy to ensure safe levels.

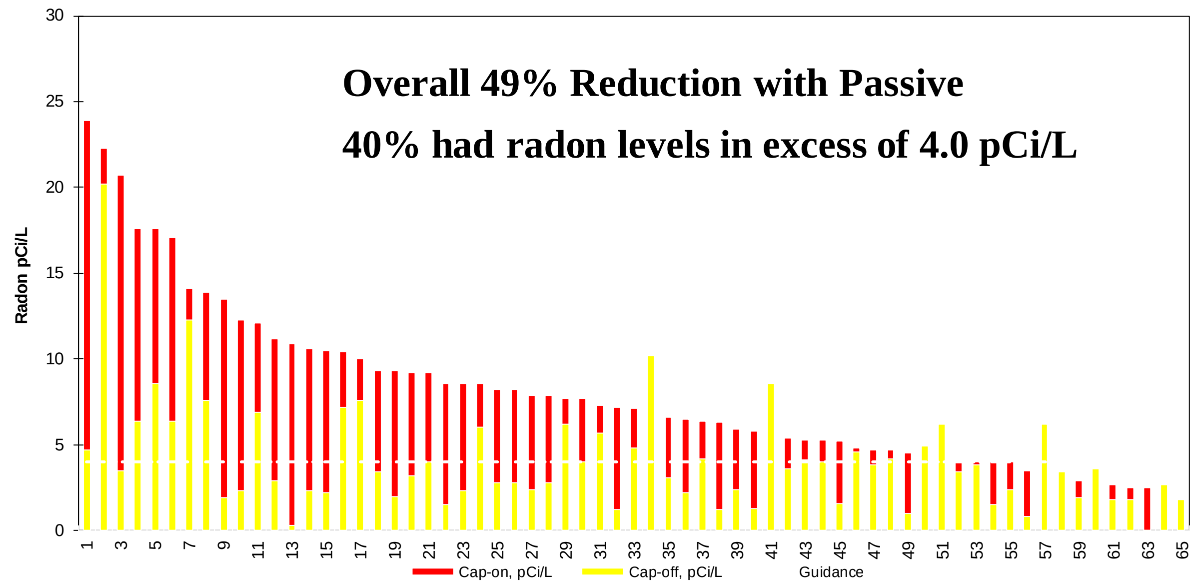
Figure 78: Capped vs. Uncapped Study Approach

Passive system capped to simulate no system

Passive system uncapped

The results of the Fort Collins study are provided below, where each of the stacked vertical bars represents both capped and uncapped short-term test results.

Figure 79: Effectiveness of Passive Radon Systems



As can be seen, at least for this study, conducted in a high radon potential area, the passive radon systems were able to reduce radon by essentially 50 percent. However, many failed to reduce the radon levels to less than the EPA action level of 4.0 pCi/L (40 percent of the cases). This illustrates why you must test the houses rather than assume the passive systems are adequate.

An alternative to building homes with passive systems is to make all systems active before they are sold. The advantages of this approach are:

- Active radon systems are more likely to reduce levels below 4.0 pCi/L
- System defects (e.g. leaks) are easy to inspect for and detect when a fan is operating
- Contractor reputation is maintained when post-construction/pre-closing tests are low
- System routing is less restrictive because the system is augmented with a fan

Although saving electricity with a passive system is a good objective, advances in the design of radon systems have made this benefit fairly negligible. Through better slab sealing and air flow reduction, the use of much smaller fans (consuming less than 15 watts of electricity) is possible. Consequently, several builders in Colorado have chosen to install active systems to simplify the closing process and reduce future liability while still providing energy conservation via the use of more energy efficient fans.

Installing active radon systems can be even more beneficial when constructing large multi-family dwellings or schools. The cost of a full radon survey to assess the effectiveness of a passive system can far outweigh the cost of installing an active system, in addition to providing much greater radon reductions.

