Study Guide for Radon Measurement Service Provider Course

This study guide can help you:

- take notes;
- read and study offline;
- organize information; and
- prepare for assignments and assessments.

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Student Verification and Interactivity

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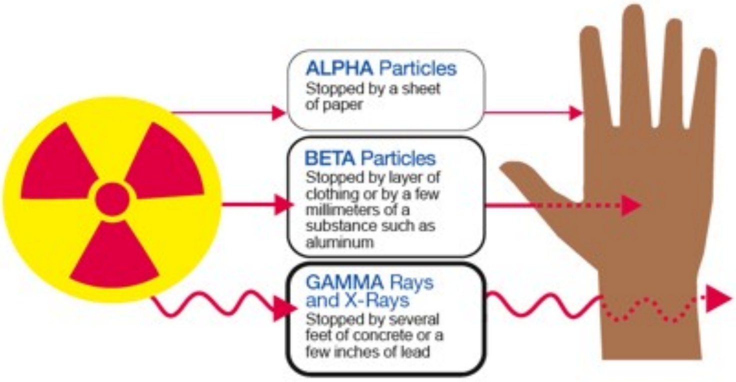
Introduction

Welcome to InterNACHI's free online *Radon Measurement Service Provider* course.



Upon successful completion of this course, the student shall be able to:

- comprehend the fundamentals about radon gas;
- understand the science of radon and radioactivity;
- communicate health risks of radon exposure;
- perform radon testing according to measurement protocols;
- perform an inspection of a radon mitigation system;
- understand the requirements for NEHA-National Radon Proficiency Program certification;
- understand the requirements for former USEPA Radon Proficiency Programs;
- perform an inspection of radon prevention building techniques;
- take the NEHA National Radon Proficiency (NEHA-NRPP) Measurement exam.

The *Radon Measurement Service Provider* course includes:

- 16 Continuing Education CEs;
- 20 sections;
- 216 photos and diagrams;
- 7 quizzes;
- 100-question final exam (drawn from a larger pool);
- instant grading;
- a downloadable, printable Certificate of Completion; and
- accreditations and state approvals.

The course covers the following categories:

- Introduction
- What is Radon?
- Radiation and Radioactivity
- What is an Atom?
- Decay Chains
- Curies, Equations and ER
- Health Risks
- Radon in Water
- Curie and Becquerel

- Alpha, Beta and Gamma
- The Geology of Radon
- Radon Entry into a House
- Radon Measurement: General Discussion
- Protocols for Radon Measurements
- Indoor Radon and RDP Measurement Protocols
- EPA and ASTM Mitigation Standards
- EPA's Radon Mitigation Standards
- Model Standards
- Building Radon Out
- InterNACHI SOP for Inspecting Radon Systems
- Radon in Water, Removal Methods

Acknowledgment

This course draws upon many resources provided by the International Association of Certified Indoor Air Consultants (www.iac2.org), the International Association of Certified Home Inspectors (www.nachi.org), and the United States Environmental Protection Agency (EPA).

Information found in this course may also be found in the following documents:

- InterNACHI's "International Standards of Practice for Inspecting Radon Mitigation Systems"
- "Ionizing Radiation Fact Book," U.S. EPA, Document 402-F-06-061, March 2007
- "Federal Provincial Territorial Radiation Protection"
- "Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings," ASTM International, Document E2121-03
- InterNACHI's International Standards of Practice for Inspecting Commercial Properties
- "Radon Mitigation Standards," U.S. EPA, Document 402-R-93-078, October 1993 (revised April 1994)
- "Building Radon Out," U.S. EPA, Document 402-K-01-002, April 2001
- "Standard Practice for Radon Control Options for the Design and Construction of New Low-Rise Residential Buildings," ASTM International, Document E 1465-07a
- "Model Standards and Techniques for Control of Radon in New Residential Buildings," U.S. EPA, Document 402-R-94-009
- "Indoor Radon and Radon Decay Product Measurements Device Protocols," EPA Document Number 402-R-92-004, July 1992
- "Protocols for Radon and Radon Decay Product Measurements in Homes," U.S. EPA, Document Number 402-R-93-003, June 1993
- "A Citizen's Guide to Radon," EPA Document Number 402-K-02-006, September 2005

- "Consumer's Guide to Radon Reduction: How to Reduce Radon levels in Your Home," U.S. EPA, Document 402-K-03-002, Revised February 2003
- "Home Buyer's and Seller's Guide to Radon," U.S. EPA, 402-K-05-005, May 2005
- "Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings," U.S. EPA, Document 402-K-03-007
- "Technical Support Document for the 1992 Citizens Guide to Radon," U.S. EPA, Document 400-R-92-011, May 1992
- "Radon Reduction Techniques for Existing Detached Houses, Technical Guidance (3rd Edition) for Active Soil Depressurization Systems," U.S. EPA, Document 625-R-93-011, October 1993
- "Radon Proficiency Program (RPP) Handbook," U.S. EPA, Document 402-R-95-013, July 1996
- "Residential Standards of Practice," International Association of Certified Home Inspectors
- "Radon Mitigation Research," U.S. EPA, Document 600-F-94-035, September 1994
- various documents provided by state environmental and health departments and Health Canada

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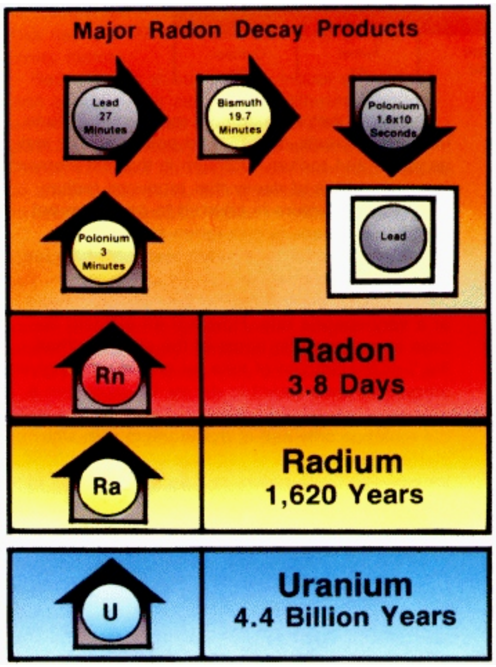
Section 1: What Is Radon?

What Is Radon?

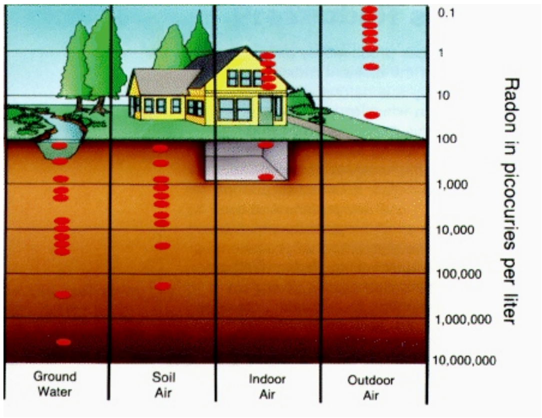
Radon is a gas produced by the radioactive decay of the element radium. Radioactive decay is a natural, spontaneous process in which an atom of one element decays or breaks down to form another element by losing atomic particles (protons, neutrons or electrons). When solid radium decays to form radon gas, it loses two protons and two neutrons. These two protons and two neutrons are called an alpha particle, which is a type of radiation. The elements that produce radiation are referred to as radioactive. Radon itself is radioactive because it also decays, losing an alpha particle and forming the element polonium.



Elements that are naturally radioactive include uranium, thorium, carbon and potassium, as well as radon and radium. Uranium is the first element in a long chain of decay that produces radium and radon. Uranium is referred to as the "parent" element, and radium and radon are called "daughters" or "progeny." Radium and radon also form daughter elements as they decay. The progeny of radon are called radon decay products, or RDPs.

The decay of each radioactive element occurs at a very specific rate. How fast an element decays is measured in terms of the element's "half-life," or the amount of time for one-half of a given amount of the element to decay. Uranium has a half-life of 4.4 billion years, so a 4.4-billion-year-old rock has only half of the uranium with which it started. The half-life of radon is only 3.8 days.

If a jar were filled with radon, only half of the radon would be left after 3.8 days. But the newly-made daughter products of radon (or RDPs) would also be in the jar, including polonium, bismuth and lead. Polonium is also radioactive. It is this element which is produced by radon in the air and in people's lungs that can hurt lung tissue and cause lung cancer.



Radioactivity is commonly measured in picocuries (pCi).

Because the level of radioactivity is directly related to the number and type of radioactive atoms present, radon and all other radioactive atoms are measured in picocuries. For instance, a house having 4 picocuries of radon per liter of air (4 pCi/L) has about eight or nine atoms of radon decaying every minute in every liter of air inside the house. A 1,000-square-foot house with 4 pCi/L of radon has nearly 2 million radon atoms decaying inside it every minute.

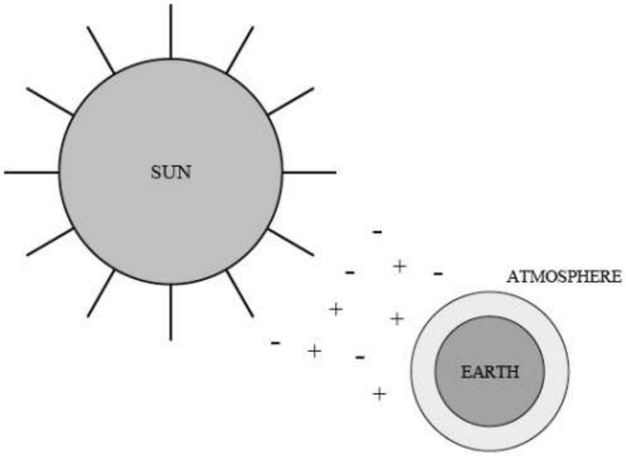
Radon levels in outdoor air, indoor air, soil air and groundwater can be very different. Outdoor air ranges from less than 0.1 pCi/L to about 30 pCi/L, but it probably averages about 0.2 pCi/L. Radon in indoor air ranges from less than 1 pCi/L to about 3,000 pCi/L, but it probably averages between 1 and 2 pCi/L. Radon in soil air (the air that occupies the pores in soil) ranges from 20 or 30 pCi/L to more than 100,000 pCi/L; most soils in the United States contain between 200 and 2,000 pCi of radon per liter of soil air. The amount of radon dissolved in groundwater ranges from about 100 to nearly 3 million pCi/L.

Natural Radiation Exposure

Since the beginning of time, all living creatures have been exposed to radiation. We live in a radioactive world. There are many natural sources of radiation which have been present since the Earth was formed. In the last century, we have added somewhat to this natural background radiation with artificial sources. However, the naturally occurring sources contribute about four to five times more radiation than human-made sources.

The three major sources of naturally occurring radiation are:

- **cosmic** radiation;
- sources in the earth's crust, also referred to as **terrestrial** radiation; and
- sources in the human body, also referred to as **internal** sources.



Cosmic

The Earth and all living things on it are constantly bombarded by radiation from space, similar to a steady drizzle of rain. Charged particles from the Sun and stars interact with Earth's atmosphere and magnetic field to produce a shower of radiation, typically beta and gamma radiation. The dose from cosmic radiation varies in different parts of the world due to differences in elevation and to the effects of the Earth's magnetic field. Cosmic radiation comes from the Sun and outer space, and consists of positively charged particles, as well as gamma radiation. At sea level, the average cosmic radiation dose is about 26 millirems (mrem) per year. At higher elevations, the amount of atmosphere shielding cosmic rays decreases and, thus, the dose increases. The average dose in the United States is approximately 28 mrem per year.

Terrestrial

Radioactive material is also found throughout nature. It is in the soil, water and vegetation. Low levels of uranium, thorium and their decay products are found everywhere. This is called terrestrial radiation. Some of these materials are ingested with food and water, while others, such as radon, are inhaled. The dose from terrestrial sources also varies in different parts of the world. Locations with higher concentrations of uranium and thorium in their soil have higher dose levels.

The major isotopes of concern for terrestrial radiation are uranium and its decay products, such as thorium, radium and radon.

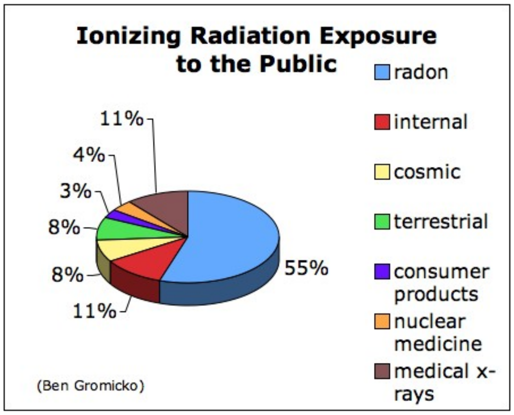
There are natural sources of radiation in the ground, rocks, building materials and potable water supplies. Radon gas is a current health concern. This gas results from the decay of natural uranium in soil. Radon, which emits alpha radiation, rises from the soil under houses and can build up in homes, particularly well-insulated homes. In the United States, the average effective whole-body dose of radon is about 200 mrem per year, while the lungs receive approximately 2,000 mrem per year.

Internal

In addition to cosmic and terrestrial sources, all humans are born with naturally occurring radionuclides, such as Potassium-40, Carbon-14, Lead-210, and other isotopes. The variation in dose from one person to another is not as great as the variation in dose from cosmic and terrestrial sources. The average annual "dose" from internal radioactive material is about 40 mrem.

Ionizing Radiation Exposure to the Public

This chart shows that of the total dose of about 360 millirems per year, natural sources of radiation account for about 82% of all public exposure, while man-made sources account for the remaining 18%.



Section 2: Radiation and Radioactivity

Radiation and Radioactivity

What is Radiation?

Radiation is energy that travels in the form of waves or high-speed particles.

When we hear the word "radiation," we generally think of nuclear power plants, nuclear weapons, and radiation treatments for cancer. We would also be correct to add microwaves, radar, electrical power lines, cell phones and sunshine to the list. There are many different types of radiation that have a range of energy forming the electromagnetic spectrum. These types of radiation have enough energy to break chemical bonds in molecules, or remove tightly bound electrons from atoms, thus creating charged molecules or atoms known as ions. This kind of radiation is referred to as "ionizing radiation."

Ionizing radiation is energy in the form of waves or particles that has enough force to remove electrons from atoms. In this course, we will refer to it simply as radiation. One source of radiation is the nuclei of unstable atoms. As these radioactive atoms (also referred to as radionuclides or radio-isotopes) seek to become more stable, their nuclei eject or emit particles and high-energy waves. This process is known as radioactive decay.

Some radionuclides, such as radium, uranium and thorium, have existed since the formation of the Earth. The radioactive gas, radon, is one type of radioactive material produced as these naturally occurring radio-isotopes decay. Human activities, such as the splitting of atoms in a nuclear reactor, can also create radionuclides. Regardless of how they are created, all radionuclides release radiation.

The major types of radiation emitted during radioactive decay are alpha particles, beta particles and gamma rays. Radiation can come from natural sources and from manufactured radionuclides. A hospital X-ray, for example, is a type of manufactured radiation.

What is Radioactivity?

Radioactivity is the property of some atoms that causes them to give off energy spontaneously as particles or rays. Radioactive atoms emit ionizing radiation as they decay.

Section 3: What Is an Atom?

What Is an Atom?

To be able to understand radiation and radioactivity, we need to understand the language of atomic structure.

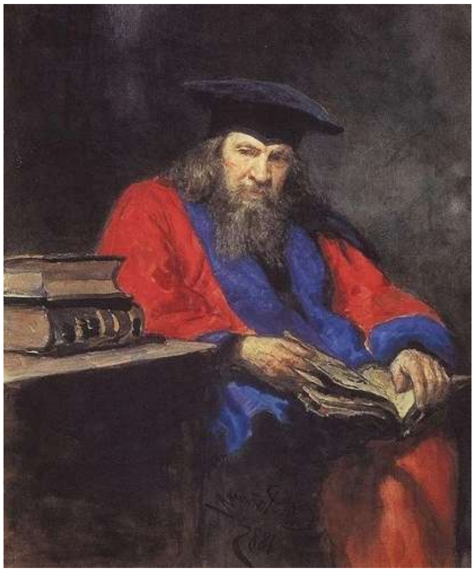
Atoms are the extremely small particles of which we, and everything around us, are made.

Democritus by Antoine Coypel

Democritus was a pre-Socratic Greek materialist philosopher in the 5th century BC. Known as "The Laughing Philosopher," Democritus believed that all matter is made up of various imperishable, indivisible elements, which he called *atoma* or "indivisible units," from which we get the English word "atom." Democritus theorized that the shape of an object's atoms determine that object's physical characteristics.

Houston Astrodome

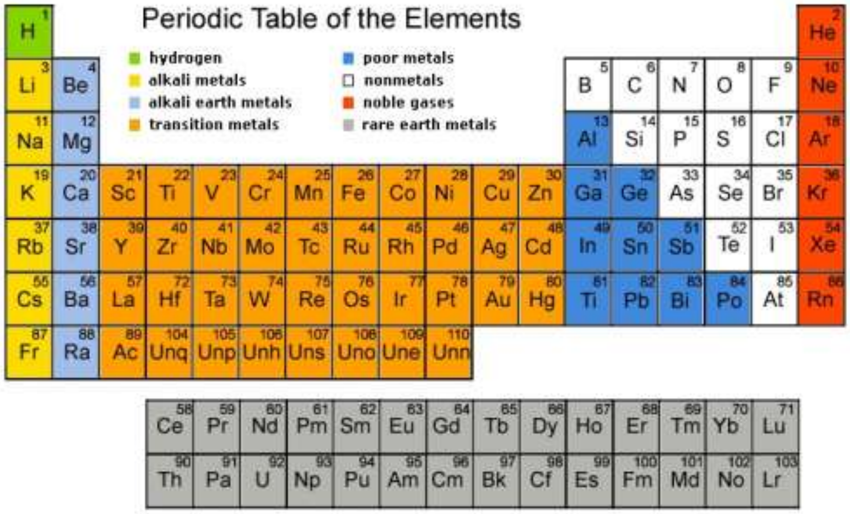
An atom is the smallest building-block of matter. Atoms are made of neutrons, protons and electrons. If one atom were the size of the Houston Astrodome, its nucleus would be roughly the size of a pea.



Dmitri Mendeleev by Ilya Repin

Dmitri Ivanovich Mendeleev (1834 – 1907) was a Russian chemist and inventor. He is credited as being the creator of the first version of the Periodic Table of Elements. Using the table, he predicted the properties of elements yet to be discovered.

There are 92 naturally occurring elements. Scientists have created many others, bringing the total number of known elements to more than 100. Atoms are the smallest units of an element that behave the same way, chemically, as the element itself does.



Periodic Table of the Elements

- 🟩 hydrogen
- 🟨 alkali metals
- 🟦 alkali earth metals
- 🟧 transition metals
- 🟦 poor metals
- ☐ nonmetals
- 🟥 noble gases
- ▨ rare earth metals

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

When Mendeleev began grouping elements, he took note of the Law of Chemical Periodicity, which states, "The properties of the elements are periodic functions of atomic number." Scientists use the Periodic Table to find out important information about various elements. The Periodic Table orders all known elements according to their similarities, categorizing elements by "groups" and "periods."

Each element is ordered by its atomic number. The atomic number is determined by the number of protons per atom. In an atom with a neutral charge, the number of electrons equals the number of protons. The Periodic Table represents neutral atoms. The atomic number for a given element is located above the element's symbol.

Beneath the atomic number is the atomic mass number. Atomic mass is measured in Atomic Mass Units, where 1 amu = (1/12) mass of carbon measured in grams. The atomic mass number is equal to the number of protons, plus its neutrons. This number is found beneath the element's symbol.

When two chemicals react with each other, the reaction takes place between individual atoms -- at the atomic level. The processes that cause materials to be radioactive -- to emit particles and energy -- also occur at the atomic level.

Atomic Structure

In the early 20th century, a New Zealand scientist working in England, Ernest Rutherford, and a Danish scientist, Niels Bohr, developed a theory about the structure of an atom that describes an atom as looking very much like our solar system.

At the center of every atom is a nucleus, which is comparable to the Sun in our solar system. Electrons move around the nucleus in "orbits," similar to the way planets move around the Sun. While scientists now know that atomic structure is more complex, the Rutherford-Bohr model is still a useful approximation to begin understanding atomic structure.

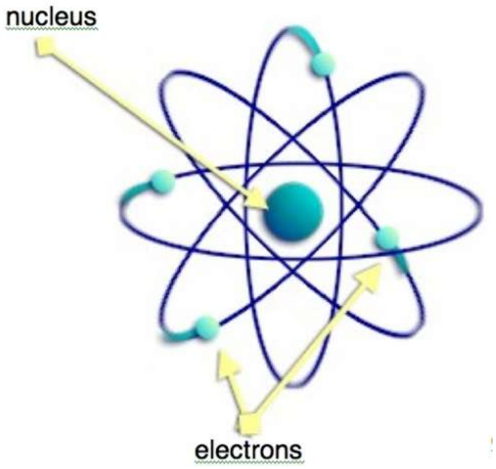
- A **nucleus** contains protons and neutrons; together, these are called nucleons.

- A **neutron** has no electrical charge and, like a proton, is about 1,800 times as heavy

as
an electron.

+ A **proton** is a positively charged particle. All atoms of an element (radioactive and non-radioactive) have the same number of protons.

Protons and neutrons in the nucleus, and the forces among them, affect an atom's radioactive properties.



The particles that orbit the nucleus as a cloud are called **electrons**. They are negatively charged, and they balance the positive electrical charge of the protons in the nucleus.

Interactions with electrons in the outer orbits affect an atom's chemical properties.

What Holds Atoms Together?

The nucleus of an atom is held together by the strong nuclear force of attraction between nucleons: proton-to-proton, neutron-neutron, and proton-neutron. It is extremely powerful, but extends only a very short distance, about the diameter of a proton or neutron.

Opposite electrical charges of the protons and electrons do the work of holding the electrons in orbit around the nucleus. Electrons closer to the nucleus are bound more tightly than the outer electrons because of their distance from the protons in the nucleus. The electrons in the outer orbits, or shells, are more loosely bound and affect an atom's chemical properties.

There are also electromagnetic forces which tend to shove the positively charged protons and, as a result, the entire nucleus apart. In contrast to the strong nuclear force, the electrical field of a proton falls off slowly over distance, extending far beyond the nucleus, binding electrons to it.

The balance between the strong nuclear force pulling the nucleus together and the positive charges of the protons pushing it apart is largely responsible for the properties of a particular kind of atom or nuclide, a unique combination of protons, neutrons, and balance of energies.

The delicate balance of forces among nuclear particles keeps the nucleus stable. Any change in the number, arrangement or energy of the nucleons can upset this balance and cause the nucleus to become unstable or radioactive. Disruption of electrons close to the nucleus can also cause an atom to emit radiation.

The amount of energy required to break up the nucleus into its parts is called the "binding energy." It is often referred to as "cosmic glue."

Atomic Shorthand

Atomic Shorthand Representing Atomic Properties

As scientists identified the nuclear properties of elements and found different forms of elements, they needed an easy way to write and keep track of the basic nuclear properties. They developed a shorthand that combines the defining pieces of information about the various forms of an element:

X stands for the chemical symbol, *Z* represents the number of protons, and *A* is its atomic mass.

(Refer to the graphics above and below for an example of this shorthand.)

- The chemical symbol for the element carbon is *C.*
- The number of protons in the nucleus *Z* is the same for any form of an element.
- *A* represents the mass of one atom of the element carbon.
- The number of neutrons in the nucleus is equal to *A* minus *Z*.

Two different forms, or isotopes, of carbon are represented below.

- The most common form of carbon (stable carbon) is represented below at the left and has 6 protons (and 6 neutrons), so it has an atomic mass of 12.

- Carbon that has 6 protons (and 8 neutrons), and an atomic mass of 14, is radioactive and is used in carbon-dating, which is a process that was developed to determine the age of archeological artifacts.

$_{6}C^{12}$ $_{6}C^{14}$

These forms of carbon are commonly referred to as Carbon-12 and Carbon-14, respectively.

As this close-up of a Period Table illustrates, the Radon-222 atom has 86 protons and, therefore, 136 neutrons, because its atomic mass is 222. Its *atomic number*is 86. The atom of radon is identified by its *atomic mass*, so it is called Radon-222.

The Rutherford-Bohr Model

In the early 20th century, scientists were struggling to understand the structure of atoms. They had parts of the answer. The electron, which has a negative electrical charge, had been discovered earlier. They knew that the basic atom had no overall charge. Together, these pieces of information made it natural to assume that the atom also contained something that carried a positive charge. Scientists guessed that since electrons are extremely small, whatever this positive matter or material was, it must make up most of the mass of an atom and be much larger than the aspects already identified.

Ernest Rutherford

Niels Bohr

Scientists Ernest Rutherford and Niels Bohr developed a theory that described the arrangement of the properties of an atom as similar to our solar system. Known as the Rutherford-Bohr Theory of Atomic Structure, it was a breakthrough in understanding the way the atom works.

Rutherford conducted experiments in which he shot relatively large, charged alpha particles at a piece of thin gold foil. He found that most of the particles passed directly through the foil, but some bounced off at odd angles, as though they had been deflected. From these results, Rutherford concluded that each atom was mostly empty space, but also contained a dense region -- a central mass -- which his alpha particles could not pass through. He also concluded that this central mass must have a positive charge in order to deflect the positively charged alpha particles.

Rutherford and Bohr theorized that an atom's parts operate similarly to our solar system. At the center of every atom is a nucleus, which is comparable to the Sun. Electrons move around the nucleus in "orbits," similar to the way planets move around the Sun.

Each orbit around the nucleus represents an energy level, and electrons cannot exist in between orbits. Orbits closer to the nucleus have lower energy. If energy is added, an electron can be "excited" to jump to a higher energy level -- an orbit farther away from the nucleus. Eventually, the electron will return to its original state, and the atom will give off energy equal to the difference between the two orbits.

In some materials, the energy is given off as X-rays. Other materials produce specific colors of visible light, or other types of electromagnetic energy.

Each orbit can hold only a certain number of electrons. The lower-energy orbits must fill up first, if the atom is to be at its "ground" state. This is the lowest energy state and, therefore, its most stable state.

With more research, scientists discovered that atomic structure is more complex, and that the Rutherford-Bohr model contained serious flaws.

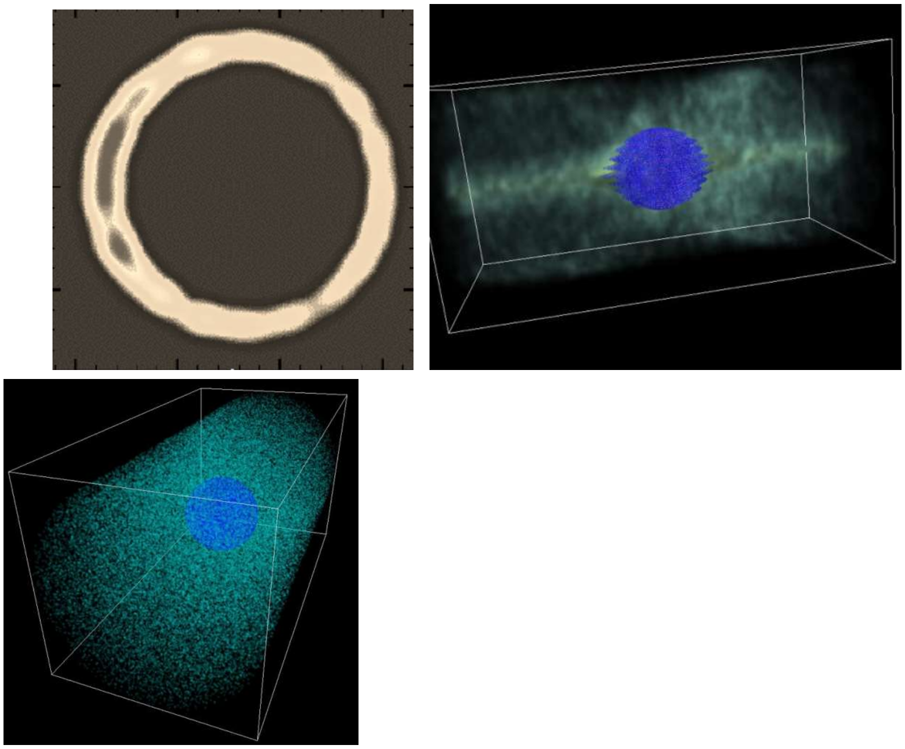
The Rutherford-Bohr model provided the first really useful view of the atom. It matched what scientists knew about chemical reactions and the way atoms behaved. It led to some predictions that were later proven correct. Bohr had rectified a serious flaw by recognizing that electrons had to be in orbits or energy states. But his analysis of the energy given off when an electron dropped from a higher-energy orbit to a lower-energy orbit didn't hold up for atoms bigger than hydrogen, which is the simplest atom, with only one proton and no neutrons. More work needed to be done on the model.

Improving the Rutherford-Bohr Model: The Schrödinger Theory of the Atom

Erwin Schrödinger

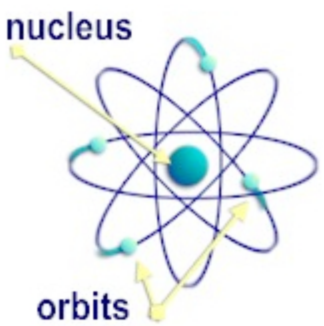
German scientist Erwin Schrödinger thought the problem with the Rutherford-Bohr theory might be in confining the electrons to specific orbits. Other scientists had developed the idea that electromagnetic energy acted like a wave sometimes, and like a particle at other times. Schrödinger thought that electrons might work the same way.

If the electrons did behave like electromagnetic energy, we couldn't know exactly where an individual electron was. We could only know the probability of its being in a particular place.

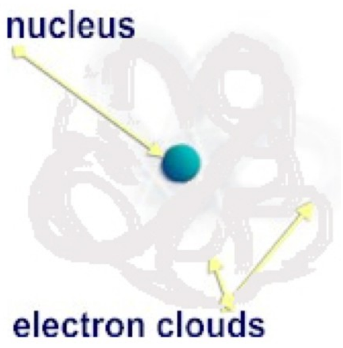


Schrödinger's "Electron Clouds"

Schrödinger replaced Bohr's well-defined orbits with probability "clouds," also known as "orbitals." He could calculate the probability that an electron would be at a particular spot in the orbital, but not know for sure. In some regions of the orbital, there was a high probability that an electron would be there. In other regions, there was a low probability of the presence of electrons. The probability distributions of orbitals are sometimes shown as "lobes" extending away from the nucleus in three dimensions.



(a)



(b)

(a) The Rutherford-Bohr model shows distinct electron orbits.

(b) Schrödinger’s model shows "electron clouds" or orbitals.

Schrödinger’s idea, and the equations he used to predict where electrons would be, solved problems that Bohr's model hadn't. It also gave scientists a better understanding of the electron and how it behaves in chemical reactions. Schrödinger’s theory of the nature of electrons also led to research in semiconductors and other technologies on an atomic scale.

Despite its technical flaws, the Rutherford-Bohr model is still useful because it is simple and helps us understand basic atomic structure.

Weighing Atoms: Atomic Mass Units

Atoms are so small that it doesn't make sense to use the same units for measuring them that we use every day, like ounces or grams. To make it easier to work with atomic weights, early radiation scientists developed new units of measurement on a more appropriate scale.

They decided to use the mass of a well-known and very common element as the basis for measurements of atomic mass. The new scale equated one atomic mass unit (AMU) to the mass of the most common carbon atom, which has 6 protons and 6 neutrons, divided by 12. So, one AMU is about the same as one proton, and also about the same as one neutron (since electrons are so much smaller that they contribute very little to the mass of an atom).

One AMU is less than 1.66×10^{-24} gram, which is 0.00000000000000000000000166 of a gram.

The International System of Units, or SI Units and Derived SI Units

Prefix	**Symbol**	**Decimal**	**Factor**
yotta	Y	1 000 000 000 000 000 000 000 000	$= 10^{24}$
zetta	Z	1 000 000 000 000 000 000 000	$= 10^{21}$
exa	E	1 000 000 000 000 000 000	$= 10^{18}$
peta	P	1 000 000 000 000 000	$= 10^{15}$
tera	T	1 000 000 000 000	$= 10^{12}$
giga	G	1 000 000 000	$= 10^{9}$
mega	M	1 000 000	$= 10^{6}$
kilo	k	1 000	$= 10^{3}$
hecto	h	100	$= 10^{2}$
deca	da	10	$= 10^{1}$

---------------- 1 --

deci	d	0.1	$= 10^{-1}$
centi	c	0.01	$= 10^{-2}$
milli	m	0.001	$= 10^{-3}$
micro	µ	0.000 001	$= 10^{-6}$
nano	n	0.000 000 001	$= 10^{-9}$
pico	p	0.000 000 000 001	$= 10^{-12}$
femto	f	0.000 000 000 000 001	$= 10^{-15}$
atto	a	0.000 000 000 000 000 001	$= 10^{-18}$
zepto	z	0.000 000 000 000 000 000 001	$= 10^{-21}$
yocto	y	0.000 000 000 000 000 000 000 001	$= 10^{-24}$

Why Some Atoms Are Radioactive

Why are some atoms radioactive?

The balance of the forces in the nucleus of an atom determines whether a nucleus is stable or unstable (radioactive).

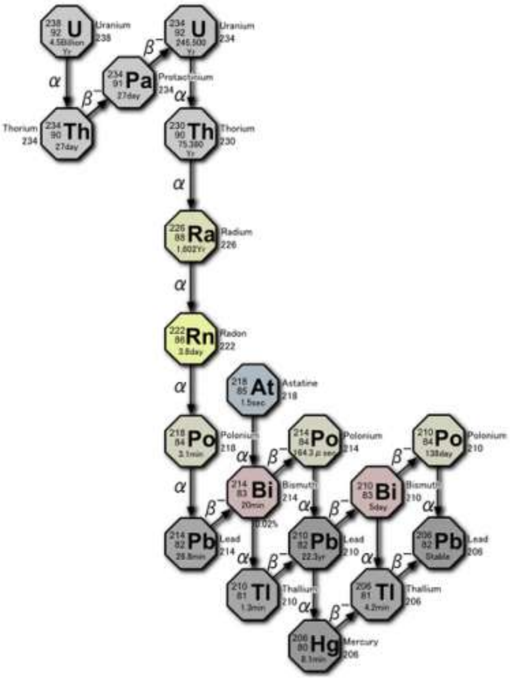
Atoms found in nature are either stable or unstable. An atom is stable if the forces among the particles that make up the nucleus are balanced. An atom is unstable or radioactive if these forces are unbalanced -- if the nucleus has an excess of internal energy. Unstable atoms are called radionuclides. The instability of a radionuclide's nucleus may result from an excess of either neutrons or protons. An unstable nucleus will continually vibrate and contort and, sooner or later, attempt to reach stability by some combination of means, such as:

- ejecting neutrons and protons;
- converting a neutron to a proton (or vice versa) with the ejection of a beta particle or positron; or
- releasing additional energy by photon or gamma-ray emission.

Can unstable atoms become stable?

Yes. As the unstable nucleus emits radiation as it disintegrates, the radionuclide transforms to different nuclides. This process is called radioactive decay. It will continue until the forces in the nucleus are balanced. For example, as a radionuclide decays, it will become a different isotope of the same element if the number of neutrons changes. It may become a different element altogether if the number of protons changes.

Often, when a radionuclide decays, the decay product -- the new nuclide -- is also radioactive. This is true for most naturally occurring radioactive materials, and for some fission products. In order to become stable, these materials must go through many steps, becoming a series of different nuclides and giving off energy as particles or rays at each step. The series of transformations that a given radionuclide will undergo, as well as the kind of radiation it emits, are characteristic of the radionuclide. This is called a decay chain.



Decay Chain by Tosaka

How long do radionuclides stay radioactive?

It depends on the kind of radioactive material. The rate of decay is one of the characteristics of radionuclides. Scientists talk about this rate as a radionuclide's radioactive half-life. It is the time required for the disintegration of one-half of the radioactive atoms that are present when measurement starts. It does not represent a fixed number of atoms that disintegrate, but a fraction. For any given radionuclide, its half-life remains constant.

What's the difference between radiation and radioactivity?

Radiation is the *energy that is released* as particles or rays during radioactive decay.

Radioactivity is the *property of an atom* that describes spontaneous changes in its nucleus that create a different nuclide. These changes usually happen as emissions of alpha or beta particles, and often gamma rays.

Every time a nucleus emits particles or energy, this is referred to as a disintegration. The number of disintegrations per unit-time, or the rate of emission, is called the activity of a sample. Since each disintegration transforms the atom into a new nuclide, "transformation" is often substituted for "disintegration" when talking about radioactive decay and activity.

Activity is expressed in becquerels or curies, with curies being the original unit and which is used more commonly in the U.S. One becquerel equals one transformation per second. One curie equals 37 billion disintegrations per second, but was originally defined as the number of disintegrations of one gram of pure radium per second.

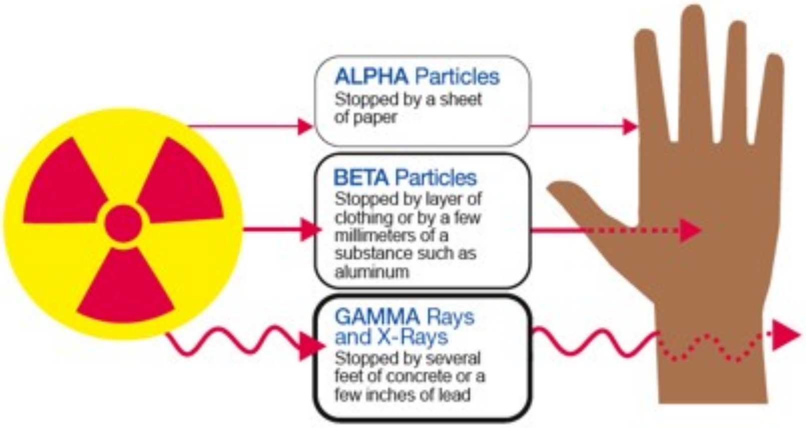
Is all ionizing radiation the same?

No. An ion is an atom (or a group of atoms) that has acquired a net electric charge by gaining or losing one or more electrons. Ionizing radiation is high-energy radiation which is capable of transforming into ions the substances through which it passes. It can be in the form of alpha or beta particles or gamma rays (photons), and each form behaves differently. The kind of radiation given off by a nucleus depends on the nature of the imbalance in the nuclear forces.

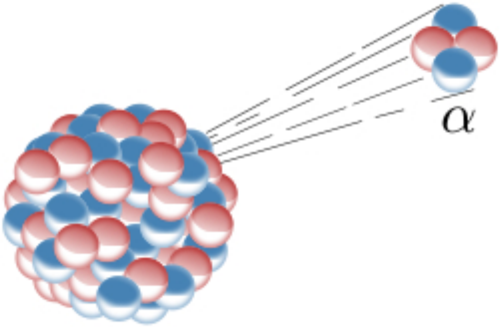
Alpha Particles

Alpha particles are energetic, positively charged particles consisting of two protons and two neutrons. They are commonly emitted in the radioactive decay of the heaviest radioactive elements, such as Uranium-238, Radium-226 and Polonium-210. Even though they are highly energetic, the high mass of alpha particles means they move slowly through the air.

The effects on human health from alpha particles depend primarily upon method of exposure. External exposure (for example, by touch) is of far less concern than internal exposure, because alpha particles lack the energy to penetrate the outer layer of skin, or even a sheet of paper.



However, radionuclides that emit alpha particles internally can be very harmful. If alpha emitters are inhaled, ingested (swallowed) or absorbed into the bloodstream (through a cut in the skin, for example), sensitive living tissue can be exposed to alpha radiation.



Alpha decay is a type of radioactive decay in which alpha particles are released from the nuclei of atoms. The atomic nucleus emits an alpha particle (two protons and two neutrons bound together into a particle), and then transforms (or decays) into an atom with a mass number which is 4 less, and with an atomic number which is 2 less.

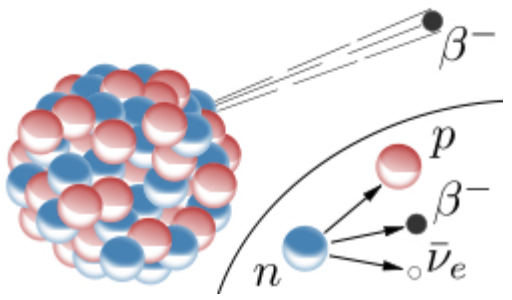
Example: Uranium-238 (U-238) ➔ Thorium-234 + Helium-4

Because of their relatively large mass, +2 charge and relatively low velocity, alpha particles are very likely to interact with other atoms and lose their energy, so their forward motion is effectively stopped within a few centimeters of air. Being relatively heavy and positively charged, alpha particles tend to have a very short "mean free path" (or the average distance a particle travels between collisions with other particles), and they quickly lose kinetic energy within a short distance from their source. This results in several MeV (million electronvolts) being deposited in a relatively small volume of material. This increases the chance of cellular damage in cases of internal contamination.

In general, external alpha radiation is not harmful since alpha particles are effectively shielded by a few centimeters of air, a piece of paper, or the thin layer of dead skin cells. Alpha particles are low in penetrating power. Even touching an alpha source is usually not harmful, though many alpha sources also are accompanied by beta-emitting radon daughters, and alpha emission is also accompanied by gamma-photon emission. If substances emitting alpha particles are ingested, inhaled, injected or introduced through the skin, then it could result in a measurable dose of harmful radiation.

Beta Particles

Beta particles are high-energy, high-speed electrons or positrons emitted by certain types of radioactive nuclei, such as Potassium-40. The beta particles are the electrons arising from the conversion of a neutron to a proton and electron, and are released by two other short-lived RDPs (radon decay products). Beta particles are emitted from the nucleus during radioactive decay. The beta particles emitted are a form of ionizing radiation also known as beta rays. The production of beta particles is termed beta decay. An unstable atomic nucleus with an excess of neutrons may undergo beta decay.



Beta particles have a higher capacity to penetrate than alpha particles do, but they are less damaging over equal distances. They can travel far in the air but can be slowed down or stopped by a layer of clothing, or by a few millimeters of a substance such as aluminum. Humans are exposed to beta particles from both fabricated and natural radiation sources, such as tritium, Carbon-14 and Strontium-90.

Beta particles cannot be stopped by a sheet of paper. Some beta particles can be stopped by human skin, but some need a thicker shield (like wood) to stop them. Some beta particles are capable of penetrating the skin and causing radiation damage in the form of skin burns. However, as with alpha-emitters, beta-emitters are most hazardous when they are inhaled or ingested. For example, if ingested, some radionuclides that emit beta particles might be absorbed into the bones.

Gamma Rays and X-Rays

Gamma Rays

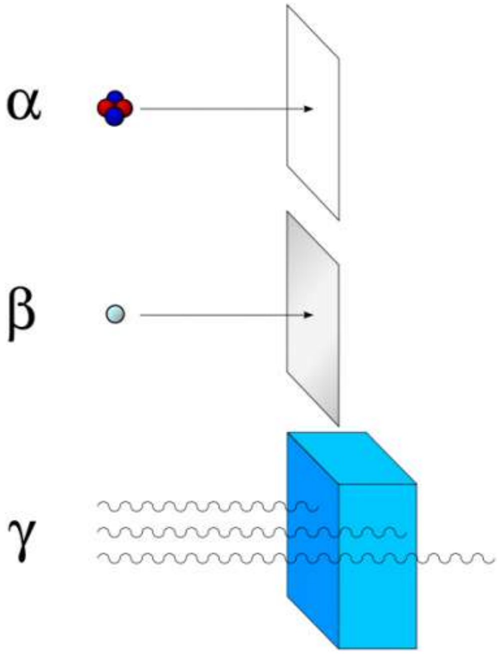
Like visible light and X-rays, gamma rays are weightless packets or bundles of energy called photons. Gamma rays often accompany the emission of alpha or beta particles from a nucleus. They have neither a charge nor a mass and have the strongest penetrating force. Gamma rays will penetrate paper, skin, wood, and other substances. Several feet of concrete or a few inches of lead may be required to stop gamma rays.

One source of gamma rays in the environment is naturally occurring Potassium-40. Fabricated sources include Cobalt-60 and Cesium-137. Gamma rays are a radiation hazard for humans. While gamma rays can easily pass completely through the body, a fraction of them will always be absorbed by human tissue and remain there. Gamma radiation can cause severe damage to internal organs. However, the amount of gamma rays emitted by radon and its RDPs is not nearly as damaging to the lungs as alpha particles.

X-Rays

X-rays are high-energy photons produced by the interaction of charged particles with matter. X-rays and gamma rays have essentially the same properties, but they differ in origin. X-rays are produced either from a change in the electron structure of an atom, or they are produced by machines. X-rays are emitted from processes occurring outside the nucleus, while gamma rays originate inside the nucleus. X-rays also are generally lower in energy and, therefore, less penetrating than gamma rays. A few millimeters of lead can stop X-rays.

Literally thousands of X-ray machines are used daily in medicine and industry for examinations, inspections and process controls. Because of their many uses, X-rays are the single largest source of fabricated radiation exposure.



Summary of the Characteristics of Radioactive Matter:

- **alpha particle:** massive size; charge of +2e; slow speed;
- **beta particle:** very small size; charge of -1e; high speed; and
- **gamma ray:** no mass; no charge; travels at the speed of light.

Quiz on Sections 1, 2 & 3

Radon is a gas produced by the radioactive decay of the element _______.

- radium
- uranium
- lead
- polonium

When solid radium decays to form radon gas, it loses two ______ and two neutrons.

- protons
- neutrons
- electrons
- atoms

Radon itself is radioactive because it also decays, losing a/n _____ particle and forming the element polonium.

- alpha
- little
- electrostatic
- power

________ is the first element in a long series of decay that produces radium and radon.

- Uranium
- Radon
- Lead
- Bismuth

Uranium has a half-life of ___ billion years.

- 4.4
- 1.2
- 0.5
- 44

The half-life of radon is only ___ days.

- 3.8
- 2
- 5.83
- 4

___________ is energy in the form of waves or particles that has enough force to remove electrons from atoms.

- Ionizing radiation
- Radion-nuclear
- Visible light
- Radon

T/F: Alpha particles lack the energy to penetrate the outer layer of dead skin.

- True
- False

T/F: Similar to beta particles, alpha particles cause about 20 times more damage inside the lungs.

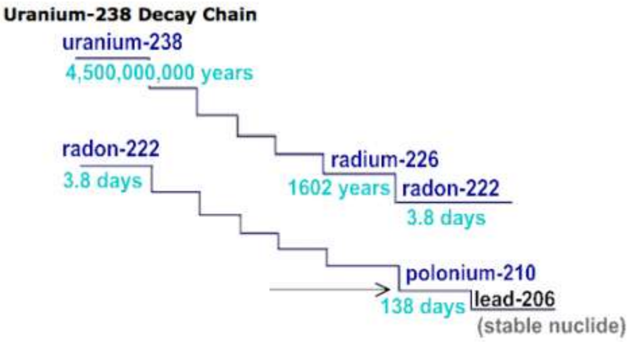
- True
- False

Section 4: Decay Chains

Decay Chains

Most naturally occurring radioactive materials and many fission products undergo radioactive decay through a series of transformations, rather than in a single step. Until the last step, these radionuclides emit energy or particles with each transformation and become another radionuclide. This series of decay, known as a decay chain, ends in a stable nuclide.

For example, Uranium-238 decays through a series of steps to become a stable form of lead. Each step in the illustration below indicates a different nuclide. (Note that only a few of the steps are labeled, and the numbers below each label indicate the length of the particular radionuclide's half-life.) At 4.5 billion years, Uranium-238 has the longest half-life of any known element. Radon-222 has the shortest half-life at 3.8 days. The last radionuclide in the decay chain pictured is Polonium-210, which transforms into Lead-210, and eventually into the stable nuclide Lead-206.

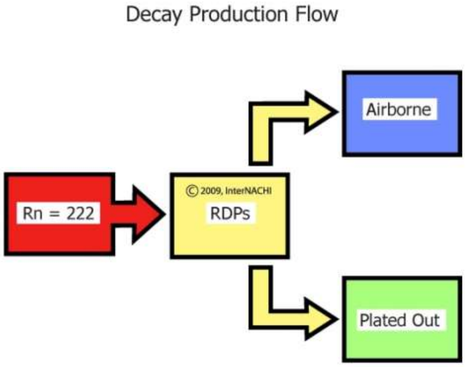


The radioactive decay chain for radon begins with uranium. Uranium decays to produce radium, which then decays into radon. Radon then decays into other RDPs (or radon decay products), which are also radioactive.

RDPs are different from actual radon is a few ways. The characteristics of RDPs include:

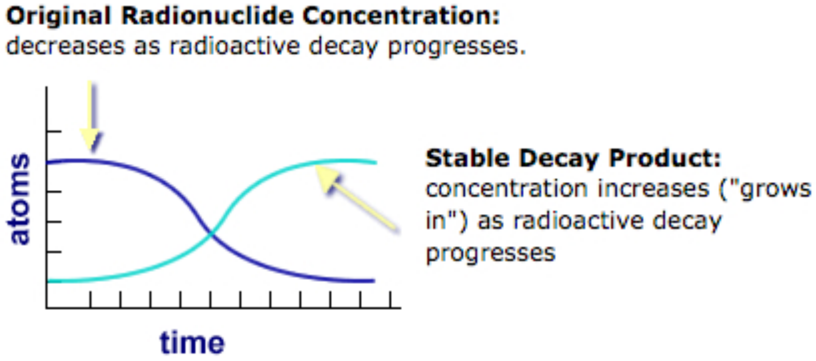
- They are the source of cell damage in the lungs.
- They are short-lived products (less than 30 minutes), but the most significant.
- They have static electrical charges.
- They are chemically reactive.
- They are solid particles, rather than gases, that act like invisible aerosols in the air.
- They are classified as heavy metals.

All of these characteristics make the decay products capable of easily attaching themselves to solid objects such as dust, smoke, walls, floors, clothing, or any other objects. If the RDPs attach to surfaces, they are no longer floating in the air and are said to “plate out." If they attach to ducts or smoke particles, they can be carried into the lungs where they can cause lung cancer.



Ingrowth

The increasing concentration of decay products and activity is called ingrowth. The illustration below shows ingrowth when the decay product is stable and the original radionuclide is replaced. In this situation, the activity decreases with decay of the original radionuclide.



How can we predict how much radioactivity will be produced?

The pattern of ingrowth varies according to the relative length of the half-lives of the original radionuclide and its decay products. Under certain conditions, decay products undergo transformation at the same rate they are produced. When this occurs, radioactive equilibrium exists. Whether equilibrium occurs also depends on the relative lengths of the half-life of radionuclides and their decay products.

Using equations that account for half-lives, the rate of ingrowth, whether equilibrium occurs, the original amount of radionuclide, and the steps in the decay chain, scientists can estimate the amount of activity that will be present at various points.

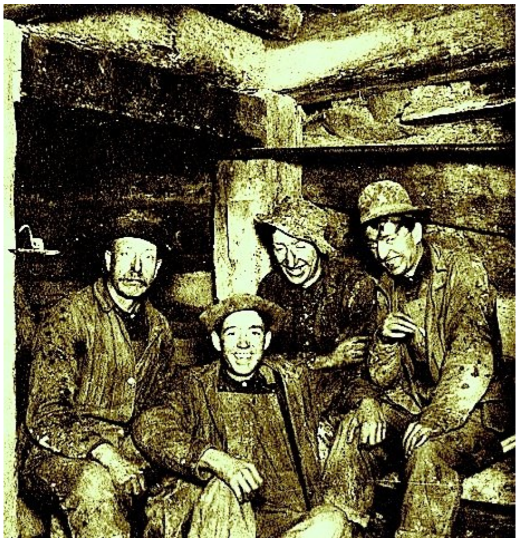
Radon Ingrowth During Uranium Decay

The importance of understanding decay chains is illustrated by the ingrowth of Radon-222 during the decay of Uranium-238. Uranium was distributed widely in the earth's crust as it formed. Given the age of the Earth, uranium's slowly progressing decay chain now commonly produces Radon-222. It is radioactive and has several characteristics that magnify its health effects:

- Radon is a gas. It penetrates soil and cracks in rocks into the air. It can seep through foundations into homes (particularly basements), and accumulate into fairly high concentrations.

- Radon decay emits alpha particles, the radiation that presents the greatest hazard to lung tissue.

- Radon's very short half-life (3.8 days) means that it emits alpha particles at a fast rate.



Radon and Uranium Miners

A higher-than-expected level of lung disease in uranium miners called attention to the effects of Radon-222. The miners worked long hours in enclosed spaces, surrounded by uranium ore and radon that seeped out of the rock. Health workers expected to see health problems in the miners that would reflect direct exposure to radiation. Instead, the predominant health problems were lung cancer and other lung diseases.

First, the health workers suspected the dust itself. They knew that high concentrations of small particles, such as coal dust, asbestos and cotton fibers, could damage workers' lungs. However, closer examination of Uranium-238's decay chain identified Radon-222 as the most likely culprit of the workers' lung diseases.

Half-Life

The rate of radioactive decay is characteristic of each radionuclide. Scientists talk about this rate as a radionuclide's radioactive half-life. It is the time required for the disintegration of one-half of the radioactive atoms that are present when measurement starts. It does not represent a fixed number of atoms that disintegrate, but only a fraction.

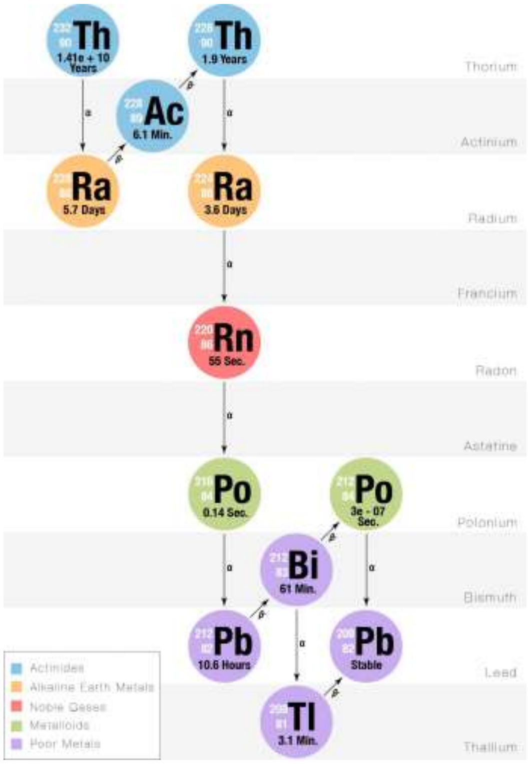
For example, if there are 100 atoms of a radionuclide that has a half-life of one minute, there will be one-half that number, or 50 atoms of the original radionuclide left one minute later. After the second minute, there will be 25 atoms of the original radionuclide left. The fact that this simple example points to the existence of 12.5 radioactive atoms after three minutes illustrates that a half-life is intended to be used for the very large number of atoms that are found in even small samples of radioactive materials. One-hundred atoms aren't going to give off much radiation.

The half-life refers to how quickly the radioactivity from a radionuclide will decrease. Its number of curies tells how active it is now.