4.2.7.2 System Inspection

Inspections are vitally important for radon mitigation systems installed during construction. This is especially true with passive systems where defects are not as easy to detect. Things to look for include:

- Improper aggregate or trench filling
- Aggregate or construction debris falling into vent riser before it is connected and routed through the building
    - Cannot be detected until an active fan is connected and no air can be extracted
    - May require tearing up slab to repair
    - May require abandoning the system and resorting to a post-construction procedure
- Improper sealing of floor-to-wall joints
    - Only visible prior to floor finish or walls being installed
- Traps added to vent pipe to avoid interferences with other systems. Traps in piping will cause water to accumulate and render the system ineffective.

The full system should be inspected prior to a final radon test being performed. To avoid costly repairs, especially in large buildings, the following inspections are recommended during construction:

- Soil gas collector prior to slab pour
    - Multiple inspections if there are multiple slab pours
- Slab caulking prior to installing interior walls and finishes
- Piping system prior to wall finishes (can be combined with previous)
- Fan and piping system after power has been supplied to fan (if activated)

It may be prudent when a passive (no fan) system is installed to temporarily hook up a fan to test airflows and identify obstructions or other installation defects.

4.3 Alternative / Trim Techniques

Soil depressurization is the primary radon mitigation method. However, there are situations where alternative methods are appropriate (See Section 4.1.2.2). These include:

- Where active soil depressurization does not fully reduce radon.
  - When sufficient negative pressure within the subgrade cannot be obtained.
- Where a system already exists within the building that through repair or modification can reduce radon as well as improve overall air quality.
  - An HVAC system in a large commercial building or school, where outdoor air flow can be increased.
- Where radon levels are relatively low and an ASD approach is very costly.
  - Example: A high-rise apartment or condominium structure where only the ground floor units are slightly elevated and routing the vent pipe system up several stories is very costly.
- When the radon source is from building materials rather than from the subgrade.

These techniques are briefly described in this section, primarily to indicate they are proper techniques. They will likely require a cooperative effort between a radon mitigation contractor and other professionals such as an HVAC contractor.

4.3.1 Dilution/Air Exchange

Dilution of indoor air could be as simple as opening a window. However, opening a window is only a temporary solution to elevated radon levels. After the window is closed, radon will re-enter and return to previous levels within a few hours. Also, opening windows during the winter, especially in a climate like Colorado's, is not a practical consideration.

A common approach to improving indoor air quality is to simultaneously exhaust stale, interior air while adding fresh, outdoor air via a heat-recovery ventilator (HRV). An HRV transfers some of the heat of the exhausted air to the incoming air, thereby reducing the energy penalty.

A few considerations should be taken into account when designing an HRV for use as a radon mitigation system:

- The heat-recovery ventilator (HRV) should treat the entire building, rather than segments of the building.
- The HRV should operate continuously when the building is occupied, rather than as a function of outdoor temperature.
- The HRV should be balanced to either neutral or slightly positive interior pressure (+0.010 inches water column).
- The HRV should be labeled as being part of a radon system for full disclosure to occupants and future owners.
- Simple dilution equations apply.
- Radon measurements should be used to verify reduction — even in new construction.
- Feasible if radon levels are 8 pCi/L or less

Dilution with an HRV can provide an alternative solution when ASD is difficult, such as when mitigating a specific ground-floor unit of a multi-story building.

4.3.2 Radon Decay Product Reduction (Radon Progeny)

It is the decay products of radon (polonium 218 and 214) that actually present the primary health risk associated with indoor radon. This is because they have such short half-lives and emit alpha particles that can damage sensitive lung tissue when inhaled. For more information, see Section 2.1.3.2.

Methods that reduce radon also reduce RDPs. However, one can also reduce RDPs where radon levels are elevated but not higher than 8-10 pCi/L. This is accomplished by passing indoor air across filters where RDPs and other particulates can be filtered out.

Devices that remove airborne particulates will also reduce RDPs by filtering out particulates to which radon decay products are attached. Newly formed radon decay products will also be reduced as they pass through a filter or come in contact with the inside of ductwork, etc.

As concerns about indoor air quality have increased over the last few decades, more buildings have HVAC systems equipped with higher quality air filters. This has occurred in schools, commercial buildings, residential structures and apartment units. Depending upon the capabilities of an existing HVAC system, air cleaners can be added to reduce RDPs as well as asthma triggers, etc.

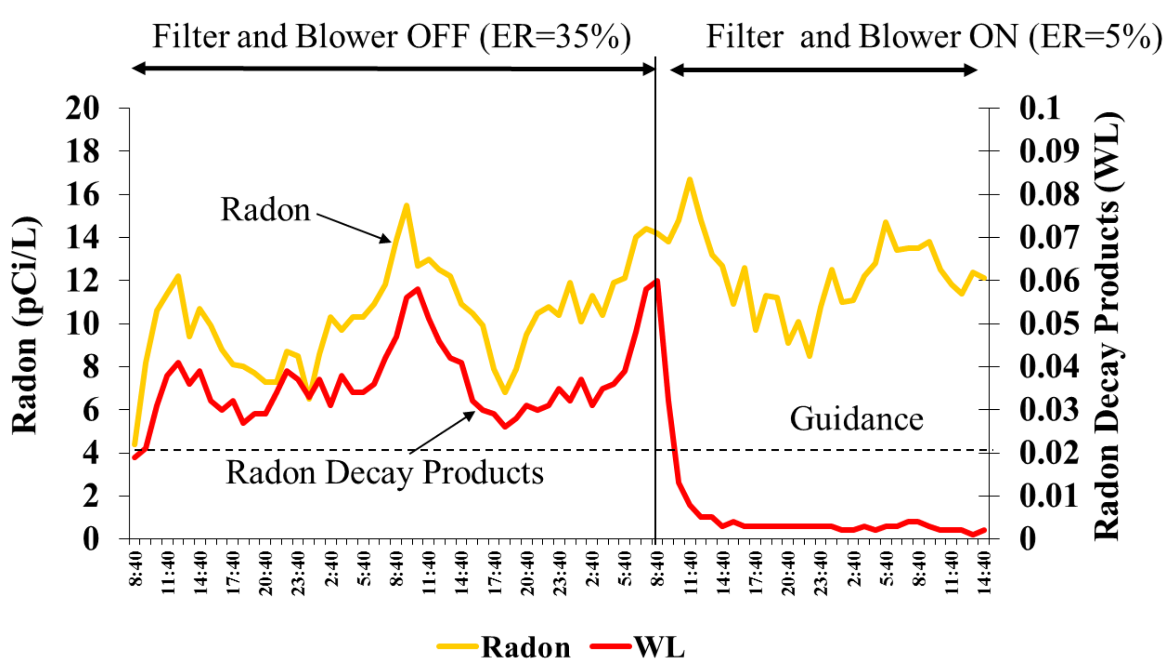
There are several key elements that need to be taken into consideration when considering RDP reduction:

- Radon gas is not reduced via air filtration.
  - Only RDPs are removed.
  - The effectiveness of this system must be verified with simultaneous radon and radon decay product measurements (See section3.1.6.1).
- As new radon enters the building, new radon decay products will be created that may be inhaled before reaching the filtration device or attaching to large airborne particles.
  - This is why filtration should only be used when radon levels are relatively low (less than 10).
  - Sometimes referred to as unattached fraction of decay products.
- Whole-house or whole-building filtration should be used to treat the entire structure rather than just an individual room – unless there is only a singular room of concern.
  - Air recirculation rates of 1.9 times the volume of the house are optimal.
    - This does not refer to exchange with outdoor air, but rather interior air recirculation through the filter media.
- Air handlers MUST be reconfigured to run continuously when heating or cooling is not in use.
  - Air recirculation rates cited above (1.9 house volume turnover/hour) are typically lower than airflow rates when heating or cooling is in use.
  - Most blower motors have the ability to operate at different fixed speeds, which the HVAC contractor can easily set.
  - In a residential setting, power consumption at lower blower settings is comparable to power consumption of an active soil depressurization fan (50-60 watts).