Each radioactive element in the radon decay chain has a different half-life. Half-life is the time required for half of the atoms of the element to decay. It is not the time for all of the atoms to decay. If you have an amount of radon with a half-life of 3.8 days, by the end of 3.8 days, you will have half as much. Another 3.8 days later, you will have half that amount, and so on. Usually, by the time 10 half-lives have passed, there is very little left.

It is important to understand the half-life process because it is this time period that radon and its decay products have to be dispersed into the environment. A period of 3.8 days is long enough for radon to move through several feet of soil. The first few radon decay products have short half-lives, but if they are inhaled, they can cause radiation damage to the inner lining of the lungs before they can be exhaled.

Radon gas, like Carbon-14 gas, is naturally occurring in our environment. It forms during the decay of Uranium-238, an element with a fairly interesting decay sequence.



The graphic above is illustrates the radium or uranium series.

Radon has no stable isotopes. However, 36 radioactive isotopes have been characterized, with their atomic masses ranging from 193 to 228. The most stable isotope is 222Rn, which is a decay product of 226Ra, a decay product of 238U. A very trace amount of the (highly unstable) isotope 218Rn is also among the daughters of 222Rn.

There are three other radon isotopes that have a half-life of over an hour: 211Rn, 210Rn and 224Rn. The 220Rn isotope is a natural decay product of the most stable thorium isotope (232Th), and is commonly referred to as thoron. It has a half-life of 55.6 seconds and also emits alpha radiation. Similarly, 219Rn is derived from the most stable isotope of actinium (227Ac)—named "actinon"—and is an alpha emitter with a half-life of 3.96 seconds. No radon isotopes occur significantly in the neptunium (237Np) decay series, though a trace amount of the (extremely unstable) isotope 217Rn is produced.

222Rn belongs to the radium and uranium-238 decay chain, and has a half-life of 3.8235 days. Its four first products (excluding marginal decay schemes) are very short-lived, meaning that the corresponding disintegrations are indicative of the initial radon distribution. Its decay goes through the following sequence:

- 222Rn, 3.8 days, alpha decaying to...
- 218Po, 3.10 minutes, alpha decaying to...
- 214Pb, 26.8 minutes, beta decaying to...

- 214Bi, 19.9 minutes, beta decaying to...
- 214Po, 0.1643 ms, alpha decaying to...
- 210Pb, which has a much longer half-life of 22.3 years, beta decaying to...
- 210Bi, 5.013 days, beta decaying to...
- 210Po, 138.376 days, alpha decaying to...
- 206Pb, stable.

The radon equilibrium factor is the ratio between the activity of all short-period radon progenies (which are responsible for most of radon's biological effects), and the activity that would be at equilibrium with the radon parent.

If a closed volume is constantly supplied with radon, the concentration of short-lived isotopes will increase until an equilibrium is reached where the rate of decay of each decay product will equal that of the radon itself. The equilibrium factor is 1 when both activities are equal, meaning that the decay products have stayed close to the radon parent long enough for the equilibrium to be reached, within a couple of hours. Under these conditions each additional pCi/L of radon will increase exposure, by 0.01 WL (see explanation of WL below). These conditions are not always met; in many homes, the equilibrium fraction is typically 40%; that is, there will be 0.004 WL of progeny for each pCi/L of radon in air.[28] 210Pb takes much longer (decades) to come in equilibrium with radon, but, if the environment permits accumulation of dust over extended periods of time, 210Pb and its decay products may contribute to overall radiation levels as well.

Because of their electrostatic charge, radon progenies adhere to surfaces or dust particles, whereas gaseous radon does not. Attachment removes them from the air, usually causing the equilibrium factor in the atmosphere to be less than one. The equilibrium factor is also lowered by air circulation or air filtration devices, and is increased by airborne dust particles, including cigarette smoke. In high concentrations, airborne radon isotopes contribute significantly to human health risk. The equilibrium factor found in epidemiological studies is 0.4.

Summary of Characteristics

Radon-222:

- is a gas;
- is odorless;
- is tasteless;
- is invisible;
- mixes with air;
- is chemically inert (or non-reactive);
- is found everywhere;
- decays by alpha-particle emission; and
- has a half-life of 3.8 days.

Radon Decay Products, or RDPs:

- are solids, called daughters or progeny;
- are chemically active;
- are electrically charged;
- can attach to air particles and cling to surfaces;
- have a ratio of progeny-to-radon gas ranging from 0.3 to 0.7 ER (equilibrium ratio), averaging 0.5 ER;
- are short-lived (from 0.2 milliseconds to 26.8 minutes);
- include Polonium-218, 214 and 210, which are alpha-particle emitters, and these alpha-particle emissions can cause physical cellular damage, such as lung cancer.

Section 5: Curies, Equations and ER

Section 5: Curies, Equations and ER

Since small amounts of material contain very large numbers of atoms, small samples can have a very large number of atoms disintegrating at the same time. It didn't take radiation scientists very long to decide that working with activities in the billions-of-disintegrations-per-second was too awkward. To make measuring the activity more convenient, they developed a new unit, the curie, named in honor of Marie Curie, a pioneer in the study of radioactive materials. Radioactive materials are measured in curies. A picocurie is one-millionth of a millionth (or a trillionth) of a curie.

How big is a curie?

A curie is defined as 37 billion disintegrations per second. The curie was originally a comparison of the activity of a sample to the activity of one gram of radium. When more accurate techniques measured a slightly different activity for radium, the reference to radium was dropped. A radioactive sample that has an activity of 74 billion disintegrations per second has a measured activity of 2 curies.

Are there smaller and larger units of activity?

The curie, abbreviated as "Ci," is a very large unit for some purposes, and a very small unit for others. Scientists use the following fractions or multiples of a curie, as well:

- picocuries (pCi) are 1 million-millionth of a curie (1×10^{-12} Ci). Picocuries are used in measuring the typically small amounts of radioactivity that are present in air and water.

- megacuries (MCi) are 1 million curies (1×10^{6} Ci), and are used in measuring the very large amounts of radioactivity released from nuclear weapons, for example.

- other fractions, such as:
  - a millicurie (1/1,000 Ci = mCi), and
  - a nanocurie (1 billionth of a curie = nCi) are used as needed.

Terms and More Equations:

- **curie (Ci):** a standard measurement for radioactivity, specifically the rate of decay for a gram of radium = 37 billion decays per second. A unit of radioactivity equal to 3.7×10^{10} disintegrations per second.

- **picocurie (pCi):** measures the rate of the radioactive decay of radon. One pCi is one trillionth of a curie, 0.037 disintegrations per second, or 2.22 disintegrations per minute.

- **picocurie per liter (pCi/L):** a unit of radioactivity corresponding to an average of one decay every 27 seconds in a volume of one liter, or 0.037 decays per second a liter of air or water: 1 pCi/L = 37 becquerels per cubic meter (Bq/m^3).

- **becquerel (Bq):** The SI or International System of Units' definition of activity is 1 Bq = 1 disintegration per second. One picocurie per liter of radon is the same as 37 bequerels per cubic meter.

The amount of radon in the air is measured in "picocuries per liter of air," or "pCi/L," which is the number of radioactive disintegrations per minute in a liter of air. A pCi/L is 2.22

disintegrations per minute for each liter. If a gallon container held air with 4 pCi/L, there would be about 4 (quarts per gallon) multiplied by 4 (pCi/L) multiplied by 2.22 disintegrations per minutes, or about 35.2 disintegrations per minutes of radon atoms in the container.

Test results are sometimes expressed in **working levels (WL),** rather than in picocuries per liter (pCi/L), using this formula: 4 pCi/L = 0.016 WL.

Radon decay products are measured in working levels (WL). Any combination of short-lived radon decay products in one liter of air will result in the ultimate emission of 1.3 x 105 MeV (million electron volts) of potential alpha energy. This number was chosen because it represents the approximate amount of alpha energy released from the decay products in equilibrium with 100 pCi of Rn-222. One working level is the concentration of short-lived RDPs produced from one liter of air containing 100 pCi of radon.

The average indoor radon level is 1.3 pCi/L.

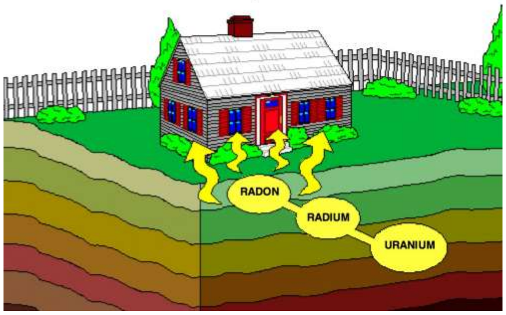
The average outdoor radon level is 0.4 pCi/L.

The EPA's **action level** for radon is 4 pCi/L. The EPA's action level for radon is 0.02 WL.

Equilibrium Ratio

There is a relationship between decay-product concentration and radon-gas concentration. Radon is said to be at "secular equilibrium" with its decay products when the radioactive activity of radon and its decay products are the same.

The equilibrium ratio for radon is expressed this way: equilibrium ratio = (WL x 100) ÷ (pCi/L). At complete equilibrium (i.e., at an equilibrium ratio of 1), 1 WL of RDPs is present when the radon concentration is 100 pCi/L. But due to ventilation and plate-out, the RDPs never reach equilibrium in a residential environment, so the ratio is never 1 inside a house. The commonly assumed equilibrium ratio is 0.5 -- the decay products are halfway toward equilibrium -- in which case, 1 WL would correspond to 200 pCi/L. However, equilibrium ratios vary with time and location, and ratios of 0.3 to 0.7 are common.



RDPs

Atoms of radioactive radon gas decay by the emission of alpha particles, and transform into Polonium-218 and, in turn, transform to Polonium-214 by successive alpha emission.

Daughters

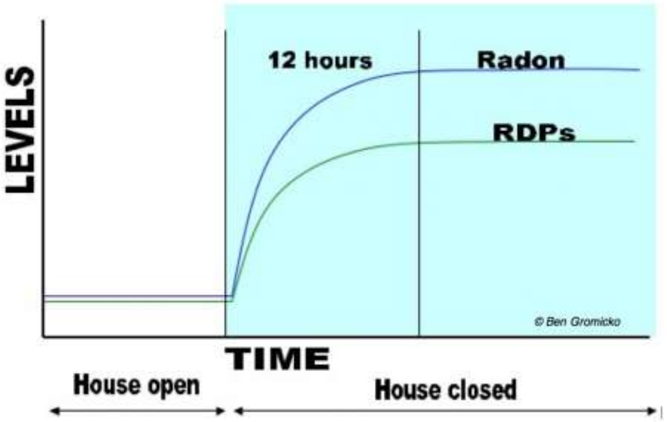
In the air of the average room, both radon and the two radioactive isotopes of Polonium are present (214 and 218), and are often referred to as radon progeny or radon decay products (RDPs). These may stay free or may attach to room aerosol (such as dust or smoke). It is these radon progeny that get deposited in airways and cause the primary risk of inhalation. Radon gas itself does not pose much risk.

Action Level

Based on the actual risk observed in uranium miners, the U.S. Environmental Protection Agency has set the action-level limit at 0.02 WL. Because radon daughter products can get deposited in ventilation systems and on other surfaces, they do not reach equilibrium with radon. Based on some experimental data from typical homes, the EPA assumes that the equilibrium ratio is 50%. The action-level limit of 0.02 WL corresponds to the derived radon concentration of 4 pCi/L when the equilibrium ratio is 50%.

There are two methods of characterizing radon: either measure radon-gas concentration, or measure radon-progeny concentration. The EPA's action-level limit is 4 pCi/L for radon gas, and 0.02 WL for radon progeny. These measurements are equivalent to each other only when equilibrium ratio is 50%. Both measurements are acceptable, as long as EPA-listed devices and methods are used. (These are also now listed as NEHA or NRSB.)

Once radon enters a home, it begins to form decay products. Some activities inside the home may affect the equilibrium. Air-filtering would remove some of the decay products, but not the radon, because it is an inert gas. Air leakage might allow some of the RDPs to escape. RDPs might cling to or "plate out" on walls, floors and other objects. All of these factors can prevent the RDPs from reaching the maximum concentration. They will eventually reach a final concentration, which is a balance of the amount of RDPs that are produced and are lost through plate-out and ventilation. It is this balance that is referred to as the equilibrium ratio. In a home, it typically takes about 12 hours for this equilibrium to be achieved, after the doors and windows have been closed.



Assumption

In order to relate the measurement of radon to an equivalent amount of radon decay products, it is necessary to assume a ratio of the amount of radon decay products that are produced and available for inhalation from the amount of radon in the air. That's what the equilibrium ratio (ER) is.

ER can be calculated as:
Equilibrium Ratio = Working Level x 100 ÷ Radon Concentration, or ER = (WL x 100) ÷ Rn.

For example, if the radon concentration is 75 pCi/L, and the decay-product concentration is 0.3 WL, the equilibrium ratio would be calculated as follows:
ER = (0.3) x (100) ÷ 75 = 0.4

This assumption -- the equilibrium ratio -- came about from extensive research and statistics available when radon in homes and buildings was starting to be investigated. The assumption of 50%, which is used today, is based on residential structures with average air-recirculation rates, with a typical range of suspended radon decay products between 30% to 70%.

This assumed equilibrium rate of 50% equates to .02 WL measurements, which is the EPA's established "action level."

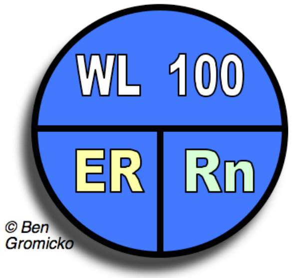
Radon = WL x 100 ÷ 0.5
4 (radon) = .02 (radon decay products) x 100 ÷ 0.5 (assumed equilibrium ratio)

ER ≠ 1

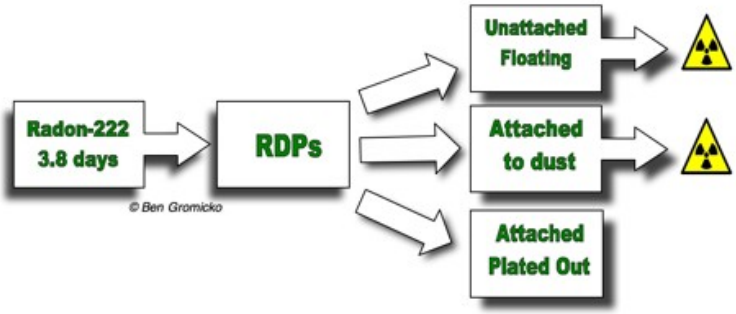
Again, an equilibrium ratio of 1 will not likely occur in any house because ventilation removes both radon and RDPs. RDPs have an electrostatic charge and will plate out by clinging to walls, floors, furniture and other solid objects. This reduces the RDP concentration without affecting the radon concentration. And it takes a while for radon entering the house to produce RDPs. As a result, the ER will always be less than 1.

The equation ER = (WL x 100) ÷ Rn can be arranged to calculate the desired expression:

ER = (WL x 100) ÷ Rn *or* **WL** = (Rn X ER) ÷ 100 *or* **Rn** = (WL x 100) ÷ ER



If the radon level is measured at 4 pCi/L and the working levels are measured at 0.02 WL, then the equilibrium ratio (ER) is equal to 0.02 x 100 ÷ 4 = 0.5, or 50%.



Unattached particles (which are solid, electrically charged particles) can be inhaled and become lodged in the lungs. When they stick to objects such as dust, smoke and pollen, RDPs can still present a health hazard if the object is small enough to float in the air. Remember that if they plate out on a wall, they are not a hazard.

If air is being circulated by fans, a lot of the RDPs can plate out on the walls, floors, furniture and other solid objects. Working levels can be lowered by using fans. The radon concentration will stay the same, but the ER will be lower. The ER is also lower after a house has been ventilated with outdoor air. The soil gas entering a house has very low decay products because RDPs will plate out in the soil. Therefore, if a house is ventilated and then closed up, it takes several hours for the decay products to return to an expected equilibrium of radon concentration.

Factors Affecting the Equilibrium Ratio

Increased air movement causes more of the hazardous RDPs to adhere to fixed objects, and they do not detach once in they make contact with an object. This decreases the amount of radon decay products available for inhalation, and also decreases the equilibrium ratio.

For instance, in buildings with large air flows or HEPA filters, the percentage of airborne radon decay products can be considerably lower than in a building without them.

If the indoor air is relatively stable, with little air movement that would remove RDPs, then the ER will likely be high, since there will be more decay products in the air. If there is a high-efficiency, whole-house air-filter system that is operating with a high degree of air movement, then a low ER would be expected.

Quiz on Sections 4 & 5

Radon decay products (RDPs) are different from radon in a few ways. For example, radon decay products are classified as heavy _______.

- metals
- gases
- fuels
- particles

If the RDPs attach to surfaces, they are said to ?______.? They are no longer floating in the air.

- plate out
- flake-out
- electro-stat
- saucer-in

T/F: Radon-222 is a gas that is visible under certain conditions.

- False

- True

T/F: RDPs are electrically charged.

- True
- False

RDPs are short-lived, all lasting less than ______ minutes.

- 30
- 2
- 65
- 0.5

T/F: The radon decay products Polonium-218, 214 and 210 are alpha-particle emitters.

- True
- False

T/F: Radon decay products are measured in working levels (WL).

- True
- False

Radon is said to be at "secular ___________" with its decay products when the radioactivity of radon (or its production rate) and the rate of decay of its RDPs are the same.

- equilibrium
- half-life
- discord
- concentrate

T/F: WL = (Rn x ER) ? 100

- True
- False

Section 6: Health Risks

Radon Causes Lung Cancer in Non-Smokers

Exposure to Radon Causes Lung Cancer in Non-Smokers and Smokers Alike

Lung cancer kills thousands of Americans every year. Smoking, radon, and second-hand smoke are the leading causes of lung cancer. Although lung cancer can be treated, the survival rate is one of the lowest for those with cancer. From the time of diagnosis, between 11 and 15% of those afflicted will live beyond five years. In many cases, lung cancer can be prevented -- this is especially true for radon.

Smoking is the leading cause of lung cancer. Smoking causes an estimated 160,000 cancer deaths in the U.S. every year, according to 2008 statistics from the American Cancer Society. And the rate among women is rising. In 1964, Dr. Luther L. Terry, then U.S. Surgeon General, issued the first warning regarding the link between smoking and lung cancer. Lung cancer now surpasses breast cancer as the Number One cause of cancer deaths among women. A smoker who is also exposed to radon has a much higher risk of lung cancer.

Radon is the Number One cause of lung cancer among non-smokers, according to EPA estimates. Overall, radon is the second leading cause of lung cancer. Radon is responsible for about 21,000 lung cancer deaths every year. About 2,900 of these deaths occur among people who have never smoked.

Second-hand smoke is the third leading cause of lung cancer and is responsible for an estimated 3,000 lung cancer deaths every year. Smoking affects non-smokers by exposing them to second-hand smoke. Exposure to second-hand smoke can have serious consequences for children's health, including asthma attacks. It can also affect the respiratory tract and make them vulnerable to bronchitis and pneumonia, etc. It may lead also to ear infections.

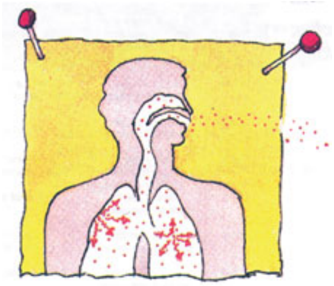
The following Web sites provide a wide range of comprehensive information about lung cancer, prevention and treatment:

- American Cancer Society: www.cancer.org
- American Lung Association: http://www.lungusa.org/
- National Cancer Institute: http://www.nci.nih.gov/
- Vanderbilt-Ingram Cancer Center: http://www.mc.vanderbilt.edu/vicc
- Memorial Sloan-Kettering Cancer Center: http://www.mskcc.org/mskcc/html/44.cfm

Radon is a Carcinogen

Two studies based on research conducted in North America and in Europe show definitive evidence of an association between residential radon exposure and lung cancer. Both studies combined data from several residential studies. They went a step beyond earlier findings and confirmed the radon health risks predicted by occupational studies of underground miners who breathed radon for years. Early in the debate about radon-related risks, some researchers questioned whether occupational studies could be used to calculate risks from exposure to radon in the home environment.

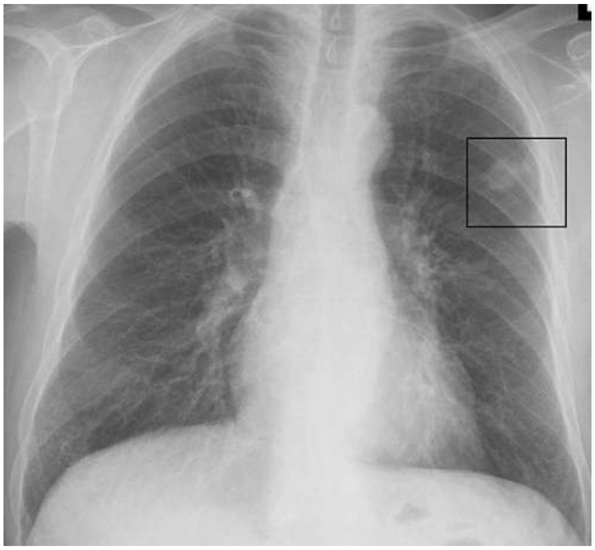
“These findings effectively end any doubts about the risks to Americans of having radon in their homes,” said Tom Kelly, director of the EPA’s Indoor Environments Division. “We know that radon is a carcinogen. This research confirms that breathing low levels of radon can lead to lung cancer.”



Why is radon the public health risk that it is?

The EPA estimates that radon is responsible for about 20,000 lung cancer deaths each year in the United States. Exposure to radon is the second leading cause of lung cancer after smoking. Radon is an odorless, tasteless and invisible gas produced by the decay of naturally occurring uranium in soil and groundwater. Radon is a form of ionizing radiation and a proven carcinogen. Lung cancer is the only known effect on human health from exposure to airborne radon. Thus far, there is no conclusive evidence that children are at greater risk of lung cancer than adults.

Radon in air is ubiquitous. It is found in outdoor air and in the indoor air of buildings of all kinds. The EPA recommends that the problem be addressed if a home's radon level is 4 pCi/L (picocuries per liter) or more. Because there is no known safe level of exposure to radon, the EPA also recommends that the problem be addressed for homes with radon levels between 2 pCi/L and 4 pCi/L. The average radon concentration in the indoor air of the average American home is about 1.3 pCi/L. The EPA bases its estimate of 20,000 radon-related lung cancers a year on this number. The average concentration of radon in outdoor air is 0.4 pCi/L, or one-tenth of the EPA’s recommended 4 pCi/L action level.



For smokers, the risk of lung cancer is significant due to the synergistic effects of radon and smoking. For this at-risk population, about 62 people in a 1,000 will die of lung cancer, compared to about seven people in a 1,000 who have never smoked. Put another way, a person who has never smoked and is exposed to 1.3 pCi/L has a 2-in-1,000 chance of dying from lung cancer, while a smoker has a 20-in-1,000 chance. The risk to smokers compared to those who have never smoked is six times greater.

The radon health risk is underscored by the fact that, in 1988, the United States Congress added Title III on Indoor Radon Abatement to the Toxic Substances Control Act. It codified and funded the EPA's then-fledgling radon program. That same year, the Surgeon General issued a warning about radon, urging Americans to test their homes and to reduce the radon level, when necessary.

Unfortunately, many Americans presume that because the action level is 4 pCi/L, a radon level of less than that is considered safe. This perception is all too common in the residential real estate market. In managing any risk, we should be concerned with the greatest risk. For most Americans, their greatest exposure to radon is inside their homes, especially in rooms that are below grade (such as basements), as well as rooms that are in contact with the ground, and the rooms directly above them.

Lung Cancer

How does radon induce cancer?

If inhaled, radon decay products (Polonium-218 and Polonium-214, solid form), unattached or attached to the surface of aerosols, dusts and smoke particles become deeply lodged in the lungs where they can radiate and penetrate the cells of mucous membranes, bronchi, and other pulmonary tissues. The ionizing radiation energy affecting the bronchial epithelial cells is believed to initiate the process of carcinogenesis. Although radon-related lung cancers are mainly seen in the upper airways, radon increases the incidence of all histological types of lung cancer, including small-cell carcinoma, Aden carcinoma, and squamous cell carcinoma. Lung cancer due to inhalation of radon decay products constitutes the only known risk associated with radon. In studies done on miners, variables such as age, duration of exposure, time since initiation of exposure, and especially the use of tobacco have been found to influence individual risk. In fact, the use of tobacco multiplies the risk of radon-induced lung cancer enormously.

What is the evidence?

More is known about the health risk of radon exposure to humans than about most other human carcinogens. This knowledge is based on extensive epidemiological studies of thousands of underground miners, carried out over more than 50 years worldwide, including on miners in the United States and Canada. In addition to the data on miners, experimental exposures on laboratory animals confirm that radon and its decay products can cause lung cancer.

Human Studies and Animal Studies

Research on lung cancer mortality in miners exposed to radon progeny is substantial and consistent. Studies of thousands of miners, some with follow-up periods of 30 years and more, have been conducted in metal, fluorspar, shale, and uranium mines in the United States, Canada, Australia, China and Europe. These studies have consistently shown an increase in the occurrence of lung cancer with exposure to radon decay products, despite differences in study populations and methodologies.

The miner studies detailed the following findings:

- At equal cumulative exposures, low exposures in the range of the EPA's 4 pCi/L action level over longer periods produced a greater risk of lung cancer than high exposures over short periods.

- Increased lung cancer risk with radon exposure has been observed even after controlling for, or in the absence of, other exposure risks, such as asbestos, silica, diesel fumes, arsenic, chromium, nickel, and ore dust.

- Non-smoking miners exposed to radon have been observed to have an increased risk of lung cancer.

Animal experiments conducted by the United States Department of Energy's Office of Energy Research, as well as those conducted in France, have confirmed the carcinogenicity of radon, and have provided insight into the nature of the exposure-response relationship, as well as the modifying effects of the exposure rates.

To date, these animal studies have produced several relevant findings for humans:

- Health effects observed in animals exposed to radon and radon decay products include lung carcinomas, pulmonary fibrosis, emphysema, and a shortening of lifespan.

- The incidence of respiratory tract tumors grew with an increase in cumulative exposure coupled with a decrease in rate of exposure.

- Increased incidence of respiratory tract tumors was observed in rats at cumulative exposures as low as 20 WLM.

- Exposure to ore dust or diesel fumes simultaneously with radon did not increase the incidence of lung tumors above that produced by radon progeny exposures alone.

- Lifetime lung-tumor risk coefficients that have been observed in animals are similar to the lifetime lung-cancer risk coefficients observed in human studies.

- In a study of rats exposed to radon progeny and uranium ore dust simultaneously, it was observed that the risk of lung cancer was elevated at exposure levels similar to those found in homes. The risk decreased in proportion to the decrease in exposure to radon progeny.

In 1988, a panel of experts convened by the World Health Organization's International Agency for Research on Cancer unanimously agreed that there is sufficient evidence to conclude that radon causes cancer in humans and in laboratory animals. Scientific committees assembled by the National Academy of Sciences (NAS), the International Commission on Radiological Protection (ICRP), and the National Council on Radiation Protection and Measurement (NCRP) also have reviewed the available data and agreed that radon exposure causes human lung cancer.

Recognizing that radon is a significant public health risk, scientific and professional organizations, such as the American Medical Association, the American Lung Association, and the National Medical Association, have developed programs to reduce the health risks of radon. The National Institute for Occupational Safety and Health (NIOSH) reviewed the epidemiological data and recommended that the annual radon progeny exposure limit for the mining industry be lowered.

Is occupational exposure to radon comparable to residential exposure?