- MERV 10 -11 filters are ideal for this purpose.
    - Common filters for large buildings.
    - Higher efficiency filters (HEPA) filters are NOT recommended. They reduce other airborne particulates so well that the radon decay products have fewer objects to attach to, thereby increasing the unattached RDPs.
    - RDPs are reduced by electrostatic attachment to media or ductwork they come in contact as well as by filtration of other particles to which they are attached.
        - This why less expensive, looser filters are better than expensive, tight filters.
    - Filters must be changed per manufacturer's recommendation.
    - Filters can be disposed of as normal.
        - RDPs decay away and the filter does not become a radioactive waste.
    - Media filters are recommended rather than electrostatic filters.

This technique can be very useful, but requires specialized skills and advanced measurement techniques of the designer. It is an additional tool to be used, especially in difficult situations or where occupants can benefit from cleaner indoor air. Figure 80 provides an example how a whole-house media filter dramatically reduced radon decay products.

Figure 80: Effect of Air Cleaner on Radon Decay Products



Note the radon gas did not change, but the RDPs dramatically dropped when the filter was turned on. This effect can only be measured with a radon decay product measurement device.

4.4 Testing After Mitigation, Retesting Frequency and Monitoring Plans

Because radon cannot be seen or smelled, the only way to know if a radon system is working properly is to test for radon (or in some cases, radon decay products).

> The only way to know if a radon system is working or continues to work is to test for radon.

4.4.1 Initial Testing After Mitigation

After a mitigation system is installed or after a building's HVAC system has been adjusted, radon levels are to be tested as follows:

- Conduct a short-term test (two to seven days) in the same location(s) where previous measurements identified a concern. (Section 3).
    - Post-mitigation tests can be started as soon as 24 hours after the completion of the system but within 30 days.
- If short-term measurements do not indicate success:
    - Repeat diagnostics.
    - Repair or augment system as needed.
        - Repeat short-term test to verify system is working properly.
- If short-term results are satisfactory:
    - Document the performance indicator reference point in order to identify changes in the system's performance that would indicate a problem.
    - Establish a maintenance program where the system is routinely checked and combined with periodic retesting.

4.4.2 Retesting Frequency and Monitoring Plan

The source of radon (uranium 238) has a half-life of essentially four billion years. Eventually the mitigation system will fail, causing indoor radon levels to return to pre-mitigation levels. Most systems are very durable and the maintenance requirements are minimal beyond simple monitoring. There are many systems in Colorado that have been successfully operating for decades, but even they will eventually fail.

After a mitigation system has been demonstrated to be properly reducing radon levels via the use of a short-term test, one should institute two concurrent monitoring plans:

4.4.2.1 System Performance Indicator Checks (Monthly)

At least monthly, check the system, performance indicator (Section 4.2.4.1.6).

- The performance indicator on a mitigation system is how one can determine if the system is still functioning as it should.
- A change in the indicator may or may not indicate that radon levels are elevated, but it does indicate that there has been a change in the mechanical aspects of the system. Examples can be:

    - A blockage in the system;
    - Reduced fan speeds (i.e. malfunctioning capacitor or motor degeneration); or
    - Electrical malfunction (e.g. circuit breaker off, etc.).
- If the malfunction is a full system shut down (i.e. fan off) repairs should be made and then short-term testing should be conducted.
- If there is a change in a system performance indicator, radon levels should be checked with an approved short-term radon measurement device before making repairs.
    - The use of consumer-grade "non-approved" devices are good indicators of system problems, but should still be verified with an approved device prior to implementing repairs.
- After any repairs are made to a system, the effectiveness of the repairs should be verified with a short-term test.
- Resume the monitoring plan once repairs are made.

4.4.2.2 Retesting Frequency

Even if a system performance indicator does not indicate a concern, periodic radon tests should be performed. The previous need for mitigation established the potential for the building to be elevated. Should the buildings conditions change or be modified, the system may not be working as it was previously.

All previously mitigated buildings should be retested immediately after major modifications have been made, such as:

- Modifications to buildings HVAC system;
- Building additions;
- Major renovations; or
- New buildings constructed on the same school campus or apartment complex.