Because questions have been raised about the appropriateness of using the epidemiological studies of underground miners as a basis for estimating the risk radon poses to the general population, the EPA commissioned the NAS to investigate the difference between underground miners and members of the general public in the doses they receive per unit-exposure due to inhaled radon progeny.

The NAS report, published in 1991, concluded that it is reasonable to extrapolate from the miner data to a residential situation, but that the effective doses per unit of exposure for people in their homes are approximately 30% less than for the miners. In its analysis, the NAS considered variables such as the amount and types of dust to which the radon decay particles would attach, the breathing rates of working miners compared to that of people at home, and the presence of women and children in the homes.

The EPA has adjusted its residential risk estimates accordingly. The result is still considerable -- it now estimates that approximately 14,000 lung cancer deaths in the United States annually are due to residential radon exposures. As more data are gathered about residential radon exposures, the risk estimates may be adjusted further.
Enough statistical evidence exists now, however, to state with certainty that, each year in the United States, thousands of deaths due to preventable lung cancer are attributable to indoor residential exposure to radon.

More information is needed to answer important questions about radon's effect on women and children -- two groups not included in the occupational studies. Although children have been reported to be at greater risk than adults for developing certain types of cancer from radiation, there is no current or conclusive evidence that radon exposure puts children at a greater risk. Some studies on miners and on animals indicate that, for the same total exposure, a lower exposure over a longer period is more hazardous than brief, high exposures. These findings increase concerns about residential radon exposures. Epidemiological control studies are underway in the U.S. and in Europe, the pooled results of which should enhance the understanding of the risk of residential exposure to radon.

What about smoking and radon exposure?

Some people ask whether the lung cancer deaths attributed to radon exposure actually may be the result of smoking. A 1989 study by researchers from NIOSH, the Centers for Disease Control, the Harvard School of Public Health, and the University of California at Davis demonstrated a greatly increased risk of lung cancer in non-smoking uranium miners exposed to high radon concentrations. Compared to typical non-smoking populations, these miners had nine to 12 times the risk of developing lung cancer.

Evidence from some of the epidemiological studies of American underground uranium miners indicates that radon exposure and smoking may have a synergistic relationship. Either smoking or radon exposure can independently increase the risk of lung cancer; however, exposure to both greatly enhances that risk.

Your chances of getting lung cancer from radon depend mostly on:

- how much radon is in your home;
- the amount of time you spend in your home; and
- whether you are a smoker, or have ever smoked.

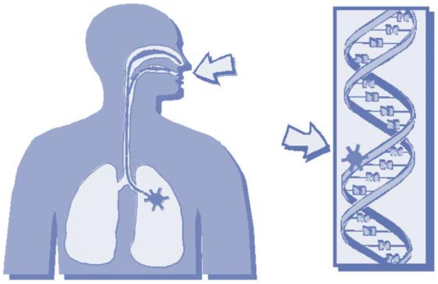
RADON RISK for SMOKERS		
Radon Level	**If 1,000 people who smoke were exposed to this level over a lifetime...**	**The risk of cancer fro radon exposure compares to...**
20 pCi/L	about 260 of them would get lung cancer.	250 times the risk of drow
10 pCi/L	about 150 of them would get lung cancer.	200 times the risk of dying in a home fire.
8 pCi/L	about 120 of them would get lung cancer.	30 times the risk of dying in a fall.
4 pCi/L	about 62 of them would get lung cancer.	5 times the risk of dying in a car crash.
2 pCi/L	about 32 of them would get lung cancer.	6 times the risk of dying from poison.

1.3 pCi/L	about 20 of them would get lung cancer.	(average outdoor radon level)
0.4 pCi/L	-----------------	(average outdoor radon level)

RADON RISK for PEOPLE WHO HAVE NEVER SMOKE

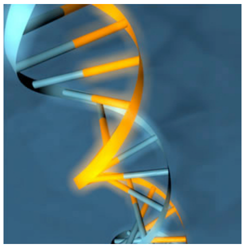
Radon Level	**If 1,000 people who have never smoked were exposed to this level over a lifetime...**	**The risk of cancer from radon exposur compares to...**
20 pCi/L	about 36 of them would get lung cancer.	35 times the risk of drowning.
10 pCi/L	about 18 of them would get lung cancer.	20 times the risk of dying in a fall.
8 pCi/L	about 15 of them would get lung cancer.	4 times the risk of dying in a fall.
4 pCi/L	about 7 of them would get lung cancer.	the same risk as dying in a car crash.
2 pCi/L	about 4 of them would get lung cancer.	the same risk as dying from poison.
1.3 pCi/L	about 2 of them would get lung cancer.	(average indoor radon level)
0.4 pCi/L	----------------	(average indoor radon level)

Genetic Damage Caused by Radon



Most of the epithelial cellular damage is not caused by breathing in radon gas itself, which is removed from the lungs during exhalation, but by radon's short-lived decay products (half-life measured in minutes or less). When inhaled, these decay products may be deposited in the airways of the lungs. The RDPs subsequently emit alpha particles as they decay further. The total amount of energy emitted by the progeny is several hundred times that produced in the initial decay of radon. The increased risk of lung cancer from radon results primarily from these alpha particles irradiating lung tissue. When an alpha particle passes through a cell's nucleus, the person's DNA is likely to be damaged. More specifically, available data indicate that alpha particle penetration of the cell's nucleus may cause genomic changes, most typically in the form of point mutations and transformations.

Since alpha particles are more massive and more highly charged than other types of ionizing radiation, they are more damaging to living tissue. As previously described, alpha radiation is able to travel only extremely short distances in the body. Thus, alpha radiation from decay of radon progeny in the lungs cannot reach cells in any other organs, so it is likely that lung cancer is the only major cancer hazard posed by radon.



By breaking the electron bonds that hold molecules together, radiation can damage human DNA, the inherited compound that controls the structure and function of cells. Radiation may damage DNA directly by displacing electrons from the DNA molecule, or indirectly by changing the structure of other molecules in the cell, which may then interact with the DNA. The latter mechanism will be described in more detail later. When one of these events occurs, a cell can be destroyed quickly, or its growth or function may be altered through a change (mutation) that may not be evident for several years.

An alpha particle emitted from radon daughter decay is in the form of a high-energy helium ion, known in scientific notation as He2+. These helium particles transverse a cell's nuclei in a linear pattern and deposit energy via linear energy transfer, or LET. This refers to the energy transferred per unit of path traveled by the ionizing particle. Since alpha particles travel short distances and are slow, compared to beta and gamma particles, their efficiency in transferring energy and affecting genomic change is very high, as is their LET quantity. Once deposited, this energy causes DNA alterations, cell-cycle stress, and occasional cell death. Epithelial cellular changes caused by the alpha particle emission from a single radon daughter can be seen with a microscope.

Risk Assessment Facts

- The EPA’s indoor radon program promotes voluntary public actions to reduce the risks from indoor radon. The EPA and the U.S. Surgeon General recommend that people perform a simple home test using kits which are now widely available in stores. If high levels of radon are confirmed, it is recommended that those high levels be mitigated or reduced using straightforward techniques.
- The EPA recently completed an updated assessment of their estimates of lung cancer risks from indoor radon, based on the NAS's 1999 report on radon titled "The Biological Effects of Ionizing Radiation (BEIR) VI." This report is the most comprehensive review of scientific data gathered on radon, and builds on and updates their previous findings. The NAS concluded that homeowners should still test and, if necessary, mitigate their exposure to elevated radon levels in their homes.
- Radon is a naturally occurring radioactive gas that is colorless, odorless and tasteless. It's naturally produced from the radioactive decay of uranium that's present in soil, rock and groundwater. It emits ionizing radiation during its radioactive decay, changing into several radioactive isotopes known as radon decay products or RDPs.
- Radon gets into the indoor air primarily from soil under building structures. Radon is a known human lung carcinogen and is the largest source of radiation exposure and risk to the general public. Most inhaled radon is rapidly exhaled, but the inhaled decay products readily deposit in the lung tissue where they irradiate sensitive cells in the airways, increasing the risk of lung cancer.
- The NAS BEIR VI Report confirmed the EPA’s long-held position that radon is the second leading cause of lung cancer, and a serious public health problem. The NAS estimates that radon causes about 20,000 lung cancer deaths each year. The report found that even very small exposures to radon can result in lung cancer. They concluded that no evidence exists that shows a threshold of exposure below which radon levels are harmless. The report also found that many smokers exposed to radon face a substantially greater risk of getting lung cancer compared to those who have never smoked. This is because of the synergistic relationship between radon and cigarette smoking.

Section 7: Radon in Water

Private Wells

Property owners with wells who have confirmed elevated indoor radon levels should also test their well water for radon. Radon in the water supply can increase the indoor radon level, although, in most cases, radon entering the home through water will be a small source of risk compared to the levels of radon entering through the soil. The EPA estimates that indoor radon levels will increase by about 1 pCi/L for every 10,000 pCi/L of radon in water. (The EPA's Office of Ground Water and Drinking Water has developed publications relating to radon in drinking water which can be found athttp://www.epa.gov/safewater/radon.html.)

How is radon tested in water?

Before testing for radon in the residential water supply, test the air. If the indoor radon level is high and the home uses groundwater, test the water. If the radon level in the air is low, there is no need to test the water. Test results are expressed in picocuries of radon per liter of water (pCi/L). In general, 10,000 pCi/L of radon in water contributes roughly 1 pCi/L of airborne radon throughout the house. The EPA currently advises consumers to take action if the total household air level is above 4 pCi/L.

For waterborne radon, a simple step is to make sure that the bathroom, laundry room and kitchen are well ventilated. If the well water has only moderate levels of radon, this may adequately reduce exposure to waterborne radon. However, if the well has high levels of radon, consider using water-treatment devices, such as granular activated-carbon (GAC) units and home aerators.

What do the results of a water test mean?

It is possible to estimate how much the radon in the water supply is affecting the indoor radon level. The formula to gauge whether indoor air levels are elevated is to subtract 1 pCi/L from the indoor air radon level for every 10,000 pCi/L of radon that was found in the water. For example: If there are 30,000 pCi/L of radon in the water, then 3 pCi/L of the indoor measurement may have come from radon in the water.

If most of the radon is not coming from the water, mitigate the indoor levels and then re-test the indoor air to make sure that the source of elevated radon was not coming from the property's well. If a large contribution of the radon in the house is coming from the water supply, homeowners want to consider installing a special water treatment system to remove radon. The EPA recommends installing a water treatment system only when there is a radon problem found in the water supply.

How is radon removed from water?

Radon can be removed from water by using one of two methods: aeration treatment, or granular activated-carbon (GAC) treatment.

Aeration treatment involves spraying water or mixing it with air, and then venting the air from the water before use.

GAC treatment filters water through carbon. Radon attaches to the carbon and leaves the water free of radon. The carbon may need special handling for its disposal if it is used at a high radon level, or if it has been used for a long time.

In either treatment, it is important to treat the water where it enters the home (at the point-of-entry) so that all the water will be treated. Point-of-use devices, such as those installed on a tap or under the sink, will treat only a small portion of the water and are not effective in reducing radon in the water. It is important to maintain home water treatment units properly. Failure to do so can lead to other water contamination problems. Some homeowners opt for a service contract from the installer to provide for carbon replacement and general system maintenance.

Where and how does radon get into drinking water?

While most radon-related deaths are due to radon gas accumulated in houses from seepage through cracks in the foundation, up to 1,800 deaths per year are attributed to radon from the household's water supply. Showering, washing dishes and laundering can disturb the water and release radon gas into the air.

What are the risks of radon exposure?

Radon's primary public health risk is by breathing in the indoor air of homes. This contributes to about 20,000 lung cancer deaths each year in the United States, according to the 1999 landmark BEIR VI Report by the NAS on radon in indoor air. Radon is the second leading cause of lung cancer in the United States. Based on a second NAS report on radon in drinking water, the EPA estimates that radon in drinking water causes about 168 cancer deaths per year, 89% from lung cancer caused by breathing radon released from water, and 11% from stomach cancer caused by drinking radon-contaminated water.

Drinking water that has high levels of radon may be a health risk, but breathing air high in radon concentration is more harmful. Breathing in radon gas over a long period of time can increase the risk of lung cancer. Drinking water contaminated by radon may increase the chances of developing stomach cancer.

What should I do if I have concerns about radon exposure?

The 1996 Safe Drinking Water Act Amendments required the EPA to establish several new, health-based drinking water regulations, including a multimedia approach to address the public health risks from radon.

Consult a healthcare provider to discuss concerns, and consider using one of the two radon-removal methods previously discussed (aeration treatment and GAC treatment).

Section 8: Curie and Becquerel

Pioneers in the Discovery of Radioactivity

Marie Curie

Marie Curie (1867-1934) and her husband, Pierre Curie (1859-1906), are perhaps two of the most famous scientists known for their contributions to the study of radioactivity. Pierre was born in Paris and Marie in Poland. They both studied at the Sorbonne. They investigated the properties of uranium and thorium and, soon after, discovered polonium. Pierre pursued the study of magnetism acting at high temperatures. Marie continued her research in chemistry and physics, and is the only person ever to receive Nobel Prizes in both disciplines. The "curie," named for her, is the unit of measurement now used in radiation research.

The Curies combined their efforts with Henri Becquerel, another scientist. In 1903, they were all awarded the Nobel Prize in physics.

Antoine Henri Becquerel

Antoine Henri Becquerel (1852–1908) was a French physicist and Nobel laureate who was responsible, along with Marie and Pierre Curie, for the discovery of radioactivity. Later, Becquerel demonstrated that the radiation emitted by uranium shared certain characteristics with X-rays, but, unlike X-rays, that radiation could be deflected by a magnetic field and, therefore, must consist of charged particles. The "becquerel" is also a unit of measurement in radiation studies.

Section 9: Alpha, Beta and Gamma

Alpha, Beta and Gamma Particles

ALPHA PARTICLES

Alpha particles (symbol α) are a type of ionizing radiation ejected by the nuclei of some unstable atoms. They are large sub-atomic fragments consisting of two protons and two neutrons.

Who discovered alpha particles?

Ernest Rutherford

As discussed earlier in this course, British scientist Ernest Rutherford discovered alpha particles in 1899 while working with uranium. His research contributed to our understanding of the atom and its nucleus through the Rutherford-Bohr planetary model of the atom.

What are the properties of an alpha particle?

For review, an alpha particle is identical to a helium nucleus having two protons and two neutrons. It is a relatively heavy, high-energy particle, with a positive charge of +2 from its two protons. Alpha particles have a velocity in air of approximately 1/20 the speed of light, depending upon the individual particle's energy.

What are the conditions that lead to alpha particle emission?

When the ratio of neutrons-to-protons in the nucleus is too low, certain atoms restore the balance by emitting alpha particles. For example: Polonium-210 has 126 neutrons and 84 protons, a ratio of 1.5-to-1. Following radioactive decay by the emission of an alpha particle, the ratio becomes 124 neutrons-to-82 protons, or 1.51-to-1.

Alpha-emitting atoms tend to be very large atoms -- that is, they have high atomic numbers. With some exceptions, naturally occurring alpha emitters have atomic numbers of at least 82 (the element lead).

Which radionuclides are alpha emitters?

There are many alpha-emitting radioactive elements, both natural and man-made:

Alpha Emitter	Atomic Number
Americium-241	95
Plutonium-236	94
Uranium-238	92
Thorium-232	90
Radium-226	88
Radon-222	86
Polonium-210	84

What happens to atoms during alpha emission?

The nucleus is initially in an unstable energy state. An internal change takes place in the unstable nucleus and an alpha particle is ejected, leaving a decay product. The atom has then lost two protons along with two neutrons.

The loss of an alpha particle actually changes the atom to a different element, because the number of protons determines the element.

Polonium-210 is an alpha emitter. During radioactive decay, it loses two protons, and becomes a Lead-206 atom, which is stable or non-radioactive.

What uses do alpha emitters have?

The positive charge of alpha particles is useful in some industrial processes:

- Radium-226 is used in cancer treatment by inserting tiny amounts of radium into the tumorous mass.

- Polonium-210 serves as a static eliminator in paper mills and other industries. The alpha particles, due to their positive charge, attract loose electrons, thus reducing static charge.

- Some smoke detectors use the alpha emissions from Americium-241 to help create an electrical current. The alpha particles strike air molecules within a chamber, knocking electrons loose. The resulting positively charged ions and negatively charged electrons create a current as they flow between positively and negatively charged plates within the chamber. When smoke particles enter the device, they attach to and interrupt the flow of charged particles, breaking the current and setting off the alarm.

How do alpha emitters get into the environment?

Most alpha emitters occur naturally in the environment. For example, alpha particles are given off by Uranium-238, Radium-226, and other members of the uranium decay series. These are present in varying amounts in nearly all rocks, soils and water.

The opportunity for environmental and human exposure increase greatly when soils and rock formations are disturbed by the extraction of minerals.

Uranium mining waste, which includes uranium mill tailings, have high concentrations of uranium and radium. Once brought to the surface, they could become airborne and enter surface water as runoff.

Mining, and current methods for processing phosphate ore for fertilizer, generate large piles or "stacks" of phosphogypsum, in which naturally occurring radium is concentrated.

How do alpha particles change in the environment?

Alpha particles don't get very far in the environment. Once emitted, they travel relatively slowly, at approximately 1/20 the speed of light, due to their electric charge and large mass. They lose energy rapidly in the air, usually expending it within a few centimeters. Because alpha particles are not radioactive, once they have lost their energy, they pick up free electrons and become helium.

Alpha particles also cannot penetrate most matter they encounter. Even a piece of paper, or the dead outer layers of human skin, is sufficient to stop alpha particles.

How can alpha particles affect people’s health?

The health effects of alpha particles depend greatly upon how exposure takes place. External exposure (external to the body) is of far less concern than internal exposure, because alpha particles lack the energy to penetrate the outer dead layer of skin.

However, if alpha emitters have been inhaled, ingested (swallowed) or absorbed into the bloodstream, sensitive living tissue can be exposed to alpha radiation. The resulting biological damage increases the risk of cancer; in particular, alpha radiation is known to cause lung cancer in humans when alpha emitters are inhaled.

The greatest exposure to alpha radiation comes from the inhalation of radon and its decay products, several of which also emit potent alpha radiation.

BETA PARTICLES

Beta particles are sub-atomic particles ejected from the nucleus of some radioactive atoms. They are equivalent to electrons. The difference is that beta particles originate in the nucleus and electrons originate outside the nucleus.

What are the properties of beta particles?

Beta particles have an electrical charge of -1. They have a mass of 549-millionths of one atomic mass unit (or AMU), which is about 1/2,000 of the mass of a proton or neutron. The speed of individual beta particles depends on how much energy they have, and varies over a wide range. It is their excess energy, in the form of speed, that causes harm to living cells. When transferred, this energy can break chemical bonds and form ions.

What happens to beta particles in the environment?

Beta particles travel several feet in the open air and are easily stopped by solid materials. When a beta particle has lost its energy, it is like any other loose electron. Whether in the outdoor environment or in the body, these electrons are then picked up by a positive ion.

How are people exposed to beta particles?

There are both natural and man-made beta-emitting radionuclides. Potassium-40 and Carbon-14 are weak beta emitters that are found naturally in our bodies. Some decay products of radon emit beta particles, but its alpha-emitting decay products pose a much greater health risk.

Beta emitters that eject energetic particles can pose a significant health concern. Their use requires special consideration of both the benefits and their potentially harmful effects.

- Phosphorus-32 and Iodine-131 are two beta emitters used in medical imaging, diagnostic and treatment procedures. For example, people who have taken radioactive iodine will emit beta particles. They must follow strict procedures to protect family members from exposure.

- Radioactive iodine may enter the environment during a nuclear reactor accident, potentially causing agricultural damage and contamination, and eventually find its way into the food supply.

- Industrial gauges and instruments containing concentrated beta-emitting radiation sources can be lost, stolen or abandoned. If these instruments then enter the scrap metal market, or someone finds one, the sources they contain can expose people to beta emitters.

Does it matter how a person is exposed to beta particles?

Yes. Direct exposure to beta particles is hazardous because emissions from strong sources can redden or even burn the skin. However, emissions from inhaled or ingested beta particle emitters are the greater concern. Beta particles released directly into living tissue can cause damage at the molecular level, which can disrupt cell function. Because they are much smaller and have less charge than alpha particles, beta particles generally travel further into tissues. As a result, the cellular damage is more dispersed.

Health Effects of Beta Particles

Beta radiation can cause both acute and chronic health effects. Acute exposures are uncommon. Contact with a strong beta source from an abandoned industrial instrument is the type of circumstance in which acute exposure could occur. Chronic effects are much more common.

Chronic effects result from fairly low-level exposures over a long period of time. They develop relatively slowly, taking five to 30 years to manifest. The main chronic health effect from radiation is cancer. When exposure is internal, beta emitters can cause tissue damage and increase the risk of cancer.

Some beta-emitters, such as Carbon-14, distribute widely throughout the body. Others accumulate in specific organs and cause chronic exposures:

- Iodine-131 concentrates heavily in the thyroid gland. It increases the risk of thyroid cancer and other disorders.

- Strontium-90 accumulates in bone and teeth.

GAMMA RAYS

A gamma ray is a packet of electromagnetic energy -- a photon. Gamma photons are the most energetic photons in the electromagnetic spectrum. Gamma rays or gamma photons are emitted from the nucleus of some unstable (radioactive) atoms.

Who discovered gamma radiation?

French physicist Henri Becquerel is credited with discovering gamma radiation. In 1896, he discovered that uranium minerals could expose a photographic plate through heavy opaque paper. The previous year, a German scientist named Wilhelm Roentgen discovered X-rays, and Becquerel reasoned that uranium emitted some invisible light, similar to X-rays. He called it "metallic phosphorescence." Actually, Becquerel had discovered gamma radiation being emitted by Radium-226, which is part of the uranium decay chain, and commonly occurs with uranium.

What are the properties of gamma radiation?

Gamma radiation is very high-energy ionizing radiation. Gamma photons have about 10,000 times as much energy as the photons in the visible range of the electromagnetic spectrum.

Gamma photons have no mass and no electrical charge -- they are pure electromagnetic energy.

Because of their high energy, gamma photons travel at the speed of light and can cover hundreds to thousands of meters in the air before expending their energy. They can pass through many kinds of materials, including human tissue. Very dense materials, such as lead, are commonly used as shielding to slow or stop gamma photons.

Their wave lengths are so short that they must be measured in nanometers, which are billionths of a meter. They range from 3/100 to 3/1,000 of a nanometer.

How does gamma radiation change in the environment?

Gamma rays travel at the speed of light and exist only as long as they have energy. Once their energy is spent, whether in air or in solid materials, they cease to exist. The same is true for X-rays.

Exposure to Gamma Radiation

Most people's primary source of gamma exposure is naturally occurring radionuclides, particularly Potassium-40, which is found in soil and water, and also meats and high-potassium foods such as bananas. Radium is also a source of gamma exposure. However, the increasing use of nuclear medicine for bone, thyroid and lung scans contributes an increasing proportion of the total for many people. Also, some man-made radionuclides that have been released to the environment emit gamma rays.

How can gamma radiation affect people's health?

Because of the gamma ray's penetration power and its ability to travel great distances, it is considered the primary hazard to the general population during most radiological emergencies. In fact, when the term "radiation sickness" is used to describe the effects of large exposures in short time periods, the most severe damage almost certainly results from gamma radiation.

Most exposure to gamma and X-rays is direct external exposure. Gamma and X-rays can easily travel great distances through air and penetrate several centimeters of tissue. Most of these rays have enough energy to pass through the body, exposing all organs. X-ray exposure is almost always in controlled environments for dental and medical procedures.

Although they are generally classified as an external hazard, gamma-emitting radionuclides can also be inhaled or ingested with water and food, and can cause exposure to internal organs. Depending on the radionuclide, they may be retained in tissue, or cleared via the urine and feces.

Quiz on Sections 6, 7, 8 & 9

_________ is the leading cause of lung cancer.

- Smoking
- Eating
- Radon
- Inhaling RDPs

_________________ is the third leading cause of lung cancer and is responsible for an estimated 3,000 lung cancer deaths every year.

- Second-hand smoke
- Radon
- Smoking
- Bronchitis

The EPA estimates that indoor radon levels will increase by about 1 pCi/L for every 10,000 pCi/L of radon in ______.

- water
- gas
- outdoor air
- indoor air

If there are 30,000 pCi/L of radon in a home's water supply, then ___ pCi/L of the indoor air measurement may have come from radon in the water.

- 3
- 4
- 1,000
- 10

Radon can be removed from water by using one of two methods: aeration treatment, or granular activated- _____ treatment.

- carbon
- hydrogen
- oxygen
- concrete

Section 10: The Geology of Radon

The Geology of Radon

The geology of radon helps explain why radon levels can vary so greatly between indoor air, outdoor air, soil air, groundwater, and even in different homes in the same area.

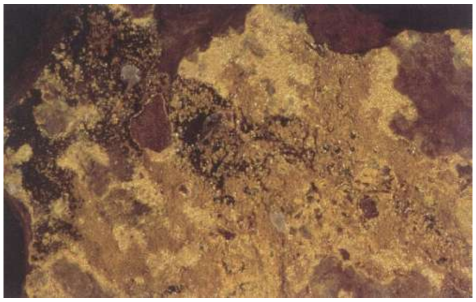
Why do some houses have high levels of indoor radon while nearby houses do not?

The reasons lie primarily in the geology of radon -- the factors that govern the occurrence of uranium, the formation of radon, and the movement of radon, soil gas and groundwater.

Studies of the geology of radon include research into how uranium and radon sources are distributed in rocks and soils, how radon forms in rocks and soils, and how radon moves. Studying how radon enters buildings from the soil and through the water system is also an important part of understanding the geology of radon.

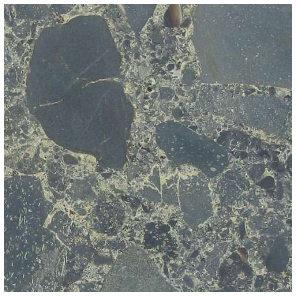
Uranium: The Source

To understand the geology of radon -- where it forms, how it forms, how it moves -- we have to start with its ultimate source: uranium. All rocks contain some uranium, although most contain just a small amount, between 1 to 3 parts per million (ppm). In general, the uranium content of a sample of soil will be about the same as the uranium content of the rock from which the soil was derived.



The bright yellow mineral tyuyamunite is one of the most common uranium-ore minerals. The photo above shows a specimen less than 3 inches wide which came from the Ridenour Mine in Arizona, near the Grand Canyon *(photo by Karen Wenrich).*

Some types of rocks have a higher-than-average uranium content. They include light-colored volcanic rocks, granites, dark shale, sedimentary rocks that contain phosphate, and metamorphic rocks derived from these rocks. These rocks and their soils may contain as much as 100 ppm of uranium. Layers of these rocks underlie various regions in the United States.



above: igneous

above: sedimentary

above: metamorphic

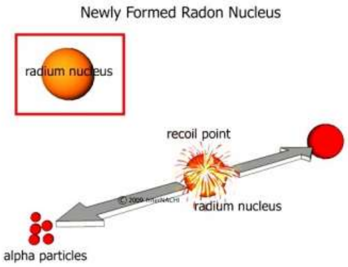
There are three major classifications of rocks: (top) igneous; (center) sedimentary; and (above) metamorphic.

The higher the uranium level is in an area, the greater the chances are that houses in the area have high levels of indoor radon. But some houses in areas with lots of uranium in the soil have low levels of indoor radon, and other houses on uranium-poor soils have high levels of indoor radon. Clearly, the amount of radon in a house is affected by factors in addition to merely the presence of uranium in the underlying soil.