Beyond retesting after major modifications, the following minimum frequency of retesting is recommended, depending on the building type:

Table 19: Recommended Retesting Frequency after Mitigation

Type of Building that Has Been Mitigated	Minimum Recommended Frequency of Retesting
Single-family residence	Once every two (2) years
School	Once every year
Apartment building	Once every two (2) years
Office building	Once every two (2) years
Childcare facility	Once every year

The method of retesting depends upon the type of structure and the HVAC system (See Table 20).

Table 20: Type of Periodic Post-Mitigation Testing Methods

Type of Building	Follow-Up Measurement Approach
Single-family residence	Short-term(minimum two-day) or long-term (minimum 91-day) test
Schools, office buildings, and large childcare centers where an energy management system creates differing environments for occupied versus unoccupied times.	Short-term tests (minimum two-day) during occupied periods, or Short-term test with a continuous monitor recording hourly readings to differentiate occupied versus unoccupied exposures
Apartment buildings	Short-term(minimum two-day) or long-term (minimum 91-day) test

When conducting periodic measurements in large buildings e.g. schools, childcare facilities and multi-family dwellings) retesting the entire building in the same manner as the initial pre-mitigation measurements were performed is critical.

For example, if previous surveys indicated only three out of 20 classrooms in a school where elevated and the rooms were successfully mitigated, periodic testing should not solely be conducted in the three rooms that were mitigated, but in all 20 ground-contact rooms.

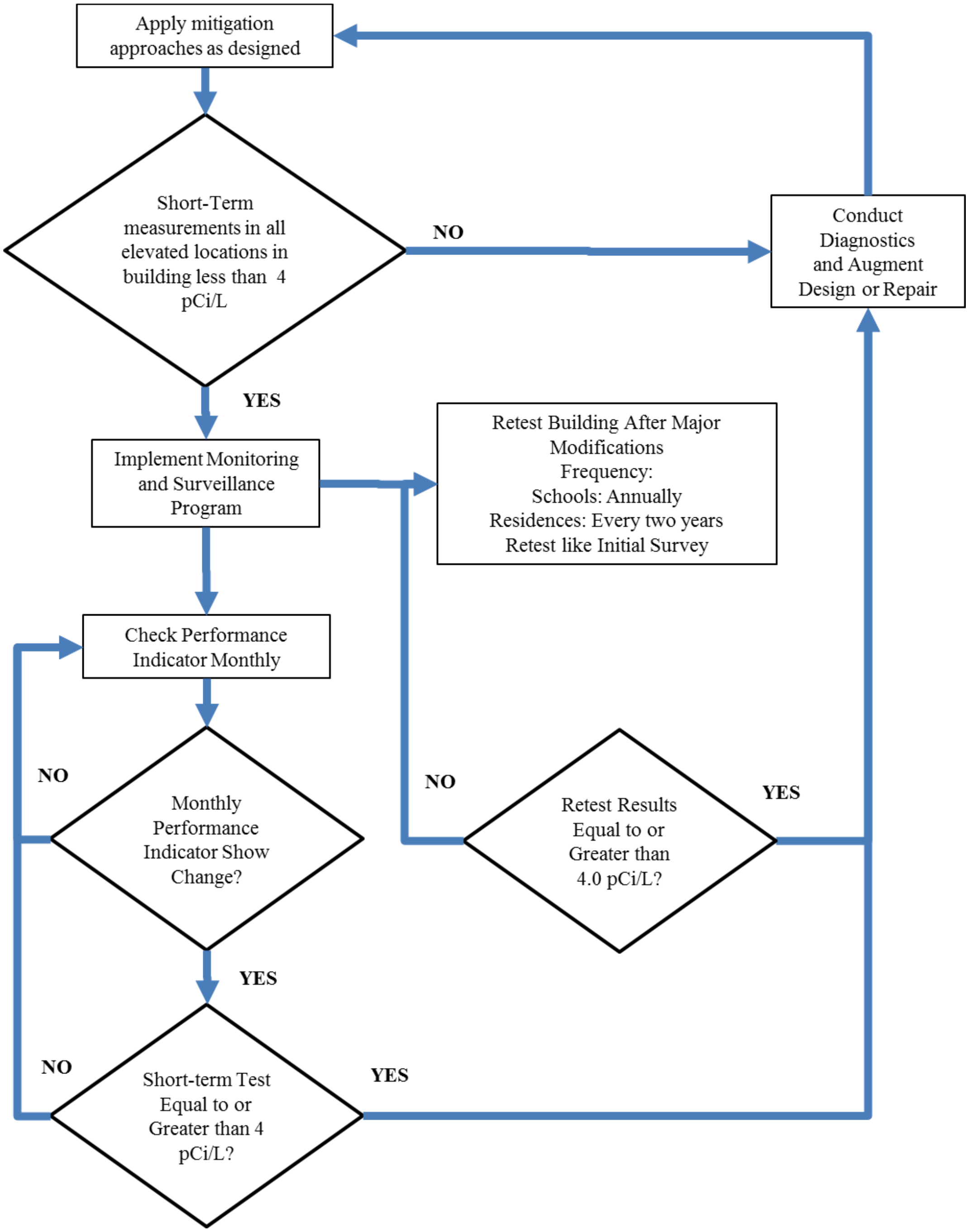
The reason for this is the three previously mitigated rooms proved that there was a strong radon source beneath the building and those rooms that were not mitigated may have been affected by the HVAC systems. Changes in the HVAC system over time can shift radon concerns to rooms that were previously not elevated.