Radon's Formation

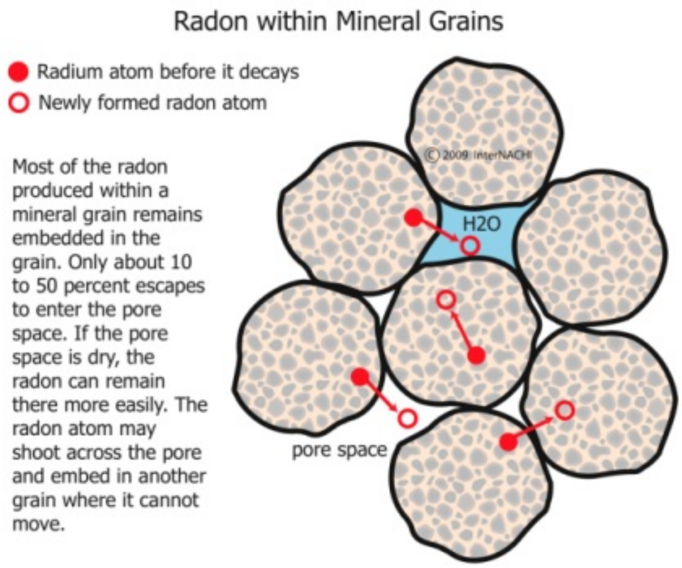
Just as uranium is present in all rocks and soils, so, too are radon and radium, because they are daughter products formed by the radioactive decay of uranium.

Each atom of radium decays by ejecting from its nucleus an alpha particle composed of two neutrons and two protons. As the alpha particle is ejected, the newly formed radon atom recoils in the opposite direction, just as a high-powered rifle recoils when a bullet is fired. Alpha recoil is the most important factor affecting the release of radon from mineral grains.



A radium atom decays into radon by releasing an alpha particle, containing two neutrons and two protons, from its nucleus.

The location of the radium atom in the mineral grain (how close it is to the surface of the grain), and the direction of the recoil of the radon atom (whether it is toward the surface or toward the interior of the grain) determine whether or not the newly formed radon atom enters the pore space between mineral grains. If a radium atom is deep within a big grain, then, regardless of the direction of recoil, it will not free the radon from the grain, and the radon atom will remain embedded in the mineral. Even when a radium atom is near the surface of a grain, the recoil will send the radon atom deeper into the mineral if the direction of recoil is toward the grain's core. However, the recoil of some radon atoms near the surface of a grain is directed toward the grain's surface. When this happens, the newly formed radon leaves the mineral and enters the pore space between the grains or the fractures in the rocks.



Most of the radon produced within a mineral grain remains embedded in the grain. Only about 10 to 50 percent escapes to enter the pore space. If the pore space is dry, the radon can remain there more easily. The radon atom may shoot across the pore and embed in another grain where it cannot move.

The recoil of the radon atom is quite strong. Often, newly formed radon atoms enter the pore space, cross all the way through the pore space, and become embedded in nearby mineral grains. If water is present in the pore space, however, the moving radon atom slows very quickly and is more likely to stay in the pore space.

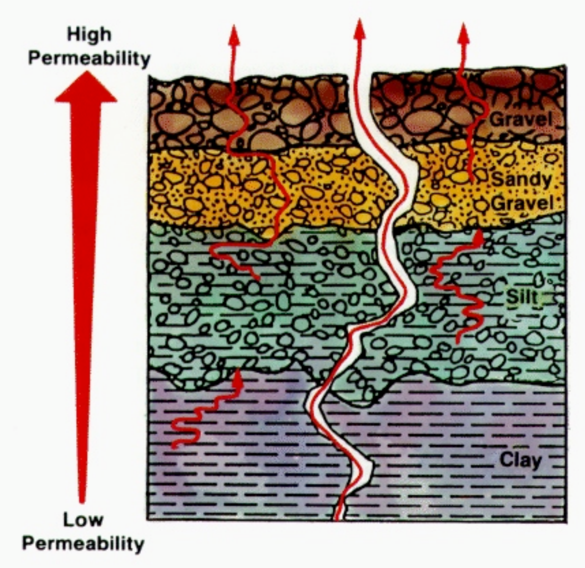
For most soils, only 10 to 50% of the radon produced actually escapes from the mineral grains and enters the pores. Most soils in the United States contain between 0.33 to 1 pCi of radium per gram of mineral matter, and between 200 to 2,000 pCi of radon per liter of soil air.

Radon's Movement

Because radon is a gas, it has much greater mobility than uranium and radium, which are fixed in the solid matter of rocks and soils. Radon can more easily leave the rocks and soils by escaping into fractures and openings in rocks and into the pore spaces between grains of soil.

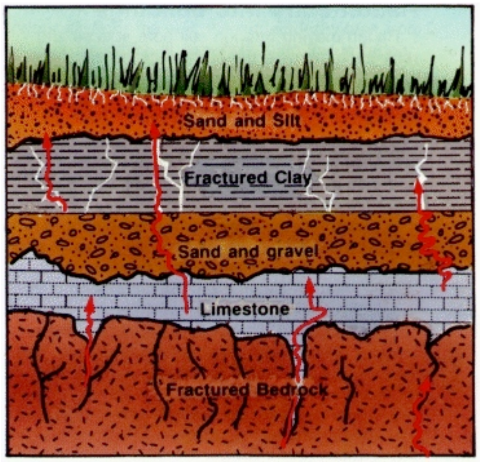
The ease and efficiency with which radon moves in the pore space or fracture affect just how much radon enters a house. If radon is able to move easily in the pore space, then it can travel a great distance before it decays, and it is more likely to collect in high concentrations inside a building.

The method and speed of radon's movement through soils are controlled by the amount of water present in the pore space (the soil's moisture content), the percentage of pore space in the soil (the porosity of the soil), and the "interconnectedness" of the pore spaces that determines the soil's ability to transmit water and air (called soil permeability).



Radon can move through cracks in rocks and through pore spaces in soils.

Radon moves more rapidly through permeable soils, such as coarse sand and gravel, than through impermeable soils, such as clays. Fractures in any soil or rock allow radon to move more quickly.



Some radon atoms remain trapped in the soil and decay to form lead; other atoms escape quickly into the air.

Radon in water moves slower than radon in air. The distance that radon moves before most of it decays is less than 1 inch in water-saturated rocks and soils, but it can move more than 6 feet, and sometimes tens of feet, through dry rocks and soils. Because water also tends to flow more slowly through soil pores and rock fractures than does air, radon travels shorter distances through wet soils than through dry soils before it decays.

For these reasons, homes in areas with drier, highly permeable soils and bedrock, such as hill slopes, mouths and bottoms of canyons, coarse glacial deposits, and fractured or cavernous bedrock, may have high levels of indoor radon. Even if the radon content of the air in the soil or fracture is within the "normal" range (200 to 2,000 pCi/L), the permeability of these areas permits radon-bearing air to move greater distances before it decays, and thus contributes to high indoor radon.

Radon Entry Into Buildings

Radon moving through soil pore spaces and rock fractures near the surface of the earth usually escapes into the atmosphere. Where a house is present, however, soil air often flows toward its foundation for three reasons:

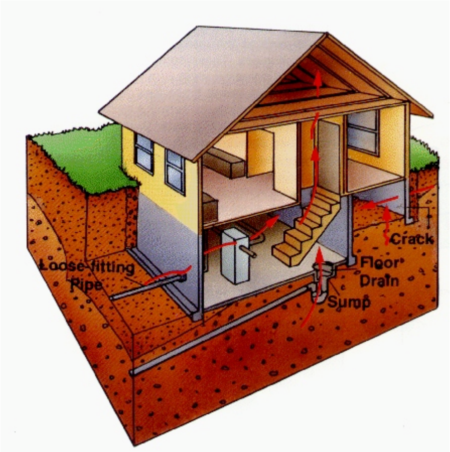
1) differences in air pressure between the soil and the house;
2) the presence of openings in the house's foundation; and
3) increases in permeability around the basement (if one is present).

In constructing a house with a basement, a hole is dug, footings are set, and coarse gravel is usually laid down as a base for the basement slab. Then, once the basement walls have been built, the gap between the basement walls and the ground outside is filled with material that often is more permeable than the original ground. This filled gap is called a "disturbed zone."

Radon moves from the surrounding soil into the disturbed zone and the gravel bed underneath. The backfill material in the disturbed zone is commonly made up of rocks and soil from the foundation site. These also generate and release radon. The amount of radon in the disturbed zone and gravel bed depends on the amount of uranium present in the rock at the site, the type and permeability of soil surrounding the disturbed zone and underneath the gravel bed, and the soil's moisture content.

The air pressure in the ground around most houses is often greater than the air pressure inside the house. Thus, air tends to move from the disturbed zone and gravel bed into the house through openings in the house's foundation. All house foundations have openings, such as cracks, utility entries, seams between foundation materials, and uncovered soil in crawlspaces and basements.

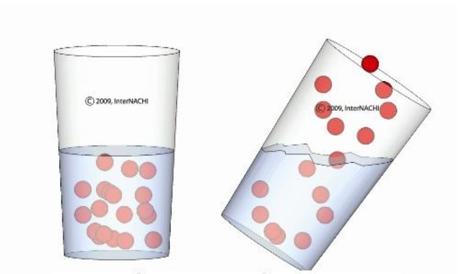
Most houses draw less than 1% of their indoor air from the soil; the remainder comes from outdoor air, which is generally quite low in radon. Houses with low indoor air pressures, poorly sealed foundations, and several entry points for soil air, however, may draw as much as 20% of their indoor air from the soil. Even if the soil air has only moderate levels of radon, levels inside the house may be very high.



Radon in Water

Radon can also enter the home through its water system. Water from rivers and reservoirs usually contains very little radon because it escapes into the air, so homes that rely on surface water usually do not have a radon problem from the water. In big cities, water processing in large municipal systems aerates the water, which allows radon to escape, and also delays the use of water until most of the remaining radon has decayed.

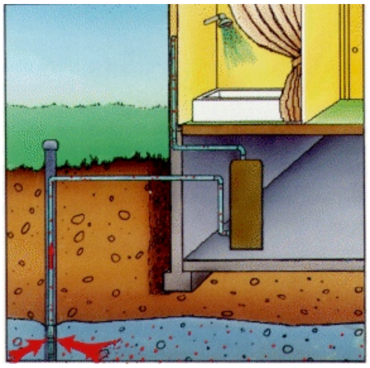
In many areas of the country, however, groundwater is used as the main water supply for homes and communities. These small public water works and private domestic wells often have closed systems and short transit times that do not remove radon from the water or permit it to decay. This radon escapes from the water to the indoor air as people take showers, wash clothes, do the dishes, and use water in general. A rule of thumb for estimating the contribution of radon from domestic water to the indoor level of airborne radon is that water with 10,000 pCi/L of radon contributes about 1 pCi/L to the level of radon in the indoor air.



Radon escapes from water when it is agitated.

The areas most likely to have problems with radon in groundwater are areas that have high levels of uranium in the underlying rocks. For example, granites in various parts of the United States are sources of high levels of radon in groundwater that is supplied to private water supplies.

In areas where the main water supply is from private wells and small public water works, radon in groundwater can add radon to the indoor air.

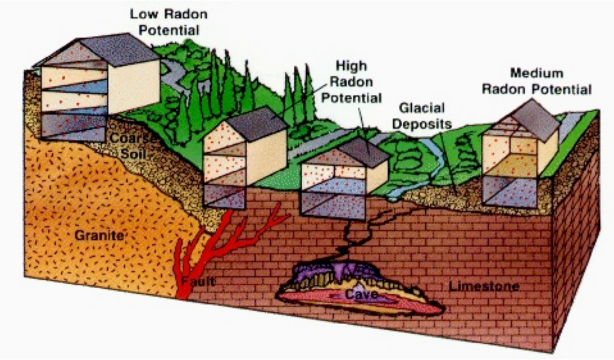


Radon Potential

One can get an idea as to how great a concern radon may be in a house by learning about the geology of the surrounding site, along with the area's radon potential. If a house is in an area with a high potential for radon, then chances are that the house may have an indoor radon problem. However, as we have learned, the way a house is built can increase the risk, so even in areas of low radon potential, some houses can have unhealthy radon levels.

Scientists evaluate the radon potential of an area and create a "radon potential" map by using a variety of data. The data include the uranium or radium content of the soil and underlying rocks, and the permeability and moisture content of the soil. Other related sources of information, such as geologic maps, maps of surface radioactivity, and soil maps, are used.

Another type of information that scientists use in determining the radon potential of an area is radon measurements of local soil air. Existing indoor radon data for homes are also useful. The data are the most direct information available about indoor radon potential, even though the houses that have been sampled may not be typical for the area, and information for the exact locations of measured houses is seldom available to the public.



Knowing the types of rock and soil at a site helps a geologist determine its radon potential.

Sources of Information on Radon Potential

Soil Surveys

The U.S. Department of Agriculture's Natural Resources Conservation Service (formerly the U.S. Soil Conservation Service), in cooperation with state and county extension offices, prepare and publish soil surveys. Other soil data from surficial (or near-surface) geologic and engineering maps are prepared and published by geoscience agencies. Many published soil surveys are available in local libraries.

Modern soil surveys include information on the physical properties and permeability data for the mapped soils at varying depths. In older soil reports, no permeability data are given, and soil names and statements regarding internal drainage must be used to estimate permeability.

Indoor Radon Data

State health departments, local agencies of environmental protection, and county and municipal health departments and districts often have data on indoor radon, which they make available to the public in summary form.

Geologic Maps

A geologic map shows the types of rocks and geologic structures in a specific area. Because different types of rocks have different amounts of uranium, a geologic map can tell a geologist the general level of uranium or radium s/he can expect to find in the rocks and soils in the area. Such maps are especially important in showing where rocks with high levels of uranium occur.

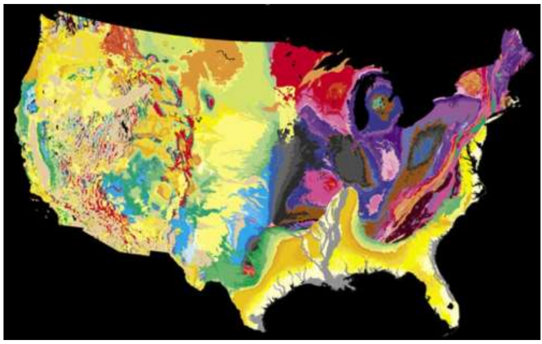
Because radon that enters buildings usually comes from several feet of the earth's top-most surface, knowing the radon levels of the surficial materials is important. Surficial geologic and engineering maps show and describe these surface materials for many regions of the United States. These maps are useful for understanding the physical properties of the materials at the surface, such as permeability, but are generally not as useful for determining what the uranium concentrations in the surface materials might be.

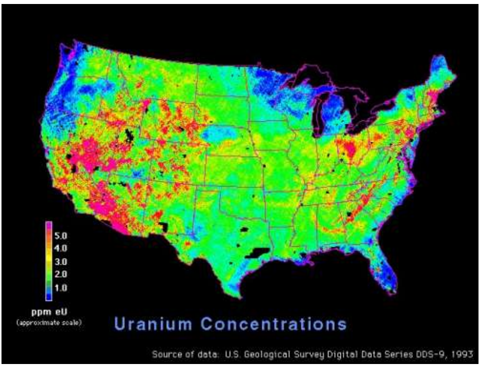
Local geologic maps are often available at:

- the U.S. Geological Survey;
- U.S. Army Corps of Engineers;
- state geological agencies;
- colleges and universities, and their libraries;
- public libraries; and
- county assessors' offices.

Radioactivity Maps

Radioactivity maps give an indication of the uranium levels of surface materials. The most common type of radioactivity map is an aero-radioactivity map, which is based on radioactivity measurements taken by aircraft flying at low altitude using instruments that measure the radioactive energy being emitted from the ground.





Source of data: U.S. Geological Survey Digital Data Series DDS-9, 1993

There is a strong correlation between areas identified on aero-radioactivity maps as having high levels of surface uranium and areas for which high levels of indoor radon have been reported. In some parts of the country, swamps and marshes are abundant and, in many of these areas, the soils at the surface are full of water, which blocks the radiation of energy. The average amount of radiated energy detected for these areas is lower than it would be if the soils were dry. The uranium content of the soils and the radon potential are likely to be underestimated in these areas.

A large amount of aero-radioactivity data was collected as part of a U.S. Department of Energy program to evaluate the uranium resources of the United States. Most of the energy detected during these flights was from rocks and soils within 800 feet of flight lines that were spaced 1 to 6 miles apart. Many major metropolitan areas were not covered by the survey because of flight restrictions. Therefore, only a small part of the entire surface of the United States was measured. The data from this survey, however, give a good indication of the background uranium concentration of soils and rocks underlying most of the United States.

The digital data from the survey were processed by the U.S. Geological Survey to produce a map showing the uranium content of surface materials in the conterminous United States (the lower 48 states). The smallest data point on the map covers an area of about 1.6 square miles, limiting the amount of detail that can be seen. It is possible to tell how parts of a region, a state, or even a county vary in surface uranium concentration, but it's impossible to tell how the presence of uranium varies from neighborhood to neighborhood or from house to house.

The U.S. Geological Survey and state geological agencies prepare and publish radioactivity maps.

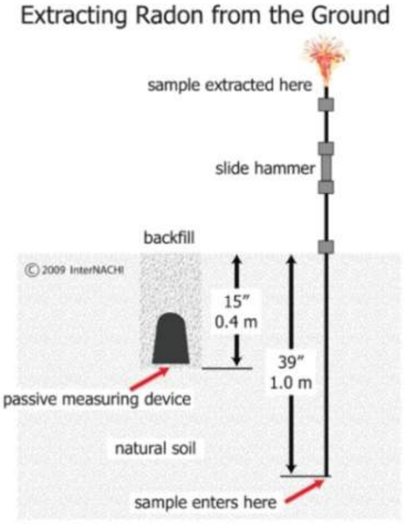
Soil-Air Radon Data

Scientists also measure radon in soil air. Data on this give direct evidence about soil radon, but extensive numbers are not commonly available. The two basic methods for measuring the radon concentration of soil air are the same as those used to measure radon in buildings. Both methods measure the alpha particles produced by the decay of the radon in the air.

One method involves burying a passive device, such as a charcoal canister or an alpha-track detector, in the soil, and leaving it open to the soil air. This method allows long-term measurements, but the devices can be affected strongly by soil moisture. In the other method, a sample of soil air is collected from a probe driven into the ground, and the radon in the sample is measured by using electronic equipment. This method provides data quickly, but these short-term measurements may vary greatly due to daily, weekly, and even seasonal changes in soil and atmospheric conditions that are averaged out during long-term measurements.

A scientist collects samples of soil air to determine its radon content.

Soil-air methods require specialized equipment because soil-air data are sensitive to many conditions and factors, such as the depth of measurement. Radon levels differ widely in the top 2 to 3 feet of soil because of variations in soil moisture and the amount of radon that escapes into the atmosphere. Taking measurements at 3 feet or deeper avoids many of the problems related to near-surface conditions, but it may be difficult in some soils.



Indoor Radon Data

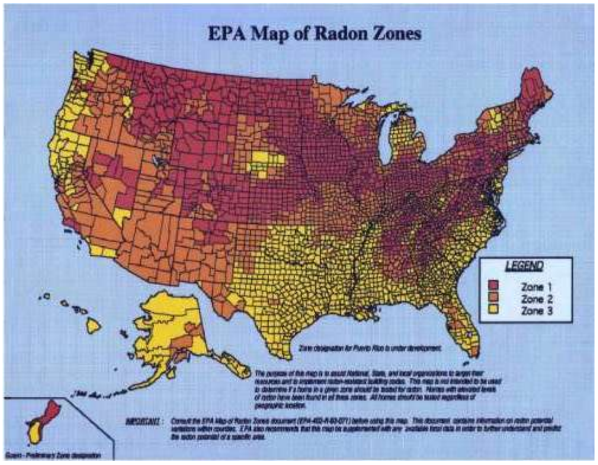
Indoor radon has been measured in many houses, schools and commercial buildings across the United States. For the most part, these measurements have been made by private homeowners using passive detection devices. Radon concentrations in some homes and businesses are measured by private companies as part of real estate transactions. Many local, state and federal agencies measure radon in buildings for which they are responsible.

Most indoor radon measurements are confidential transactions between homeowners and measurement vendors. The data from these private measurements are not generally available to the public. When they are available, the data are usually given as summaries by state, county or zip code. Nonetheless, these summaries are useful in determining which areas of the counties, states or entire regions of the United States seem likely to have elevated indoor radon levels.

By careful examination and correlation, scientists can evaluate the effects of varying geology and soils on actual readings of indoor radon. The indoor radon information can be used as an additional aid to create a radon potential map, or it can be used as a way of expressing the radon potential of areas mapped by the geologist. However, differences in house construction also can contribute to variations in the indoor radon levels.

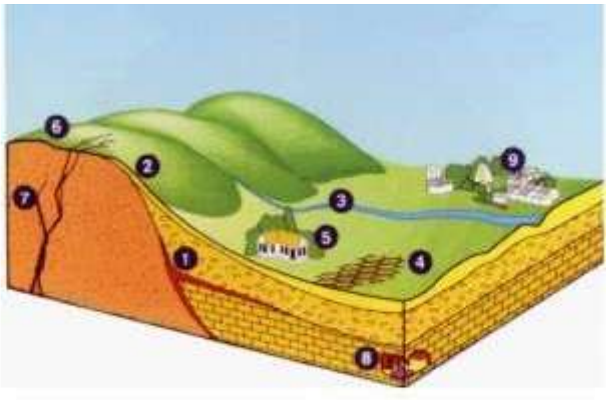
Radon Potential Maps

Scientists create radon potential maps by combining a variety of data, such as the locations of rocks containing high levels of uranium, locations of fractures, aero-radioactivity data, soil data on permeability and radon content, and indoor radon data. Not all of these types of data are available for every area, and radon potential maps for different areas may vary if they are based on different types of data.



Evaluating Radon Potential

Again, by knowing something about the geology and soils of the area, scientists can evaluate the radon potential for the rocks and soils of housing sites and areas of interest. These factors can increase the probability that an area will have above-average areas of radon.



1. Uranium-rich rocks occur in the area.
2. Highly permeable soils are present.
3. Soils are well-drained or dry most of the time.
4. Soils form deep cracks during dry times of the year.
5. The site is located on a hill or slope.
6. The soils are thin, and bedrock is close to the surface.
7. Underlying rocks are fractured.
8. The underlying rock contains limestone caverns.
9. High levels of indoor radon have been reported in the county or neighborhood.

Section 11: Radon Entry into a House

Radon Entry into a House

Common Radon Entry Points

There are four main factors that permit radon to seep into homes. All homes have some type of radon-entry pathway:

1. Uranium is present in the soil nearly everywhere in the United States.

2. The soil is permeable enough to allow radon to migrate into a home through the slab, basement or crawlspace.

3. There are pathways for radon to enter the basement, such as small holes, cracks, plumbing penetrations and sump pumps.

4. A difference in air pressure between the basement or crawlspace and the surrounding soil draws radon into the home.

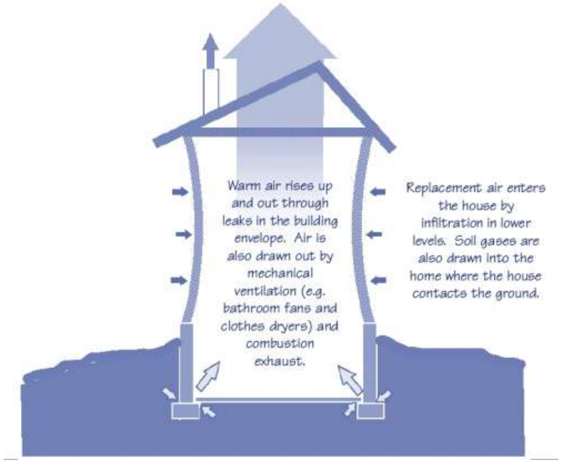
Radon enters through:

1. cracks in otherwise solid floors;
2. gaps in suspended floors;
3. cracks in walls;
4. cavities inside walls;
5. gaps around service pipes;
6. construction joints; and
7. the water supply.

How does air pressure affect radon entry?

The air pressure in a house is generally lower than in the surrounding air and soil, particularly at the basement and foundation levels. This difference in pressure causes a house to act like a vacuum, drawing in air containing radon, as well as other soil-gases, through cracks in the foundation and other openings. Some of the replacement air comes from the underlying soil and can also contain radon.

One reason this pressure difference occurs is because exhaust fans remove air from inside the house. When this air is exhausted, outside air enters the house to replace it. Another cause for a pressure difference is that warm air rises and will leak from openings in the upper portion of the house when temperatures are higher indoors than outdoors. This condition, known as a stack effect, causes unconditioned replacement air to enter the lower portion of the house.



Does foundation type affect radon entry?

Because radon can literally be sucked into a home, any home can potentially have a radon problem. All conventional house construction types have been found to have radon levels exceeding the action level of 4 pCi/L.

Basement

Radon can enter through floor-to-wall joints, control joints and cracks in the slab.

Crawlspace

The vacuums that exist within a home are exerted in the crawlspaces, causing radon and other gases to enter the home from the earthen area below. Even with crawlspace vents, a slight vacuum is still exerted in the crawlspace. Measurements of homes with crawlspaces have shown elevated radon levels.

Slab-on-Grade

Radon can enter a home regardless of whether it has a basement. Slabs built on grade can have just as many openings to allow radon to enter as do basements.

Manufactured Homes

Unless these buildings are set up on piers without any skirting placed around them, interior vacuums can cause radon to enter these types of homes, as well.

Can radon be kept out by sealing all the cracks?

Sealing large cracks and openings is important when sealing a home, both in the lower portion of the home to reduce radon entry points, and in the upper portion of the home to reduce stack effect. However, field research has shown that attempting to seal all of the openings in a foundation is both impractical and ineffective as a stand-alone technique. Radon can enter through very small cracks and openings, and they can be too small to locate and effectively seal. Even if all cracks could be sealed during construction, which would be costly, building settlement may cause new cracks to occur. Therefore, sealing large cracks and openings is one of the key components of radon-resistant construction, but it's not the only technique that should be employed.

1. Install a sub-slab or sub-membrane depressurization system.

The objective of these systems is to create a vacuum beneath the foundation, which is greater in strength than the vacuum imposed on the soil by the house itself. The soil-gases that are collected beneath the home are piped to a safe location to be vented directly outdoors.

Usually, a 4-inch layer of clean, coarse gravel is used beneath the slab to allow the soil gas to move freely underneath the house. Other options include installing a loop of perforated pipe or a soil-gas collection mat (also known as drainage mat or soil-gas matting).

2. Use mechanical barriers to prevent soil-gas entry.

Plastic sheeting and foundation sealing and caulking can serve as barriers to radon entry, as well as the entry of other soil gases, and, of course, moisture.

Polyethylene sheeting should be placed on top of the gas-permeable layer to help prevent the soil gas from entering the home. The sheeting also keeps concrete from clogging the gas-permeable layer when the slab is poured.

Sealing and caulking help reduce stack effect, and thus reduce the negative pressure in lower levels of the home. Also, sealing and caulking the rest of the building envelope reduce the stack effect in the home.

3. Install air-distribution systems so that soil air is not mined.

Simply adding the vent pipe and junction box is extremely effective for reducing radon, and it's so cost-effective that even Habitat for Humanity, which relies on donations and grants for its funding, has been adding these features in many of its homes. An electrical junction box is wired in case an electric venting fan is needed later to activate the system.

A 3- or 4-inch PVC or other gas-tight pipe (commonly used for plumbing) should be installed and run from the gas-permeable layer through the house and roof to safely vent radon and other soil gases above the house. Although some builders use 3-inch pipe, field results have indicated that passive systems tend to function better with 4-inch pipe.

Air-handling units and all ducts in basements, especially in crawlspaces, should be sealed to prevent air and radon from being drawn into the system. Seamless ducts are preferred for runs through crawlspaces and beneath slabs. Any seams and joints in ducts should be sealed.

What pulls the soil gas through the pipe?

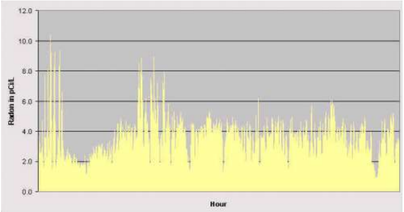
If the pipe is routed through a warm space (such as an interior wall or the furnace flue chase, following local fire codes), the stack effect can create a natural draft in the pipe. Because this method requires no mechanical devices, it is considered a passive soil-depressurization system.

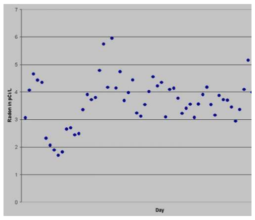
If further reduction is necessary to bring radon levels in a home below the action level of 4 pCi/L, an in-line fan can be installed in the pipe to activate the system. The system is then considered an active soil-depressurization system. The future installation of the fan can be made easier with a little planning during construction.

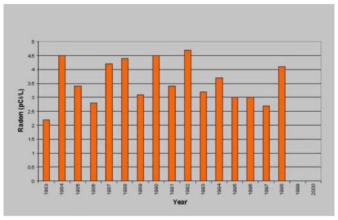
Radon gas is approximately 7½ times heavier than air. It is a "noble" gas with no chemical affinity, but it is influenced by air movements and pressure. In a house with forced-air heating and cooling, radon gas can be easily distributed throughout the entire dwelling. When radon gas is discharged via a radon mitigation system above the roof, the radon concentration depletes dramatically with distance from the point of discharge. In fact, the radon gas concentration approaches background levels at 3 to 4 feet from the discharge point. The EPA disallowed ground-level discharge of radon primarily because of the potential for re-entrainment of the gas into the house, and because of the possibility of children being exposed to high radon levels. The concentration of radon gas at the discharge point can be tens of thousands of picocuries per minute.

Daily Variations Inside a House

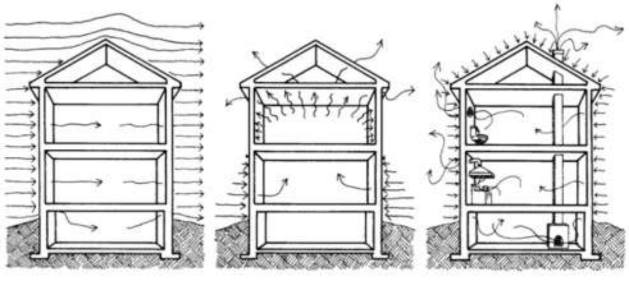
Indoor radon levels depend upon a number of variables and can fluctuate significantly from day to day. Short-term tests (particularly tests between two to five days) may, in some cases, reflect an unusual peak in the radon concentration, thus indicating a need for remedial action which may not actually be necessary.







Pressure and temperature differentials, weather conditions such as wind and rain, and the operation of mechanical equipment all contribute to fluctuating levels of radon inside a house. During cold-weather seasons with closed-house conditions, elevated radon levels can be found in the lowest level of the house.



Air pressure inside a home is usually lower than air pressure in the soil around the home's foundation. Because of this difference in pressure, the house acts like a vacuum, drawing radon in through foundation cracks and other openings.

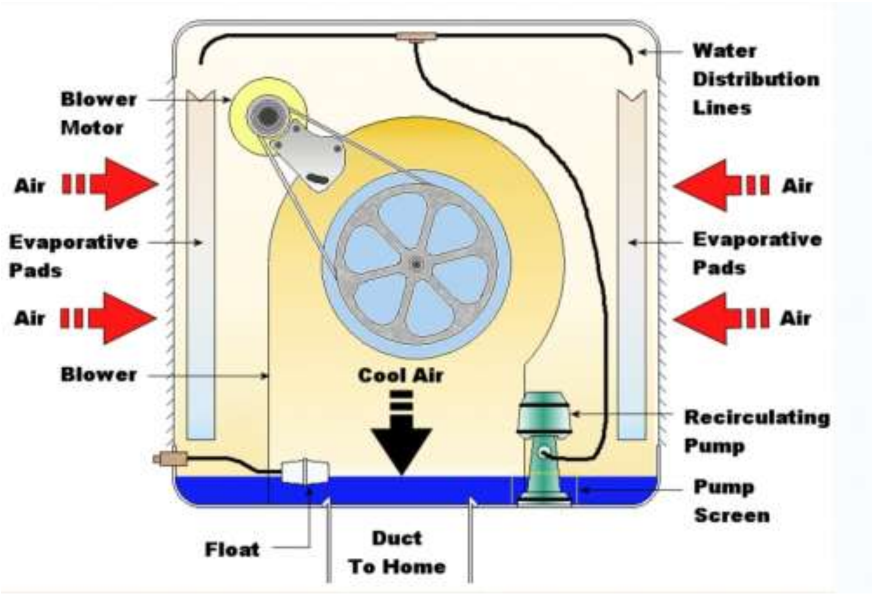
A house sucks in air like a vacuum.

Radon entry by air pressure from below grade is the main way radon enters a house. When air exits a house, air-pressure differentials between the indoors and outdoors are created.

Wind-induced pressure differentials acting on a structure's shell may affect both radon entry into the structure, and indoor radon displacement that exits the structure, depending on the wind speed, direction, frequency, wave span, and the structure's features. Wind blowing directly toward a side of a structure may cause an increase in pressure at the structure's wall in order to conserve the change in momentum initiated by the change of wind velocity from the free stream area to almost zero at the wall-side.

The most significant convective component of radon transport from the sub-structure area into the interior, and from the interior to the outdoors, is due to the pressure-driven air-flow processes. Mechanisms which generate air-pressure gradients depend on environmental and indoor operational factors. The environmental factors that induce pressure differences include temperature differences, wind, meteorological conditions, and atmospheric pressure changes. The indoor operational factors can be divided into human- and non-human-induced indoor operational factors. The non-human factors result from mechanically induced pressurization or depressurization of the indoor environment by household appliances, as well as by heating, ventilation and air-conditioning (HVAC) systems. Human-induced indoor operational factors are characterized by effects such as opening windows and doors.

Evaporative or Swamp Coolers



Evaporative or swamp coolers can affect indoor radon levels. A swamp cooler brings air into the house using a blower fan. The cooler pressurizes the building's interior with positive pressure. This lowers the indoor radon level. Evaporative coolers should not be operated during short-term radon measurements.

Quiz on Sections 10 & 11

T/F: All rocks contain some uranium, although most contain just a small amount -- between 1 to 3 ppm (parts per million) -- of uranium.

- True
- False

Houses with low indoor air pressure, poorly sealed foundations, and several entry points for soil air may draw as much as _____% of their indoor air from the soil.

- 20
- 52
- 78
- 100

The air pressure in a house is generally _____ the air pressure in the surrounding air and soil, particularly at the basement and foundation levels.

- lower than

- higher than
- equal to
- damper than

T/F: Radon can enter a home regardless of whether there is a basement, because slabs built on grade can have just as many openings as basements do to allow radon to enter.

- True
- False

Radon gas is approximately ____ times heavier than air.

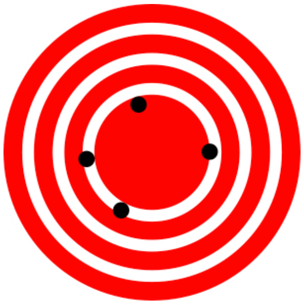
- 7?
- 20?
- one-half
- 2

Section 12: Radon Measurement: General Discussion

Accuracy and Precision of a Radon Test

The precision of a radon test is measured by quality-control tests called "duplicates."

Accuracy is the degree of closeness of a measured or calculated quantity to its actual or true value. Accuracy is closely related to precision, also called reproducibility or repeatability, which is the degree to which further measurements will show similar results. The result of a measurement can be accurate but not precise, precise but not accurate, neither or both. A measurement is considered valid if it is both accurate and precise.



Accuracy refers to the degree of validity, while precision refers to the degree of reproducibility. The analogy used here to explain the difference between accuracy and precision is this target comparison. In this analogy, repeated measurements are compared to the arrows that are shot at the target. Accuracy describes the closeness of the arrows to the bull's-eye at the target's center. Arrows that strike closer to the bull's-eye are considered more accurate. The closer a system's measurements are to the accepted value, the more accurate the system is considered to be.

To continue the analogy, if a large number of arrows is shot, precision would be determined by the size of the arrows' cluster. (When only one arrow is shot, precision refers to the size of the cluster one would expect if this were repeated many times under the same conditions.) When all the arrows are grouped tightly together, the cluster is considered precise because all the arrows struck close to the same spot, if not necessarily near the bull's-eye. The measurements, therefore, are considered precise, though not necessarily accurate.

Radon Measurement Duration

Radon levels in a home or building can vary significantly over time. In fact, it is not uncommon to see radon levels in a home change by a factor of two to three over a one-day period. Variations from season to season can be even larger. The highest radon levels are usually observed during winter months. As a result, a long-term measurement period will give a much better indication of the annual average radon concentration than measurements of shorter duration. Long-term measurements are typically three to 12 months in duration. During this type of measurement, there are no requirements for the occupants to change their lifestyle once the measurement devices have been put in place. Health Canada recommends that a radon test performed in a home or public building be a long-term measurement. Health Canada does not recommend a test of duration less than one month. A minimum of three months is recommended, and 12 months is optimum.

In rare cases, a more rapid indication of the radon concentration may be required. Under such circumstances, a short-term measurement of less than three months' duration (more typically two to seven days) can be performed. However, short-term measurements should be used with caution. Testing durations of less than two days (48 hours) are never acceptable to determine radon concentrations for purposes of assessing the need for mitigation. Since radon concentrations vary over time, it is strongly recommended that the result of any short-term measurement be confirmed with a follow-up long-term measurement. The follow-up measurement should be made at the same location as the initial measurement. A single, short-term measurement does not provide sufficient data on which to base a decision to mitigate. In such cases, a follow-up measurement is always necessary for mitigation decision-making, regardless of the initial measurement result.

Long-Term Tests

Long-Term Radon Measurement Devices

There are several radon measurement devices that may be used to test a home or building for radon. These devices fall into two broad categories: those used for long-term measurements (testing period of three to 12 months in duration); and those designed for short-term measurements (testing period of less than three months and, more typically, between two to seven days).

Alpha-Track Detector

These detectors use a small piece of special plastic or film inside a container with a filter-covered opening. Air being tested diffuses (a passive detector), or it is pumped (an active detector) through a filter covering a hole in the container. When alpha particles from radon and its decay products strike the detector, they cause damage tracks. At the end of the test period, the container is sealed and returned to a laboratory for reading. The laboratory counts the damage marks (tracks) left by the alpha particles. The radon exposure duration of an alpha-track detector is usually one to 12 months.

Alpha-track devices are relatively inexpensive. They are convenient to handle and use. They can be distributed by mail. They are small and not cumbersome to set up in a house. They do not need electrical power. They can be used for long-term tests.

Electret Ion Chamber

This device consists of a special plastic canister (the ion chamber) containing an electrostatically-charged disk detector or electret. The detector is exposed during the measurement period, allowing radon to diffuse through a filter-covered opening into the chamber. The radon decays. The RDPs release alpha, beta and gamma radiation. The radiation produces ions and electrons. The electrons are attracted to a positively charged electret disk. Ionization resulting from the decay of radon produces a reduction in the charge on the electret. The drop in voltage on the electret is related to the radon concentration. The change in the voltage is calculated to an average radon concentration for the testing time period.

The detectors may be read in the home using a special analysis device to measure the voltage, or it may be mailed to a laboratory for analysis. The electret voltages are measured before and after deployment. There are two types of chambers. The large chambers are used for short-term measurement tests. The small chambers are used for long-term tests. This type of detector may be deployed for one to 12 months.

Digital Continuous Radon Monitor

This detector plugs into a standard wall outlet much like a consumer-grade carbon monoxide detector, and it continuously monitors for radon. It is a passive device based on an ion chamber. It allows the homeowner to take radon measurements in different areas of the home. After being plugged in for an initial period of 48 hours, the device displays the average radon concentration continuously.

Short-Term Tests

Short-Term Radon Measurement Devices

Activated Charcoal Adsorption

These devices utilize an airtight container filled with activated charcoal and covered with a screen and filter. The detector is opened in the area to be sampled and exposed to the air for a specified period of time. Radon present in the air adsorbs onto the charcoal, which is a process by which gases or vapors condense to create a thin film. At the end of the sampling period, the container is sealed and then sent to a laboratory for analysis using a scintillation detector. Charcoal detectors may be subject to effects from drafts and high humidity. These detectors are normally deployed for measurement periods of two to seven days.

Charcoal Liquid Scintillation

This method is very similar to the activated charcoal detector in that it employs a small vial of activated charcoal for sampling the radon. Following exposure, the vial is sealed and returned to a laboratory for analysis by treating the charcoal with a scintillation fluid, then the fluid is analyzed using a scintillation counter. These detectors are also deployed for periods between two to seven days.

Electret Ion Chamber

This is the same device described for long-term tests. However, variations in the design of the electret allow for a short-term measurement as well. The short-term electret ion chamber is deployed for two to seven days.

Continuous Radon Monitoring

This device measures radon and produces results in pCi/L. This detection category includes devices that record real-time, continuous measurements of radon gas over a series of minutes, and then report the results in hourly increments. Air is either pumped (in active mode) or diffuses into a counting chamber (in passive mode), which is typically a scintillation cell or ionization chamber. The RDPs are filtered out. Alpha particles are counted from radon (active mode) or radon and its RDPs (passive mode). The result using this type of detector is normally available at the completion of the test in the home or building without additional processing or analysis. These detectors are usually deployed for a minimum of 48 hours.

When an alpha-scintillation cell is used, the room air is continuously collected in a scintillation cell, and the RDPs are filtered out. The alpha particles cause the cell's scintillation material coating to release light. The "glows" are then counted by a photo-multiplier tube.

When a pulsed ion chamber is used, the ions are created from the alpha radiation. The ions are detected by the electrometer. The test produces results in short-term averages.

When a solid-state silicon detector is used, the alpha particles from the radon and its RDPs impact a silicon chip. The impacts produce electrical pulses. The pulses are measurable and counted. The counts are averaged. This test is passive only. It needs a power supply, and it has relatively low efficiency.

Continuous Working Level Monitoring

These devices record real-time continuous measurement of the radioactive decay products of radon in the air. Radon decay products are sampled by continuously pumping air through a filter. Alpha particles from the decay of products trapped on the filter are counted to determine the concentration of radon decay products in the air sampled. Continuous working-level monitors should be deployed for a minimum of 48 hours.

Specialized Measurement Devices

A number of other specialized measurement methods are also available for radon testing. However, they all require a skilled technician and/or specialized analytical equipment to achieve proper sampling results. These requirements tend to make these measurement methods more expensive than those previously described, and thus they are not commonly used for radon testing in homes or public buildings. Instead, these methods find greater application in research work or to evaluate the success of radon reduction efforts. A list of these methods is provided for information purposes. The methods listed may only be used for short-term measurements. These devices include:

1. grab-radon/activated charcoal;
2. grab-radon/pump-collapsible bag;
3. grab-radon/scintillation cell;
4. three-day integrating evacuated scintillation cell;
5. pump-collapsible bag (one-day);
6. grab working-level; and
7. radon progeny (decay product) integrating sampling unit.

Action Levels, Mitigation and Water

Radon and the EPA

In 1986, the United States Environmental Protection Agency recommended that all homes be tested for radon. In 1987, the National Institute for Occupational Safety and Health recommended that exposure for underground miners be reduced from 4 WLM to 1 WLM per year. In 1988, the U.S. Congress enacted the Indoor Radon Abatement Act, which set a national goal for the reduction of radon in buildings compared to the ambient level of outdoor air.

As a result, the EPA set an action level of 4 pCi/L for indoor radon. The EPA recommends that if radon is found above 4 pCi/L, those levels should be mitigated. There is still some risk at a level below 4 pCi/L, and the EPA suggests that people may want to mitigate their homes to get them as close to the ambient outdoor level as possible. Outdoor air has an average of approximately 0.4 pCi/L.

Other countries have adopted different action levels. The following chart lists some of these international action levels.

International Comparison of Radon Action Levels

Country	Existing Dwellings	New Buildings
Canada	200 Bq/m^3 (5.4 pCi/L)	
Finland	22 pCi/L	5 pCI/L
Germany	8 pCI/L	8 pCI/L
Ireland	5 pCI/L	5 pCI/L
Norway	22 pCI/L	5 pCI/L
Sweden	11 pCI/L	4 pCI/L

Spain	11 pCI/L	5 pCI/L
Switzerland	5 pCI/L	
United Kingdom	5 pCI/L	5 pCI/L
United States	4 pCI/L	4 pCI/L

Canada

Recent research by Health Canada estimates that 16 per cent of lung cancer deaths among Canadians are attributable to indoor radon exposure, making radon gas the second leading cause of lung cancer after tobacco smoking. Action to reduce the radon level should be taken in a home whenever the average annual radon concentration exceeds 200 Bq/m^3 and the radon level should be reduced to a value as low as practicable.

Radon Measurement

Even though the biological effects of radon are caused by RDPs, radon gas is usually measured, rather than RDPs. This is because there are fewer variables in radon measurements because gas concentration is not affected by circulation or plate-out, it is easier to make time-weighted measurements of radon gas, and radon gas measurements are a good indicator of RDPs.

There are three basic methods of sampling for radon, as described previously:

- time-integrated sampling;
- grab-sampling; and
- continuous monitoring.

The most common measurement method is time-integrated sampling, where a device is exposed to the radon gas for a measured amount of time. Charcoal canisters and alpha-track devices are typical of passive devices used in most homes. Charcoal devices are usually left out for two to seven days, then sealed up and sent to a laboratory where they are analyzed. Alpha-track devices are usually left out for longer periods, typically three months to one year. Both types are simple and inexpensive to use.

Continuous monitors and grab-sampling usually require expensive, complex electronic equipment. These require constant calibration to maintain accuracy. Professionals and scientists doing research use this type of equipment.

For short-term devices, the following protocols should be followed:

- Closed-house conditions must be maintained all during the test, and if the test is only two or three days, the house must be closed up 12 hours before the test.

- The test devices must be placed in the lowest occupied level of the home. For real estate measurements, an unfinished basement would be tested.

- The device should not be placed near doors, windows, air currents, sunlight or heat sources. Areas of high humidity should be avoided. Devices should be placed at least 20 inches off the floor, 4 inches from other objects, 12 inches from walls, and 12 inches from ceilings.

Results of the test, if above 4 pCi/L, should be verified by either deploying a second device in the same location, or by deploying a long-term device.

The National Environmental Health Association (NEHA.org) and the National Radon Safety Board (NRSB.org) maintain lists qualified testers on their Web sites.

Radon Mitigation

Mitigation can be accomplished by addressing elevated radon levels via:

- sources of radon in the soil, building material and/or well water;
- transport mechanisms that drive radon into a building, usually through pressure differentials;

- radon entry-pathways that allow radon to enter a structure, usually through cracks or openings in the foundation, or open crawlspaces; and
- the accumulation of radon and RDPs in the building.

Of these, controlling radon transport by pressure-driven entry is the most common mitigation technique employed. This is called active soil depressurization (ASD). This technique creates a suction or area of low pressure beneath the structure that is stronger than the partial vacuum applied to the soil by the building.

ASD systems are comprised of pipes connected to a fan which draws gases from under the building. Radon is captured and vented to the outside before it has a chance to enter the home.

Several types of ASD systems include:

- sub-slab depressurization systems;
- drain tile depressurization systems;
- sub-membrane depressurization systems;
- block-wall depressurization systems; and
- a combination of the above methods.

All of these ASD systems require expert installation, additional sealing of openings into the home, and, of course, testing to verify that radon levels have been reduced to below 4 pCi/L.

Professional radon mitigators, such as those taking measurements, are also listed by NEHA and NRSB.

Radon in Water

Soil gas is the largest natural source of radon in homes. However, well water can be a significant factor if dissolved radon at high concentrations is found.

It takes high levels of radon in water to result in a significant elevation of radon in air. The EPA uses a rule of thumb of 1:10,000. That is, if 10,000 pCi/L of radon are measured in the water, indoor radon concentrations are increased by 1 pCi/L.

Recent studies have indicated that elevated levels of radon in water are not only an inhalation threat, but may be an ingestion hazard as well, increasing the risk of stomach cancer.

In 1992, the EPA proposed a maximum contaminant level (MCL) of 300 pCi/L for public water supplies. At this time, this MCL has not been promulgated. There is also an alternate MCL being proposed of 4,000 pCi/L, but what the water supplier has to do to be eligible to qualify for this has not been established. As a result of these proposed MCLs, radon may become the most commonly treated contaminant in well water. Radon in well water in Colorado, for example, averages well above the proposed MCL.

Treatment for Radon in Water

There are three recognized treatment methods to remove radon from water:

- storage of the water until the radon decays and depletes;
- aeration to strip the radon from the water; and
- the use of granular activated-carbon (GAC) filters.

Water storage until the radon decays is somewhat impractical, since it takes 27 days for radon to decay (depleted 99%). For a typical family of four using 300 gallons of water per day, they would need 8,100 gallons of storage. A tank this large is impractical and expensive.

Aeration is the preferred method of treatment for radon in water. As the water is aerated, radon is released and piped outside. This method requires another pump to pressurize the pressure tank, a radon fan, and biological treatment of the aerated water, as it may be contaminated by the air used for aeration.

Granular activated-carbon filters remove radon in water by adsorbing the radon onto the carbon. However, gamma radiation results from the RDPs that accumulate in the filter. The filter needs to be shielded or remotely located to prevent radiation hazards to the occupants.

Section 13: EPA Protocols for Indoor Radon Measurements

The EPA's Guide to Measurement Protocols

United States
Environmental Protection
Agency

Air And
Radiation

EPA

Protocols For Radon And
Radon Decay Product
Measurements In Homes

EPA Publication 402-R-93-003 (June 1993):

Protocols for Radon and Radon Decay Product Measurements in Homes

This document is used for guidance for testing radon levels in homes. One condition of participation in the agency's former National Radon Proficiency Program (RPP) was conformance with these protocols, as well as those contained in its companion document, the *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 402-R-92-004, July 1992). Together, these protocol documents provide the technical support for the agency's radon policies and guidance for consumers that are included in the *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003, March 1993), *A Citizen's Guide to Radon* (EPA 402-K-92-001), and the *Consumer's Guide to Radon Reduction* (EPA 402-K-92-003, August 1992).

Table of Contents

Part 1: Introduction

Part 2: Discussion of Guidelines Presented in the *Citizen's Guide to Radon*

Part 1: Introduction

This document presents the U.S. Environmental Protection Agency's (EPA) technical guidance for measuring radon concentrations in residences. It contains protocols for measuring radon for the purpose of deciding on the need for remedial action, as presented in the 1992 *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a), and in the *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993).

The guidance for determining the need for mitigation is different in several key aspects from previously issued recommendations, and this document supersedes a previous report (EPA 520/1-86-014-1) published in February 1987 (U.S. EPA 1987). The technical basis for these policy changes is supplied in the Technical Support Document for the 1992 *Citizen's Guide to Radon* (EPA 400-R-92-011; U.S. EPA 1992g), and the revised policies are described in Part 2 of this report.

Part 3 of this report describes the agency's recommended protocols for measuring radon for a real estate transaction. This guide elaborates on agency recommendations published in the *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993). The radon testing guidelines in the *Home Buyer's Guide* were developed specifically to deal with the time-sensitive nature of home purchases and sales, and the potential for radon device interference. The guidelines are somewhat different from those in other EPA publications, such as the 1992 *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a), which provide radon testing and reduction information for non-real estate situations. Therefore, Parts 2 and 3 of this document will have different guidance for different situations.

This report is limited to discussions of agency guidance regarding detector placement, measurement duration, multiple measurements, and the interpretation of measurement results. The EPA has also issued a technical report describing measurement techniques, titled *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004) and published in 1992 (U.S. EPA 1992c). That report provides technical information for measuring radon concentrations with continuous radon monitors, alpha-track detectors, electret ion chambers, charcoal canisters, unfiltered alpha-track detectors, and grab-radon techniques; it also provides guidance for measuring radon decay product concentrations with continuous working-level monitors, radon progeny integrating sampling units, and grab-radon decay product techniques.

EPA Documents Providing Guidance on Radon Measurements:

- *A Citizen's Guide to Radon* (EPA 1992a; EPA 402-K-92-001);
- *Consumer's Guide to Radon Reduction* (EPA 1992b; EPA 402-K-92-003);
- *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 1992c; EPA 520-402-R-92-004);
- *Radon Mitigation Standards* (EPA 402-R-93-078, October 1993; revised April 1994);

- *Home Buyer's and Seller's Guide to Radon* (EPA 1993; EPA 402-R-93-003);
- *Radon Measurements in Schools* (EPA 402-R-92-014); and
- *Protocols for Radon and Radon Decay Product Measurements in Homes* (EPA 402-R-92-003).

This report provides guidelines that are primarily intended to aid state radon control programs, lists other organizations conducting indoor radon measurements, and provides homeowners with detailed information on radon measurements. The guidelines can be adopted as part of a state program or can be provided by states to interested individuals as recommendations. The designated methods that were used in the RPP are listed in Exhibit 1-2 (see chart to follow). A two-letter code for each method has been adopted, although ATDs (AT), RPISUs (RP) and EICs/ECs (ES or EL) may still be referred to by their traditional acronyms.

The EPA recognizes that radon concentrations in buildings may vary over time. Furthermore, concentrations at different locations in the same house often vary by a factor of two or more. The EPA has carefully evaluated these findings, as well as other factors, and has developed policies for ensuring that the most representative and useful information is supplied by the measurement results. These guidelines may be evaluated periodically and refined to reflect the increasing knowledge of, and experience with, indoor radon.

The EPA recommends that initial measurements be short-term tests performed under closed-building conditions. An initial short-term test, which lasts for two to 90 days, ensures that residents are informed quickly, should a home contain very high radon levels. Long-term tests, which are conducted for longer than 90 days, give a better estimate of the year-round average radon level. The closer the long-term test is to 365 days, the more representative it will be of annual average radon levels.

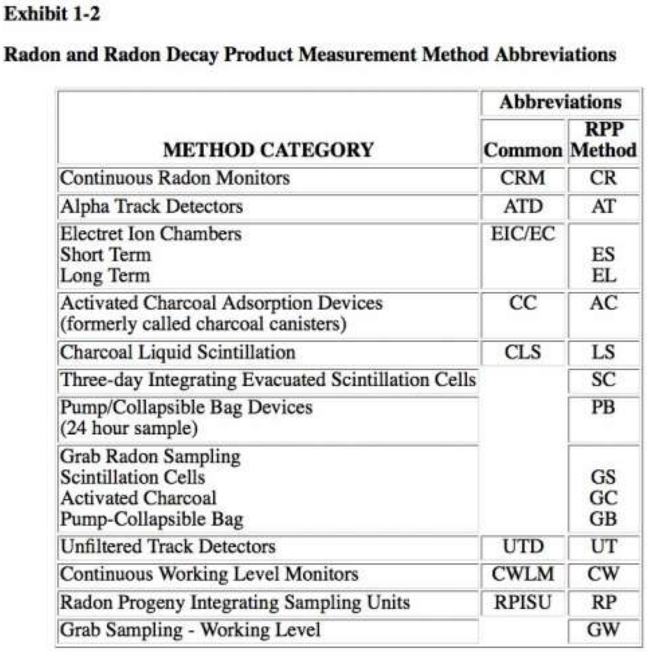


Exhibit 1-2

Radon and Radon Decay Product Measurement Method Abbreviations

METHOD CATEGORY	Abbreviations	
	Common	RPP Method
Continuous Radon Monitors	CRM	CR
Alpha Track Detectors	ATD	AT
Electret Ion Chambers	EIC/EC	
Short Term		ES
Long Term		EL
Activated Charcoal Adsorption Devices (formerly called charcoal canisters)	CC	AC
Charcoal Liquid Scintillation	CLS	LS
Three-day Integrating Evacuated Scintillation Cells		SC
Pump/Collapsible Bag Devices (24 hour sample)		PB
Grab Radon Sampling		
Scintillation Cells		GS
Activated Charcoal		GC
Pump-Collapsible Bag		GB
Unfiltered Track Detectors	UTD	UT
Continuous Working Level Monitors	CWLM	CW
Radon Progeny Integrating Sampling Units	RPISU	RP
Grab Sampling - Working Level		GW

Part 2: The EPA's Citizen's Guide to Radon

Guidelines Presented in the EPA's *Citizen's Guide to Radon*

2.1 Introduction and Summary

The *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a) presents a measurement strategy for assessing radon levels in homes for the purpose of determining the need for remedial action. This measurement strategy is intended to reduce the risk to public health from exposure to radon in the air in homes. The strategy begins with an initial measurement made to determine whether a home may contain radon concentrations sufficient to cause high exposures to its occupants.