> When retesting a previously mitigated school, office building, or apartment, all ground contact areas should be retested rather than just the ones that previously showed elevated radon levels and were mitigated.

4.4.2.3 Overall Strategy for Post Mitigation Testing and Monitoring

Figure 81 illustrates the Post-Mitigation and Maintenance/Surveillance Plan

Figure 81: Post-Mitigation Retesting and Monitoring



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6 GLOSSARY

AARST	AARST: American Association of Radon Scientists and Technologists. An industry association for professionals engaged in offering radon measurement and mitigation services. Also, involved in establishing consensus standards/protocols for radon measurement and mitigation.
ABS Pipe	Common black plastic pipe used in construction-can be pressure rated.
Action Level	A level of radon exposure where action such as retesting or mitigation is recommended. US Action level is 4.0 pCi/L.
Active System	Passive system with the addition of a fan to more actively draw radon from the soil.
Aggregate	A coarse material, such as gravel, placed below the slab (also gravel, broken stone or sand, with which cement and water are mixed to form concrete).
Alpha Decay	A positively charged subatomic particle emitted during decay of certain radioactive elements. For example, an alpha particle is released when radon-222 decays to polonium-218. An alpha particle is indistinguishable from a helium atom nucleus, which consists of two protons and two neutrons.
Alpha Track Detector	A long-term detector for radon. It consists of a plastic material or celluloid film, in which alpha radiation leaves damage tracks that can be counted under a microscope after the plastic material is etched in NaOH (sodium hydroxide) solution.
ASD	Active soil depressurization: A means by which soil gas is extracted from the soil beneath a foundation.
ASHRAE	American Society of Heating Refrigeration and Air-Conditioning Engineers. An organization that establishes standards and guidance for mechanical ventilation systems in addition to many other aspects of indoor environment control.
Back drafting	A condition where the normal movement of combustion products up a flue, resulting from the buoyant forces on the hot gases, is reversed so that the combustion products can enter the house. Back-drafting of combustion appliances (such as fireplaces and furnaces) can occur when depressurization in the house overwhelms the buoyant force on the hot gases. Back drafting can also be caused by high air pressures at the chimney or flue termination.
Bearing partition or wall	A partition supporting any vertical load other than its own weight.
Bq/m3	Becquerel per cubic meter similar to pCi/L but is the unit of measure of radon decay in scientific international units. This is commonly used in Europe and Canada. 37 Bq/m3 = 1 pCi/L.
CDPHE	Colorado Department of Public Health and Environment.
CFM Cubic feet per minute	A measure of the volume of a fluid (liquid or gas) flowing with a fixed period of time.

CMU or Concrete Masonry Unit	Composite material fabricated in modular units, typically used to fabricate foundation walls in conjunction with mortar. Sometimes referred to as block, cinder block, and concrete block.
CRM	Continuous Radon Monitor. A device that measures and records radon in specified time increments (usually hourly) This allows one to see changes in radon levels. Requires professional periodic calibration.
Condensation	Water formed by warm, moist air contacting a cooler surface.
Daylight Drain	A drain pipe that is laid horizontally around the foundation to collect sub-surface water. The drainpipe will continue from the building until it breaks grade and reaches daylight.
DTD	Drain tile depressurization: A type of active soil depressurization system that functions by drawing a vacuum on a buildings surface water drainage system.
DWV	Drain Waste and Vent A non-pressure rated pipe suitable use for drains.
Entrainment	In the case of radon systems it is where the discharged gases of a radon system inappropriately enter a building through a window or other opening.
EPA	U.S. Environmental Protection Agency.
Fire collar or fire barrier	Obstructions across air passages in buildings to prevent the spread of hot gases and flames; horizontal blocking between wall studs.
Footing	A concrete or stone base which supports a foundation wall and which is used to distribute the weight of the house over the soil or subgrade underlying the house. The bases upon which the foundation and posts rest.
Forced Air	A central furnace or heat pump that functions by recirculating the house air through a heat exchanger in the furnace. Distinguished from a central hot water space heating system or electric resistance heating.
French Drain	Typically a French drain is a perforated pipe that has been installed in a trench at the bottom of a footing. The purpose of which is to collect surface water to allow it to flow by gravity to a sump or off a hillside so as to divert water away from the foundation. These can be installed either inside or outside the foundation wall. They are typically installed on the side of a building where surface water is most likely to impact the foundation, such as on the uphill side but not necessarily on the downhill side. In its early forms, this was a trench of large aggregate along or below a foundation that would allow water collected in the trench to soak down through the soil.
Grade or Grade Line	The level of the ground around a building.
HVAC	Heating, Ventilation, and Air Conditioning. Mechanical system by which the indoor air within a building is tempered.
Inches WC	Inches of water column. A measure of differential pressure. In this case, typically in the range of a few thousandths of an inch differential is sufficient house vacuum necessary to draw radon in through the foundation into the building.

Make-up Air	As used here, an outdoor supply of fresh air provided into the house to provide the required draft air (and combustion air) needed for proper movement of products of combustion up the flues of combustion appliances. Such "make-up air" may be needed in cases where an ASD system is found to be creating back drafting of combustion appliances through depressurization of the house. The term "make-up air" can also be used to describe the supply of outdoor air into the house in general, to prevent house depressurization by combustion appliances, and exhaust fans, in cases where an ASD system has not been installed. "Make-up air" can also be used to refer to fresh air drawn into the cold air return of forced-air furnace systems to ventilate and perhaps even pressurize the house.
Mitigation	The act of making less severe; reduction; relief. The reduction of radon in a building.
Multi-Family	A building containing multiple single family dwellings such as an apartment building or a condominium complex. Living units are separate dwellings separated by occupancy separations.
Non-flowable gun grade caulk	Refers to caulks, which are sufficiently viscous, such that the caulk bead will tend to retain its shape prior to curing. They are distinguished from flowable caulks. Non-flowable caulks are less effective at setting into cracks and irregularities in the opening being sealed, but are required in cases where the opening does not provide a channel to contain the fluid movement of the flow able caulks, or where the opening is on a vertical surface.
NRPP	National Radon Proficiency Program - a national board for certifying radon professionals.
NRSB	National Radon Safety Board - a national board for certifying radon professionals.
Partition wall	An interior wall.
Passive System	Short for passive sub-slab depressurization system. Approach for reduction of radon levels which utilizes barriers to radon entry and stack effect reduction techniques to reduce the rate of radon entry, plus the installation of a PVC pipe running from beneath the slab to the roof. Works by using natural pressure differentials between the air in the pipe, the rest of the home and the outside air.
pCi/L	Pico curies per liter: A measure of the rate of decay that is occurring within a liter of air or water. This is the primary unit of measure used in expressing radon levels.
Perimeter Drain	A water drainage system that is routed around a footing either inside or outside the perimeter of a house. Typically refers to a perforated pipe laid in a rock filled trench designed to collect and drain water off a hillside or to a sump. Highly effective drain tile depressurization system that utilizes these to create a negative pressure field around and beneath the home.
Permeability	A measure of the ease with which a fluid (liquid or gas) can flow through a porous medium. Sub-slab permeability generally refers to the ease with which soil gas can flow underneath a concrete slab. High permeability facilitates gas movement under the slab, and hence generally facilitates the implementation of sub-slab depressurization systems for remediation.
PFE Pressure Field Extension	The extent to which the sub-slab area is depressurized by the suction applied at a suction point.
Post and Beam	A type of building frame in which cross beams rest directly upon vertical posts.