The EPA recommends that initial measurements be short-term tests placed in the lowest lived-in level of the home, and performed under closed-building conditions. An initial short-term test ensures that residents are informed quickly, should a home contain very high levels of radon. Short-term tests are conducted for between two days to 90 days. Closed-building conditions should be initiated at least 12 hours prior to testing for measurements lasting less than four days, and are recommended prior to tests lasting up to a week.

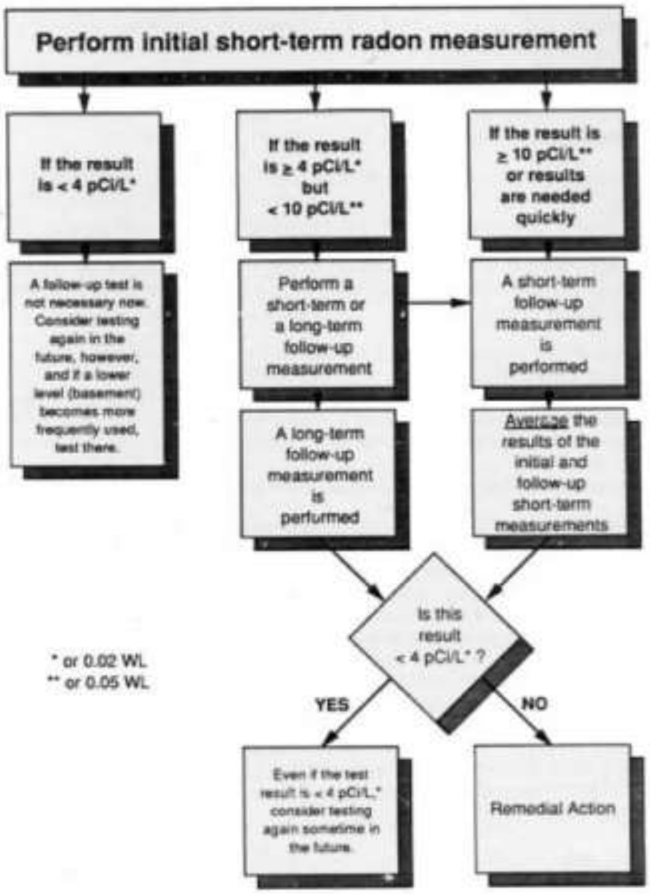
If the short-term measurement result is equal to or greater than 4 picocuries per liter (pCi/L), or 0.02 working levels (WL), a follow-up measurement is recommended. Follow-up measurements are conducted to confirm that radon levels are high enough to warrant mitigation. If the result of the initial measurement is below 4 pCi/L (or 0.02 WL), a follow-up test is not necessary. However, since radon levels change over time, the homeowner may want to test again sometime in the future, especially if living patterns change and a lower level of the house becomes occupied or used regularly.

There are two types of follow-up measurements that may be conducted, and the choice depends, in part, on the results of the initial test. An initial measurement result of 10 pCi/L (or 0.05 WL) or greater should be followed by a second short-term test under closed-building conditions. If the result of the initial measurement is between 4 pCi/L (or 0.02 WL) and 10 pCi/L (or 0.05 WL), the follow-up test may be made with either a short-term or a long-term method. Long-term tests are conducted for longer than 90 days, as they give a better estimate of the year-round average radon level. The closer the long-term measurement is to 365 days, the more representative it will be of annual average radon levels. On the other hand, short-term tests yield results more quickly and can be used to make mitigation decisions. If the long-term follow-up test result is 4 pCi/L (or 0.02 WL) or higher, the EPA recommends remedial action. If the average of the initial and second short-term results is equal to or greater than 4 pCi/L (or 0.02 WL), radon mitigation is recommended. These recommendations are summarized in Exhibit 2-1:

Exhibit 2-1

Exhibit 2-1

Recommended Testing Strategy for
Determining the Need for Mitigation in Homes



In certain instances, such as may occur when measurements are performed during different seasons or under different weather conditions, the initial and follow-up tests may vary by a considerable amount. Radon levels can vary significantly between seasons, so different values are to be expected. The average of the two short-term test results can be used to determine the need for remedial action.

The testing strategy policies presented assist homeowners in deciding on the need for mitigation with a high level of confidence that their decision is correct (EPA 400-R-92-011; U.S. EPA 1992g).

2.2 Measurement Location

Short-term or long-term measurements should be made in the lowest lived-in level of the house. The following criteria should be used to select the location of the detectors within a room on this level.

The measurements should be made in the lowest level which contains a room that is used regularly. Test areas include family rooms, living rooms, dens, play rooms and bedrooms. A bedroom on the lower level may be a good choice because most people generally spend more time in their bedrooms than in any other room in the house. If there are children in the home, it may be appropriate to measure the radon concentration in their bedrooms or in other areas where they spend a lot of time, such as a play room, that are situated in the lowest levels of the home.

In general, measurements should not be made in kitchens, laundry rooms or bathrooms. The measurements should not be made in a kitchen because of the likelihood that an exhaust-fan system exists, as well as changes in small, airborne particles (caused by cooking), might affect the stability of WL measurements. Measurements should not be made in a bathroom because relatively little time is spent in a bathroom, because high humidity may affect the sensitivity of some detectors, and because of the likelihood that the use of a fan may temporarily alter radon or decay product levels.

Although radon in water may be a contributor to the concentration of airborne radon, radon in the indoor air should be measured before any diagnostic water radon measurements are made. (Diagnostic measurements may be made in the bathroom; however, such diagnostic measurements should not be used to determine the need for mitigation.)

A location should be selected where the detector will not be disturbed during the measurement period and where there is adequate room for the device.

The measurement should not be made near drafts caused by heating, ventilating and air-conditioning vents, doors, fans or windows. Locations near heat, such as on appliances, near fireplaces, or in direct sunlight, as well as areas of high humidity should be avoided.

Because some detectors are sensitive to increased air motion, fans should not be operated in the test area. Forced-air heating or cooling systems should not have the fan operating continuously unless it is a permanent setting.

The measurement location should not be within 3 feet (90 cm) of doors, windows or other potential openings to the outdoors. If there are no doors or windows to the outdoors, the measurement should not be within 1 foot (30 cm) of the exterior wall of the building.

The detector should be at least 20 inches (50 cm) from the floor, and at least 4 inches (10 cm) from other objects. For those detectors that may be suspended, an optimal height is in the general breathing zone, such as 6 to 8 feet (2 to 2.5 meters) from the floor.

Sound judgment is required to determine what space actually constitutes a room. Measurements made in closets, cupboards, sumps, crawlspaces or nooks within the foundation should not be used as a representative measurement.

2.3 Initial Measurements

2.3.1 Rationale

The EPA recommends that a homeowner assessing the need for mitigation should first make a short-term test. Short-term measurements can be simple, produce results quickly, and allow the public to make decisions about radon reduction that are cost-effective and protective of human health.

The duration of short-term measurements can range from 48 hours to 90 days, depending upon the method used.

2.3.2 Closed-Building Conditions

Short-term measurements lasting between two and 90 days should be made under closed-building conditions. Closed-building conditions are necessary for short-term measurements in order to stabilize the radon and radon decay product concentrations, and increase the reproducibility of the measurement. Windows on all levels and external doors should be kept closed (except during normal entry and exit) during the measurement period. Normal entry and exit include a brief opening and closing of a door, but -- to the extent possible -- external doors should not be left open for more than a few minutes. In addition, external-internal air-exchange systems (other than a furnace), such as high-volume, whole-house and window fans, should not be operating. However, attic fans intended to control attic (and not whole-building temperature or humidity) should continue to operate. Combustion or make-up air supplies must not be closed.

In addition to maintaining closed-building conditions during the measurement, closed-building conditions for 12 hours prior to the initiation of the measurement are required for measurements lasting less than four days, and are recommended prior to measurements lasting up to a week. Normal operation of permanently installed energy-recovery ventilators (also known as heat-recovery ventilators or air-to-air heat exchangers) may also continue during closed-building conditions. In houses where permanent radon mitigation systems have been installed, these systems should be functioning during the measurement period.

Closed-building conditions will generally exist as normal living conditions in northern areas of the country when the average daily temperature is low enough so that windows are kept closed. Depending on the geographical area, this can be the period from late fall to early spring. In some houses, the most stable radon levels occur during late fall and early spring, when windows are kept closed but the house heating system (which causes some ventilation and circulation) is not used. Available information about variations of indoor radon levels in a particular area can be used to choose a measurement time when the radon concentrations are most stable.

It may be necessary, however, to make measurements during mild weather when closed-building conditions are not the normal living conditions. It will then be necessary to establish some more rigorous means to ensure that closed-building conditions exist prior to and during the measurements.

Those performing measurements in southern areas that do not experience extended periods of cold weather should evaluate seasonal variations in living conditions, and identify if there are times of the year when closed-building conditions normally exist. Ideally, measurements should be conducted during those times. The closed-building conditions must be verified and maintained more rigorously when they are not the normal living conditions. Air-conditioning systems that recycle interior air can be operated during the closed-building conditions when radon measurements are being made. However, homeowners should be aware that any air circulation system could alter the radon decay product concentration without significantly changing the radon concentration.

Short-term tests lasting just two or three days should not be conducted during unusually severe storms or periods of unusually high winds. Severe weather will affect the measurement results in several ways. First, a high wind will increase the variability of radon concentration because of wind-induced differences in air pressure between the building's interior and its exterior. Second, rapid changes in barometric pressure increase the chance of a large difference in the interior and exterior air pressures, consequently changing the rate of radon influx. Weather predictions available on local news stations can provide sufficient information to determine if these conditions are likely. While unusual variations between radon measurements may be due to weather or other effects, the measurement system should be checked for possible problems.

2.3.3 Interpretation of Initial Measurement Results

If the initial measurement result is less than 4 pCi/L (or 0.02 WL), follow-up measurements are likely not needed. There is a relatively low probability that mitigation is warranted if the result is less than 4 pCi/L (EPA 400-R-92-011; U.S. EPA 1992g). Even if the measurement result is less than 4 pCi/L, however, a homeowner may want to test again sometime in the future. If the occupants' living patterns change, or if renovations are made to the house and they begin using a lower level as a living area (such as a basement), a new test should be conducted on that level.

The average year-round indoor radon level is estimated to be about 1.3 pCi/L, and about 0.4 pCi/L of radon is normally found in outside air. The U.S. Congress has set a long-term goal that indoor radon levels be no more than outdoor levels. There is some risk from radon levels below 4 pCi/L, and the EPA recommends that the homeowner consider reducing the radon level if the average of the first and second short-term measurements (or if a long-term follow-up measurement) is between 2 and 4 pCi/L (between 0.01 and 0.02 WL). While it is not yet technologically achievable for all homes to have their radon levels reduced to outdoor levels, the radon levels in some homes today can be reduced to 2 pCi/L or below.

If the result of the short-term measurement is equal to or greater than 4 pCi/L, the occupant should conduct a follow-up measurement using a short-term or long-term test, as described in Part 2.4.

2.4 Follow-Up Measurements

2.4.1 Rationale

The purpose of a follow-up measurement is to provide the homeowner with enough information to make an informed decision as to whether to mitigate to reduce radon levels. The follow-up measurement, whether it is short-term or long-term, provides an additional piece of information to confirm that radon levels are high enough to warrant mitigation. There are two major reasons a second measurement is necessary. First and foremost, radon levels fluctuate over time, and a second short-term measurement, when averaged with the first test result, will provide a more representative value for the average radon level during the period of the test. If a long-term follow-up measurement is conducted, that result should provide an even more accurate representative value for the long-term average radon concentration. The second reason for making a follow-up measurement prior to mitigation is that there is a small chance of laboratory or technician error in all measurements, including radon measurements, and a second test will serve as a check on the first test.

A follow-up test is necessary regardless of the initial test result. Homes tested using the protocol in this section should not be mitigated on the basis of a single short-term test.

2.4.2 Short-Term and Long-Term Follow-Up Testing

Follow-up testing should be conducted in the same location as the first measurement.

A follow-up test can be conducted with either a short-term or long-term measurement device. Long-term tests (longer than 90 days) will produce a reading that is more likely to represent the home's year-round average radon level than a short-term test. However, if the initial test result is high (for example, greater than about 10 pCi/L, or 0.05 WL), or if results are needed quickly, the EPA recommends a second short-term test. This will allow the homeowners to obtain information necessary to decide quickly on the need for mitigation. If the result of the initial measurement is not severely elevated (between 4 pCi/L and 10 pCi/L, or between 0.02 WL and 0.05 WL), then either a short-term or long-term test can be taken.

If the long-term follow-up test result is 4 pCi/L or higher, then the EPA recommends remedial action. Likewise, if the average of the initial and second short-term results is equal to or greater than 4 pCi/L, radon mitigation is recommended. These recommendations are summarized in Exhibit 2-1.

As with the initial short-term test, the second short-term test should be conducted under closed-building conditions (as described in Part 2.3.2). These conditions, however, are not necessary for long-term tests (those lasting longer than 90 days).

Part 3: The EPA's Home Buyer/Seller Guide

Part 3: Discussion of the Guidelines Presented in the EPA's *Home Buyer's and Seller's Guide to Radon*

3.1 Introduction

The unique nature of a real estate transaction, involving multiple parties and financial interests, presents radon measurement issues not encountered in non-real estate testing. The EPA's objectives for issuing recommended protocols for radon measurements for real estate transactions are intended to reduce misunderstandings and protect the public health in several ways. First, it seeks to provide home buyers, sellers, real estate agents and testing organizations with a common basis for understanding the recommended procedures for radon measurements. Second, the widespread implementation of these guidelines will produce results that are reliable indicators of the need for mitigation. A significant proportion of radon measurements are conducted as part of real estate transactions, and all aspects of these transactions are carefully scrutinized, so specific guidance from the EPA can help ensure trustworthy measurements. When the results are interpreted properly and the appropriate remedial action is taken, these protocols will assist the buyer and seller in reducing the risk to the occupants from radon exposure. The availability of nationally recognized protocols for radon measurement, and for the interpretation of the measurement results, can greatly assist home buyers, sellers, real estate agents, builders, lenders and radon measurement experts.

These protocols are designed for use in residential buildings, as described in the EPA document, *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993). While that document offers general information on radon and testing, this report presents a more technical description of the EPA's recommendations, including discussion of guidelines for the interpretation of measurement results. As with all of the EPA's policies regarding radon measurements, these guidelines have been developed after review and assistance from the radon measurement community and the EPA's Science Advisory Board. Technical information on a variety of radon measurement methods is available in the EPA report titled *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; EPA 1992c). These and other EPA publications are available at their

Web site and from state and regional EPA offices.

The radon testing guidelines in the *Home Buyer's and Seller's Guide to Radon* have been developed specifically to deal with the time-sensitive nature of home purchases and sales, and the potential for radon device interference. These guidelines are somewhat different from the guidelines in other EPA publications, such as the 1992 *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a), which provide radon testing and reduction information for non-real estate situations.

The EPA investigated a variety of options for real estate testing. It recommends testing in advance of putting the house on the market. A long-term test, which is conducted for longer than 90 days, is the most representative indication of the annual average radon concentrations in a home. However, for time-sensitive real estate transactions, the *Home Buyer's Guide* offers three short-term testing options. Short-term tests are conducted from two days to 90 days, depending on the measurement device. Based on extensive quantitative analyses to evaluate the frequency with which long-term and short-term testing results lead to the same mitigation decision, the EPA and its independent Science Advisory Board concluded that short-term tests can be used to assess whether a home should be remediated.

The reliability of each radon measurement made for a real estate transaction, or for any purpose, is highly dependent upon the existence and documentation of an adequate quality assurance program implemented by both the tester and the analysis laboratory. All the parties involved in the real estate transaction depend upon the testers doing their jobs. This includes ensuring that the measurements are valid via the performance of quality control measurements and activities, and detecting measurement interference. The protocols outlined in this section were developed by the EPA for testers and homeowners adhering to the quality assurance practices summarized in Part 4.4, and in the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c).

Three options were determined to be satisfactory and are described here. The availability of three options will allow flexibility on the part of the party purchasing the test. Each of these options will produce results that can be used to determine the need for mitigation.

Both Options 1 and 2 require the use of two measurements made for similar durations. Both measurements should report results in units of pCi/L or both in WL. Similar durations mean that the two measurements must be made for a similar time period, with a two-hour grace period. Specific information on measurement methods (listed in Exhibit 3-1) can be found in the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols*.

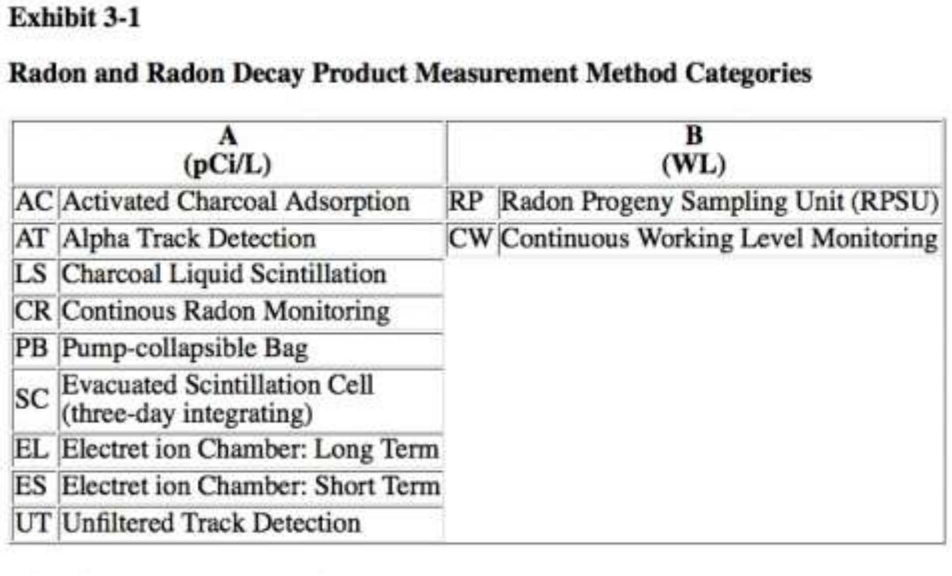


Exhibit 3-1

Radon and Radon Decay Product Measurement Method Categories

A (pCi/L)		B (WL)	
AC	Activated Charcoal Adsorption	RP	Radon Progeny Sampling Unit (RPSU)
AT	Alpha Track Detection	CW	Continuous Working Level Monitoring
LS	Charcoal Liquid Scintillation		
CR	Continous Radon Monitoring		
PB	Pump-collapsible Bag		
SC	Evacuated Scintillation Cell (three-day integrating)		
EL	Electret ion Chamber: Long Term		
ES	Electret ion Chamber: Short Term		
UT	Unfiltered Track Detection		

3.2 Options for Real Estate Testing

3.2.1 Option 1: Sequential Testing

Sequential tests should be conducted under conditions that are as similar as possible, in the same location, and using similar devices and durations. Both should produce results in the same units (pCi/L or WL). That is, both methods should be from Column A, or both from Column B of Exhibit 3-1. Any EPA-recognized method may be used. In addition, the results of the first test should not be reported prior to making the second measurement; both measurements should be reported at the same time in order to discourage tampering that may occur if the first test is known to be greater than 4 pCi/L (or 0.02 WL). Note that measuring with different methods (for example, with AC and ES) may increase the potential for differences or measurement bias between the results. The results of both measurements should be reported, and the average of the two results should be used to determine the need for mitigation. There will be some variation between the two results, which may be caused by the radon levels fluctuating in response to weather or other factors. If the variation is unusually large, it may be due to weather or other effects, but the measurement system should be checked for possible problems.

3.2.2 Option 2: Simultaneous Testing

This option involves the use of two tests, conducted simultaneously and side-by-side, made for similar durations, and producing results in the same units (i.e., both methods should be from Column A, or both should be from Column B of Exhibit 3-1). As with Option 1, using different methods for the two measurements (for example, ES and LS) may increase the potential for differences between the two results. The two test results should be averaged to determine the need for remedial action. The collocated devices should be placed 4 inches (10 cm) apart.

Because radon measurements, like any measurements, usually do not produce exactly the same results, even for simultaneous testing, there will typically be a difference between the two results. The EPA offers the following guidance to testers for judging when two simultaneous, side-by-side measurements disagree to such an extent that two additional measurements should be performed.

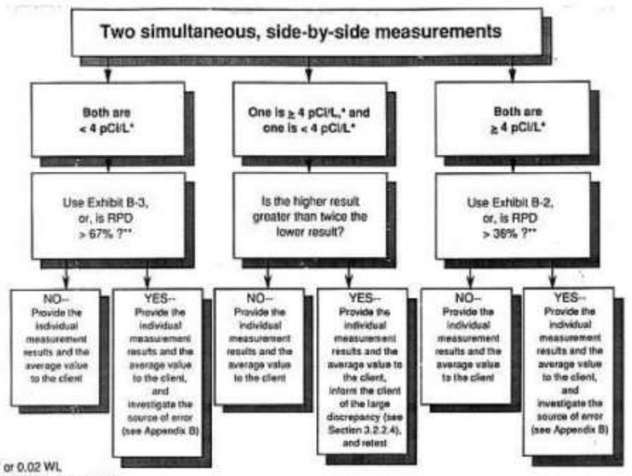
The results of the simultaneous measurements will fall into one of the three categories discussed below and illustrated in Exhibit 3-2.

3.2.2.1 Both Measurement Results Equal to or Greater Than 4 pCi/L (or 0.02 WL)

In this case, the average of the two results will be equal to or greater than 4 pCi/L, or 0.02 WL, and mitigation is recommended. The tester should report both measurement results, as well as the average of the two results.

Exhibit 3-2

Deciding on a Retest When Measurements Vary Significantly



* or 0.02 WL
** Refer to *Appendix B*
RPD = Relative Percent Difference = Difference/Average

3.2.2.2 Both Measurement Results Less Than 4 pCi/L (or 0.02 WL)

In this case, the average of the two measurements will be less than 4 pCi/L (or 0.02 WL), and both measurement results and the average result should be reported to the client.

3.2.2.3 One Measurement Result Greater Than 4 pCi/L (or 0.02 WL), and One Measurement Result Less Than 4 pCi/L (or 0.02 WL)

This is a special situation in which the average of the results is critical. To assist testers in ensuring that the difference between two measurements is small enough so that clients may have confidence in and understand the results, the EPA offers the following simple guidance.

If the higher result is twice (or more) the lower result, then the two results are not within a factor of two, and a re-test should be conducted. Part 3.2.2.5 provides language for informing the client that a re-test is warranted.

If the higher result is less than twice the lower result, then the two results are within a factor of two, and a re-test is not necessary. The results of both measurements, and the average of the two results, should be reported to the client. (See Part 4 for more detailed information on quality assurance and quality control procedures.)

3.2.2.4 Precision Recommendations

Measurements near the lower limit of detection (LLD) for the measurement system often have large and varying precision errors, and it is difficult to assign any sort of probability level to very low results.

Simultaneous measurement results that are equal to 4 pCi/L (or 0.02 WL) or greater should, however, exhibit some agreement. An example control chart for the precision that may be expected is shown as Exhibit B-2 in Appendix B, which was constructed using an average relative difference of 14%. ("Relative percent difference" is defined as the difference divided by the average.) Using Exhibit B-2, a relative percent difference greater than 36% should be observed less than 1% of the time. Based upon this, the EPA recommends that any side-by-side, simultaneous measurements with results greater than or equal to 4 pCi/L, and which exhibit a relative percent difference greater than 36%, would provide justification for informing the client that the two results do not show agreement. However, since both results are greater than 4 pCi/L, the EPA recommends mitigation in this case. Testers should investigate the source of the error (see Appendix B).

Results between 2 pCi/L and 4 pCi/L (or 0.01 WL and 0.02 WL) should also exhibit some agreement. The level of agreement expected should be based upon the tester's experience with duplicate measurements made with that technique in this range of radon concentrations. An example control chart for the precision that may be expected in this region is shown as Exhibit B-3 in Appendix B, which was constructed using an average relative percent difference of 25%. Using this chart, a relative percent difference between duplicates greater than 67% should be observed less than 1% of the time. Based on this, the EPA recommends that any side-by-side, simultaneous measurements with results less than 4 pCi/L, and which exhibit a relative percent difference greater than 67%, would provide justification for informing the client that the two results do not show agreement, but that both are less than 4 pCi/L and, therefore, mitigation is not recommended. Testers should investigate the source of the error (see Appendix B).

3.2.2.5 Recommended Language for Informing the Client That a Re-test is Warranted

If a re-test is warranted (see Part 3.2.2.3), the EPA recommends that the tester inform the client that the EPA provides guidance for how well two measurements should agree, that the measurements performed fall outside the range, and that a re-test should be conducted. A re-test should consist of measurements performed according to one of the protocols outlined in Parts 3.2.1, 3.2.2 or 3.2.3.

3.2.3 Option 3: Single Test Option

This option requires an active continuous monitor (method CR or CW) that has the capability to integrate and record a new result at least every four hours. If the monitor cannot integrate over a period of four hours or less, then an additional (secondary) passive or active measurement device must be used. Shorter integration periods and more frequent data logging afford greater ability to detect unusual variations in radon or radon decay product concentrations. The minimum measurement period is 48 hours. The first four hours of data from a continuous monitor may be discarded or incorporated into the result using system correction factors (EPA 520-402-R-92-004; EPA 1992c). There must be at least 44 contiguous hours of usable data to produce a valid average. (The "backing out" of data [i.e., removal of portions imbedded in the two days] to account for weather or other phenomena will invalidate the measurement.) The periodic results should be averaged to produce a result that is reported to the client.

The best way to increase confidence in a radon measurement is to perform a second measurement with another measurement device. The second measurement, which may be made with a passive or active device, can be used simultaneously or sequentially, as discussed in Options 1 and 2 (Parts 3.2.1 and 3.2.2). If the two measurements are performed simultaneously, their results should be evaluated following the guidance in Part 3.2.2. If the two measurements were performed sequentially, it can be expected that the two results will be different. As discussed in Part 3.2.1, the difference between sequential tests may be due to radon levels fluctuating in response to weather or other factors.

However, there are other approaches or features that can be used to increase the confidence in a measurement result obtained using a single active monitor test. These include the use of a device's self-diagnostic features, and data validation or verification procedures that could be employed before and/or after the measurement. Examples of such approaches are the use of check sources before and after each measurement, and the use of spectrum read-outs. These capabilities are examples, and different technologies may be able to perform other similar self-diagnostic or quality assurance checks. Other features that increase the confidence in a single active test include (but are not limited to) the ability to check air-flow rates and voltage meters before and after each measurement. Measurement companies should incorporate such checks into their routine instrument performance checks as part of their standard operating procedures.