Post Tension Slab	Post-tensioned slabs use high-strength tensioned steel strands to compress the slabs, keeping the majority of the concrete in compression. This gives a very efficient structure, which minimizes material usages and decreases the economic span range when compared to reinforced concrete.
PVC Pipe	Common white pipe used in construction can be pressure rated.
Radon	An odorless, tasteless, and invisible radioactive gas, which occurs naturally in rocks and soils as a breakdown product of uranium. It is found in high concentrations in soils and rocks containing uranium, granite, shale, phosphate, and pitchblende. It is also found in soils contaminated with certain industrial wastes (those from uranium or phosphate mining) and in underground water supplies. Radon-222 is the primary isotope of concern, and has a half-life of 3.82 days.
RDP	Radon Decay Products, a family of elements that radon gas naturally decays into. Behave as solids. In particular, polonium 218 and polonium 214 are alpha emitters that cause health effects related to radon gas exposure.
Ridge	The top edge of the roof where two slopes meet.
Rim Joist (Band Joist)	The perimeter horizontal timber or beam supporting a floor or a ceiling.
RRNC	Radon resistant new construction: Features that can be incorporated during a buildings construction that would facilitate radon reduction if post construction testing reveal elevated indoor radon levels.
Sch. Or Schedule	Refers to the wall thickness of pipe. Typically Sch. 40 is used in radon applications.
Sleeper	A wood member placed over or imbedded in the concrete or earthen floor to provide a nailing base for a wood floor.
SMD	Sub-membrane depressurization. Where a polyethylene sheet is laid on an exposed earth area such as a crawlspace and radon laden soil gases are extracted from beneath the plastic sheeting and exhausted outdoors.
Soakaway	See Daylight Drain.
Soil Gas	Gas, which is always present underground, in the small spaces between particles of the soil or in crevices in rock. Major constituents of soil gas include nitrogen and oxygen (from the outdoor air), water vapor, and carbon dioxide. Radon is also a soil gas if Radium 226 is in the soil.
SSD	Sub Slab Depressurization. An active soil depressurization method that draws radon laden soil gas from beneath a slab via one or more discrete holes through the slab (suction points).
Stack Effect	The temperature difference to affect the displacement of warm air by cooler air in a thermal chimney, such that the lighter warm air rises through the distribution space, construction opening, or the thermal barrier and breaches.
Sub-slab communication	The effect of creating vacuum beneath a slab and being able to detect the vacuum at various locations under the slab.
Suction hole or pit	The hole cut through a concrete slab from which either a vacuum cleaner (for diagnostic purposes) or a mitigation fan will evacuate the sub-slab soil gas.

Time Integrated Sampling	Sampling conducted over a specific time period (from a few days to a year or more) with results reported as an average value for that period.
Vapor Barrier	A product or system designed to limit the free passage of a gas (typically water vapor) through a building envelope component (wall, ceiling, or floor. Such products and systems may be continuous or non-continuous discrete elements, which are sealed together to form a continuous barrier against air (or vapor) infiltration (most commonly, a plastic sheet under a house slab).
Ventilation Rate	The rate at which outdoor air enters the house, displacing house air. The ventilation rate depends on the tightness of the house shell, weather conditions, and the operation of appliances (such as fans) influencing air movement. Commonly expressed in terms of air changes per hour or cubic feet per minute. The ventilation rate includes both natural ventilation (infiltration) and mechanical ventilation.
WHO	World Health Organization.