Additional features that can increase confidence in measurement results are those that detect measurement interference; these features are discussed in Part 3.5. For example, a continuous monitor that offers a variety of ways to detect tampering may serve to deter, as well as detect, interference with the monitor's operation or with proper closed-building measurement conditions. Potential tampering indicators include the ability of a monitor to record changes in temperature, humidity, or movement of the monitor during the measurement.

Instruments with greater efficiency or sensitivity, or a high signal-to-noise ratio (see Glossary for definitions of these terms), can achieve results with less uncertainty than instruments with low efficiency, poor sensitivity, or low signal-to-noise ratio. The reliability of any type of equipment, however, needs to be established and documented via a complete quality assurance program. This includes routine instrument performance checks prior to and after each measurement, annual calibrations, semi-annual instrument cross-checks, the performance of duplicate measurements in 10% of the measurement locations, and frequent background and spiked measurements.

3.3 Measurement Location

The EPA recommends that measurements made for a real estate transaction be performed in the lowest level of the home which is currently suitable for occupancy. This means the lowest level that is currently lived in, or a lower level that is not currently used, such as a basement, which a buyer could use for living space without renovations. Measurements should be made in a room that is used regularly, such as a living room, play room, den or bedroom. This includes a basement that can be used as a recreation room, bedroom or play room. This provides the buyer with the option of using a lower level of the home as part of the living area with the knowledge that it has been tested for radon.

3.4 Measurement Checklist

The EPA presents the following checklist to help ensure that a radon measurement conducted for a real estate transaction is done properly. The seller should be able to confirm that all the items in this checklist have been followed. If the tester cannot confirm this, another test should be made.

- **Before the radon test:**

  Notify occupants of the importance of proper testing conditions. Give occupants written instructions or a copy of the EPA's *Home Buyer's and Seller's Guide to Radon*, or a state-required alternative, and explain the directions carefully.

  The radon measurement equipment used should be listed by some proficiency organization or listed by the state. Follow the manufacturer's instructions that come with the device.

  If a testing professional conducts the test, s/he should be listed with some national or state-listed program. Check with the State Radon Contact for more information. Under the former National Radon Proficiency Program (RPP), the EPA recommended that photo identification should be provided to the client or homeowner before or at the time of the test, and the contractor's identification number should be clearly visible on the test report.

  The test should include method(s) to prevent or detect interference with testing conditions or with the testing device itself.

  Conduct the radon test for minimum of 48 hours. Some devices must be exposed for longer than the 48-hour minimum.

  Check to see if an active radon reduction system is in the house. Before starting a short-term test lasting less than four days, make sure the active system has been operating for at least 24 hours before beginning the test.

The EPA recommends that short-term radon testing, which lasts for no more than a week, be done under closed-building conditions. Closed-building conditions require keeping all windows closed, keeping doors closed except for normal entry and exit, and not operating fans or other machines that bring in air from outside. Note that fans that are part of a radon-reduction system, or small exhaust fans operating for only short periods of time, may run during the test.

When doing short-term testing lasting less than four days, it is important to maintain closed-building conditions for at least 12 hours before the beginning of the test, as well as for the entire testing period. Do not operate fans or other machines that bring in air from the outside.

- **During the radon test:**

  Maintain closed-building conditions during the entire time of a short-term test, especially for tests shorter than one week.

  Operate the home's heating and cooling systems normally during the test. For tests lasting less than one week, only operate air-conditioning units that recirculate interior air.

  Do not disturb the test device at any time during the test.

  If a radon-reduction system is in place, make sure the system is working properly and will be in operation during the entire radon test.

- **After the radon test:**

  If a high radon level is confirmed, mitigate the level. The EPA's *Home Buyer's and Seller's Guide to Radon* recommends the next steps that should be taken, such as contacting a qualified radon reduction contractor to lower the home's radon level.

  The radon tester or homeowner should be able to verify or provide documentation asserting that testing conditions were not violated during the testing period.

3.5 Interference-Resistant Testing

The EPA strongly encourages the use of radon testing devices with interference-resistant features inherent in or associated with the device.

Interference with a radon measurement is defined as the altering of test conditions prior to or during the measurement to either change the radon or RDP concentrations, or to alter the performance of the measurement equipment. The following discussion reviews some of the types of test interferences, and methods of detecting and preventing such interferences.

Test interference typically causes measurement results to be lower than if all proper test conditions were maintained. False low results have been primarily associated with testing during a real estate transaction, although they also happen when the occupants of the dwelling are not properly informed about the necessary test conditions. Test interference can also inadvertently increase measurement results, although the intent is to lower the results.

The dwelling's current occupant may have an interest in the test results being as low as possible to avoid hindering the sale of the dwelling or incurring the added expense of having to install a mitigation system. The potential for test interference puts the professional radon tester in the position of verifying that the equipment and the required test conditions were maintained. A measurement result that is below the action guideline may be suspect if the tester cannot verify that the necessary test conditions were maintained.

If the tester arrives at a property and finds windows or doors open, or suspects that closed-building conditions were not maintained for 12 hours prior to arrival, then the tester should extend the testing time period to account for this condition.

3.5.1 Influencing the Test Area's Concentration

The primary method of temporarily reducing radon levels is to ventilate the test area with outdoor air. Ventilation will slow down radon entry by reducing negative pressure in the test area and by diluting the reduced radon concentration. Even small openings of a single window in the test area can have an effect. Ventilating the floors above the test area has significantly less effect, unless the test area is connected with the ventilated room(s) by an operating central air-handling system.

Radon decay product levels are sensitive to air movement. As air movement increases, decay products will plate out on walls and other surfaces, including fans, thereby reducing airborne decay product concentrations. Decay products will be further reduced if the fan also includes a filter. Radon levels are, however, not affected by filtering or air movement.

It is also possible to alter concentrations in a tight room if the heating system is operating in an abnormal fashion. Since this may not be the typical operation of the system, it is, in effect, interfering with normal house conditions.

It is important to recognize that test interference can increase radon or decay product levels, despite an intent to lower the results.

3.5.2 Equipment Interference

The primary method of interfering with testing equipment is to move the detector to an area of low radon concentration. Other types of interference vary in their ability to influence different types of detectors. For example, interfering with the air-sampling mechanisms can maintain the radon concentration at the time of interference, or cause a large decrease in the reported concentration. Similarly, covering a decay product or charcoal detector could cause a large drop in the reported values, while other types of radon detectors would show only a reduced response time to changes in the test area level. In addition, charcoal detectors are sensitive to heat. Some active radon monitors and open-face charcoal canisters are also sensitive to high humidity. Any detector that yields a single result could be turned off or sealed in its container or lid during most of its exposure period.

3.5.3 Preventing Interference

The EPA recommends that a radon measurement conducted for a real estate transaction be performed using tamper-resistant testing techniques. It is more advantageous for the tester and the client to prevent interference than to simply detect it. Preventing interference can best be accomplished by:

- educating the client about the necessary test conditions;
- including in the standard documentation for each measurement an agreement (signed by the client) listing the necessary test conditions, and the client's agreement not to interfere with the conditions;
- including in such an agreement a statement that any test interference that is detected will be documented in the report, and will nullify the test results;
- informing the client that interference with the test conditions may increase the radon levels; and
- informing the client that the tester is using interference-detecting techniques, and that these allow the detection and documentation of test interference.

3.5.4 Interference-Resistant Detectors

The following is a partial list of common equipment and measures that can serve to prevent and/or detect test interference. There may be other methods available. Equipment that offers a combination of tamper-detecting features also offers a greater chance of detecting interference.

The ability to integrate and record frequent radon measurements over short intervals (an hour or less) is an important tamper-detection feature. Continuous (active) monitors that provide frequent measurements can indicate unusual concentration changes that can be indicators of test interference.

Measuring other parameters may provide additional indicators of test interference, such as a detector tilt-indicator, or a continuous recording of pump-flow rate.

A motion indicator can also document when the detector is approached or moved.

A simultaneous, multiple-day, continuous measurement of both radon and decay product concentrations will produce a series of equilibrium-ratio values. These values can be inspected for unusual swings or abnormal levels, possibly indicating interference.

Measurement of CO_2 levels can indicate changes in the test area's infiltration rate of outdoor air.

The performance of a grab-radon measurement, a grab-decay product measurement, or both, before and after a longer-term measurement can offer useful information. For example, the initial and final concentrations and equilibrium ratios can be compared for consistency.

Frequent temperature readings may help to indicate changes in the test area's infiltration rate of outdoor air.

Humidity (as well as temperature) recordings can be especially helpful in identifying potentially unusual changes in test conditions that occur during the test period that might not be detected simply through data logging.

Instruments that do not allow occupants to view preliminary results (via a visible printer or screen) may reduce occupants' interference.

Placement indicators can also indicate if a detector has been tampered with or moved. The position of the detector should be noted so that, upon retrieval, any handling of the detector can be indicated by a change in its position. A detector may be hung or placed slightly over the edge of its support to discourage covering it. Passive detectors may be hung or suspended in a radon-permeable bag that uses a unique strap and seal to prevent removing or covering it. Cages can be equipped with a movement indicator to deter handling of the cage or the detector within it.

Seals can be a practical and effective method for detecting and discouraging test interference. Non-sealable caulks and/or tapes can be used to verify that detectors have not been altered or moved, and that windows or non-primary exterior doors have not been opened.

Unless the detector has other mechanisms for detecting interference, seals should be placed on the lowest operable windows and non-primary exterior doors, as well as between the detector and its support, and any other components of the detector that could be tampered with. It may be advisable to place a seal on the furnace-control fan switch. It may also be necessary to attach to the caulk seal something fragile that protrudes out to indicate any handling or covering of the detector.

A number of different products or combination of products can be used for tamper seals. For a seal to be effective, it needs, at minimum, the following unique qualities:

1. The seal must adhere readily to a multitude of surfaces, and yet be easily removed without marring the surface.

2. It needs to be non-re-sealable or show evidence of disturbance.

3. It must be unique enough to prevent easy duplication.

4. It should be visible enough to discourage tampering.

The tamper-resistance of the seal can be increased by using caulk over the seal edges or by slicing a large portion of the center of the seal to ensure that it is broken in case of tampering.

Most paper or plastic tapes and caulks have only some of these qualities. There are, however, a number of seals manufactured specifically for radon testing. It would be advisable to use one of these products and follow the manufacturer's installation recommendations. The best caulking to use as a seal is a removable weather-stripping caulk. This type of caulking adheres readily to most surfaces, yet comes off easily without leaving a mark or being re-sealable.

Upon retrieval of the detector, the tester should carefully inspect the following:

- that all closed-building conditions are still being maintained;
- any changes in the detector's placement;
- the condition of all seals; and
- any abnormal variations in any of the measurements made.

This information should be recorded, as described in Part 4.3.5.

Part 4: General Procedural Recommendations

4.1 Introduction
4.2 Initial Client Interview
4.3 Measurement Recommendations
4.4 Quality Assurance in Radon Testing
4.5 Standard Operating Procedures

4.1 Introduction

This section outlines basic procedural recommendations for anyone involved in the measurement of radon in homes related to both real estate and non-real estate transactions.

4.2 Initial Client Interview

Reasonable efforts should be made to determine whether the home is new and/or occupied, and who will be in charge of the home during the measurement period. Testing organizations should inform the client of:

- the appropriate EPA testing recommendations as outlined in this report, the 1992 *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a), and/or the *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993); and,

- the types of devices they will be using for that test, as well as EPA documentation indicating that the testing organization is proficient.

4.3 Measurement Recommendations

4.3.1 Selecting a Measurement Approach

The purpose of the measurements, as well as budget and time constraints, dictate the protocol used. Measurements for the purpose of assessing the need for mitigation should be made according to the guidance discussed in Part 2 of this document; Part 3 outlines options for protocols for measurements made for real estate transactions. Organizations that provide consultant services, or place or retrieve devices, should review the protocol options and the client's needs, and inform the client of the building's and test period conditions necessary for conducting valid measurements. In some areas, companies may offer different types of radon service agreements. Some agreements allow for a one-time fee that covers both testing and, if needed, radon reduction.

Adherence to the EPA's device protocols outlined in *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c) was a requirement for participation in the EPA's former National Radon Proficiency Program (RPP).

4.3.2 Written Measurement Guidance

Measurement organizations should provide clients with written measurement instructions that clearly explain the responsibilities of the client (and the occupant, if different) during the test period. Written and verbal guidance should be in accordance with the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols*. At a minimum, the guidance should include a statement as to whether the device measures radon or radon decay products, and a discussion of the units in which all results will be reported.

The results of radon decay product measurements should be reported in working levels (WL). If the WL value is converted to a radon concentration and is reported to the homeowner, it should be stated that this approximate conversion is based on a 50% equilibrium ratio, unless the actual equilibrium ratio is determined. In addition, the report should indicate that this ratio is typical of the home's environment, but that any indoor environment may have a different and varying relationship between radon and its decay products. Additionally, the instructions should include:

- a description of closed-building conditions, and a stated requirement that these conditions be maintained 12 hours prior to and during all short-term measurements lasting less than four days and, preferably, for those lasting up to one week;

- directions that the building's heating, ventilating and air-conditioning (HVAC) system and any existing mitigation system should be normally operated 24 hours prior to and during all measurements;

- specific information on the minimum and maximum duration of exposure for the device;

- should the client be performing the test, procedures for placing, retrieving and handling the device; and

- a written non-interference agreement (see Parts 3.5.3 and 4.3.4) to be signed and returned by the client who confirms that they followed all instructions and did not interfere with the conditions or the measurement device. Include the introduction of unconditioned air into the home or closure of normally accessible areas of the home. In this case, the measurement organization should inform the client that these conditions will invalidate measurement results. The tester should then decline to conduct a measurement until the conditions have been corrected.

A permanent radon-reduction system should be fully operational for at least 24 hours prior to testing to determine the mitigation system's effectiveness. The mitigation system is to be operated normally and continuously during the entire measurement period.

4.3.3 Non-Interference Controls

The measurement organization should provide clients with a written statement that discusses the importance of proper measurement conditions and of not interfering with the measurement device or building conditions. This non-interference agreement should be signed and returned by the client confirming that they followed all written instructions and did not interfere with the measurement device.

Organizations that place and retrieve devices should, in addition to providing written guidance, take steps to identify attempts to interfere with the measurement device or building conditions. The reader should refer to Part 3.5 for more information on tamper-resistant testing.

The signed non-interference agreement, a description of all non-interference controls employed, and a statement addressing any observed breaches of the non-interference agreement and/or controls should be made part of the measurement documentation for each test.

4.3.4 Measurement Documentation

Measurement organizations should record sufficient information on each measurement in a permanent log to allow for future data comparisons, interpretations and reports to clients. The EPA recommends that a measurement log be kept with the following information, to be maintained for five years (additional method-specific documentation is outlined in the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols*):

- a copy of the final report, including the measurement results, and the statement outlining any recommendations concerning re-testing or mitigation provided to the building's occupant or agent;

- the address of the building measured, including zip code;

- the exact locations of all measurement devices deployed. It is advisable to diagram the test area, noting the exact location of the detector;

- the exact start and stop dates of the measurement duration (and any times required for analysis);

- a description of the device used, including manufacturer/model/type, and identification (serial) number;

- a description of the condition of any permanent vents, such as crawlspace vents or combustion air supply to combustive appliances;

- a description of any variations from or uncertainties about standard measurement procedures, closed-building conditions, or other factors that may affect the measurement result;

- a description of any non-interference controls used, and copies of signed non-interference agreements; and

- a record of any quality-control measures associated with the test, such as results of simultaneous or secondary measurements.

4.4 Quality Assurance in Radon Testing

Anyone providing measurement services using radon or RDP measurement devices should establish and maintain a quality-assurance program. These programs should include written procedures for attaining quality assurance objectives, and a system for recording and monitoring the results of the quality assurance measurements, as described below. The EPA offers general guidance on preparing quality assurance plans (QAMS-005/80; U.S. EPA 1980); a standard template prepared by a radon industry group is also available (AARST 1991). The quality assurance program should include the maintenance of control charts and related statistical data, as described by Goldin (Goldin 1984), by the EPA (EPA 600/9-76-005; U.S. EPA 1984), and in Appendix B.

4.4.1 Calibration Measurements

Calibration measurements are measurements made in a known radon environment, such as a calibration chamber. Detectors requiring analysis, such as charcoal canisters, alpha-track detectors, electret ion chambers, and radon progeny integrating samplers are exposed in a calibration chamber and then analyzed. Instruments providing immediate results, such as continuous working-level and radon monitors, should be operated in a chamber to establish individual instrument calibration factors.

Calibration measurements must be conducted to determine and verify the conversion factors used to derive the concentration results. These factors are determined normally for a range of concentrations and exposure times, and for a range of other exposure and/or analysis conditions pertinent to the particular device. Determination of these calibration factors is a necessary part of the laboratory analysis, and is the responsibility of the analysis laboratory. These calibration measurement procedures, including the frequency of tests and the number of devices to be tested, should be specified in the quality assurance program maintained by manufacturers and analysis laboratories.

4.4.2 Known Exposure Measurements

Known exposure measurements or spiked samples consist of detectors that have been exposed to known concentrations in a radon calibration chamber. These detectors are to be labeled and submitted to the laboratory in the same manner as ordinary samples to preclude special processing. The results of these measurements are used to monitor the accuracy of the entire measurement system. Suppliers and analysis laboratories should provide for the blind introduction of spiked samples into their measurement processes, and the monitoring of the results in their quality assurance programs. All organizations providing measurement services with passive devices should conduct spiked measurements at a rate of three per 100 measurements, with a minimum of three per year, and a maximum required of six per month.

Providers of measurements with active devices were, under the EPA's former RPP, required to re-calibrate their instruments at least once every 12 months and perform cross-checks with RPP-listed devices at least once every six months. Participation in the EPA's former National Radon Proficiency Program did not satisfy the need for annual calibration, as this program was a performance test and not a calibration procedure.

4.4.3 Background Measurements

Background measurements are required both for continuous monitors and for passive detectors requiring laboratory analysis. Users of continuous monitors must perform sufficient instrument background measurements to establish a reliable instrument background and to check on instrument operation. (For more specific information on how often background measurements should be made, refer to the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols*.)

Passive detectors requiring laboratory analysis require one type of background measurement made in the laboratory and another in the field. Suppliers and analysis laboratories should routinely measure the background of a statistically significant number of unexposed detectors from each batch or lot to establish the laboratory background for the batch, as well as the entire measurement system. This laboratory blank value is subtracted by the laboratory from the field sample results reported to the user, and should be made available to the users for quality assurance purposes. In addition to these background measurements, the organization performing the measurements should calculate the lower limit of detection (LLD) for its measurement system, according to the U.S. Department of Energy. The LLD is based on the detector and analysis system's background and can restrict the ability of some measurement systems to measure low concentrations.

Providers of passive detectors should employ field controls, called blanks, equal to approximately 5% of the detectors that are deployed, or 25 each month, whichever is smaller. These controls should be set aside from each detector shipment, kept sealed and in a low-radon environment, labeled in the same manner as the field samples (to preclude special processing), and returned to the analysis laboratory along with each shipment. These field blanks measure the background exposure that may accumulate during shipment and storage, and the results should be monitored and recorded. The recommended action to be taken if the concentrations measured by one or more of the field blanks is significantly greater than the LLD is dependent upon the type of detector. (More information is available in the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols*.)

4.4.4 Duplicate Measurements

Duplicate measurements provide a check on the quality of the measurement result, and allow the user to make an estimate of the relative precision. Large precision errors may be caused by detector manufacture, and/or improper data transcription or handling by suppliers, laboratories or technicians performing placements. Precision error can be an important component of the overall error, so it is important that all users monitor precision.

Duplicate measurements for both active and passive detectors should be side-by-side measurements made in at least 10% of the total number of measurement locations, or 50 each month, whichever is smaller. The locations selected for duplication should be distributed systematically throughout the entire population of samples. Groups providing measurement services to homeowners can do this by providing two measurements (instead of one) to a random selection of purchasers, with the measurements made side-by-side. As with spiked samples introduced into the system as blind measurements, the precision of duplicate measurements should be monitored and recorded in the quality assurance records. The analysis of data from duplicates should follow the methodology described in Appendix B. If the precision estimated by the user is not within the precision expected of the measurement method, the problem should be reported to the analysis laboratory and the cause investigated.

4.4.5 Routine Instrument Performance Checks

Proper functioning of analysis equipment and operator usage require that the equipment and measurement system be subject to routine checks. Regular monitoring of equipment and operators is vital to ensure consistently accurate results. Performance checks of analysis equipment include the frequent use of an instrument check source. In addition, important components of the device (such as a pump and pump flow rate, battery or electronics) should be checked prior to each measurement, with the results noted in a log. Each user should develop methods for regularly monitoring their measurement system, and for recording and reviewing results. Regular monitoring can be daily, or at least prior to each measurement.

4.4.6 Quality Assurance Plans

All organizations should develop, implement, revise periodically, and maintain a detailed quality assurance plan (QAP) appropriate to each device or method used. (This was a requirement for participation in the EPA's former National Radon Proficiency Program. Specific guidance on the necessary quality control measures for each measurement method is provided in the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols*.)

Organizations that do not use continuous monitors or do not analyze detectors also need to write and follow a QAP, and conduct quality control measurements. These include duplicate, blank and spiked measurements as described in Part 4.4.

For further information on the former Radon Proficiency Program (RPP), contact the EPA at:

U.S. Environmental Protection Agency
Office of Radiation and Indoor Air/Indoor Environments Division (6609J)
401 M St. SW
Washington, DC 20460

phone: (202) 564-9370; fax: (202) 565-2038

Operating Procedures

Organizations performing radon measurements should have a written, device-specific standard operating procedure (SOP) in place for each radon measurement system they use. An SOP must include specific information describing how to operate and/or analyze a particular measurement device. Organizations that analyze devices should develop their own SOP, or adapt manufacturer-developed SOPs for their device(s). Organizations that receive results from a laboratory should have a device-specific SOP for each brand/model/type of device that they use. All SOPs should be consistent with the appropriate protocol outlined in the EPA's *Indoor Radon and Radon Decay Product*

Measurement Device Protocols.

4.6 Providing Information to Consumers

Organizations should provide the client with the following information:

- Devices that will be placed by the customer must be accompanied by instructions on how to use the device. These instructions should be consistent with the EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols*, and include specific information on the minimum and maximum length of time that the device must be exposed.

- The organization should provide, in addition to the measurement results, information on how to mitigate, especially if the results are elevated. The EPA's *Consumer's Guide to Radon Reduction*, or state-required brochures, provide this information. If the *Consumer's Guide* brochure is used, it should be reproduced in its entirety. The company's name may not be placed on the brochure so as to avoid any suggestion of the EPA's endorsement.

4.7 Reporting Test Results

Organizations should report radon measurement results to clients within a few weeks of retrieving exposed devices or receiving an exposed device that has been delivered for analysis. At a minimum, the client report should contain the following information:

- measurement results reported in the units that the device measures. Any measurement results based on radon gas (pCi/L of air) should be stated to no more than one decimal place (e.g., 4.3 pCi/L). Any measurement result based on working levels of radon decay products (WL) should be reported to no more than three decimal places (e.g., 0.033 WL). Any conversions from WL to pCi/L, or from pCi/L to WL, should be presented and explained clearly. If the WL value is converted to a radon concentration, it should be stated in the report to the homeowner that this approximate conversion is based on a 50% equilibrium ratio, unless the actual equilibrium ratio is determined. In addition, the report should indicate that this ratio is typical of the home's environment, but that any indoor environment may have a different and varying relationship between radon and its decay products;

- the dates of the measurement period, and address of the building tested;

- a description of the device used, its manufacturer, model or type, and the device identification (serial) numbers;

- the name (and any relevant identification numbers) of the organization and individual placing and retrieving the device, and the organization analyzing the device, if they are different;

- a statement concerning any observed tampering or deviations from the required test conditions;

- organizations that offer measurement services with grab-sampling devices should provide clients with written notification stating that grab-sample results can be useful diagnostic tools, but should not be used for deciding whether or not to mitigate; and

- diagnostic measurements should be reported as "for diagnostic purposes only."

4.8 Temporary Risk-Reduction Measures

Contractors should refer the home's occupants and agents to the EPA's *Radon Mitigation Standards* (U.S. EPA 1992d) or to the *Consumer's Guide to Radon Reduction* for information on temporary and permanent risk-reduction measures.

If any radon-reduction efforts are identified during the measurement procedures, testers should inform clients that altered conditions during the measurement will invalidate the results, and they should further decline to conduct a measurement until the conditions have been corrected.

4.9 Recommendations for Mitigation

The measurement organization should inform the client that the EPA recommends mitigating exposure for houses with radon levels equal to or greater than 4 pCi/L, and that the EPA recommends in its *Consumer's Guide to Radon Reduction* the use of EPA Radon Contractor Proficiency (RCP)-listed and/or state-listed mitigation contractors to perform the work. Because the EPA has closed its National Radon Proficiency Program, consumers should contact their state's Radon Contacts to verify any state requirements for measurement and mitigation service providers in their states.

Organizations should refer clients to their state radon office for copies of the EPA's *Consumer's Guide to Radon Reduction*, and for any requirements for radon service providers on their own state-listed or other privately-listed mitigators.

Homes should also be tested again after they are mitigated to ensure that radon levels have been reduced. If the occupants' living patterns change and they begin occupying a lower level of their home (such as a basement), the home should be re-tested on that level. In addition, it is a good idea for homes to be re-tested sometime in the future to be sure radon levels remain low.

4.10 Worker Safety

Individuals and organizations should comply with all applicable Occupational Safety and Health Administration (OSHA) standards and guidelines relating to occupational worker exposure, health and safety. Information on worker health and safety contained in EPA or state publications is not considered a substitute for any provisions of the Occupational Safety and Health Act of 1970, or for any standards issued by OSHA.

Appendix

Interpretation of the Results of Side-by-Side Measurements

1. Assessment of Precision (Precision Error)
2. Examples of Control Charts for Precision Error
3. Interpretation of Precision Control Charts

1. Assessment of Precision (Precision Error)

Because radon and working-level measurements, like all measurements, usually do not produce exactly the same results, even for simultaneous (duplicate) co-located measurements. The objective of performing simultaneous or duplicate measurements is to assess the precision error of the measurement method, or test how well two side-by-side measurements agree. This precision error is the "random" component of error, as opposed to the calibration error, which is systematic. The precision error, or the degree of disagreement between duplicates, can be composed of many factors. These include the error caused by the random nature of counting radioactive decay, the slight differences between detector construction (for example, small differences in the amount of carbon in activated-carbon detectors), and differences in handling of detectors (for example, differences in accuracy of the weighing process, and variations of analysis among detectors).

It is critical to understand, document and monitor the precision error. This knowledge and documentation will allow the tester to characterize the precision error for clients. Furthermore, the continual monitoring of precision provides a check on every aspect of the measurement system.

There is a variety of ways to quantitatively assess the precision error based on duplicate measurements. It is first necessary to understand that precision is characterized by a distribution; that is, the side-by-side measurements will exhibit a range of differences. There is some chance that any level of disagreement will be encountered due merely to the statistical fluctuations of counting radioactive decays. The probability of encountering a very large difference between duplicates is smaller than the chance of observing a small difference similar to those that are routinely observed. It is important to recognize that a few high precision errors do not necessarily mean that the measurement system is flawed.

Ideally, the results of duplicates should be assessed in a way that allows for the determination of what level of chance is associated with a particular difference between duplicates. This will allow for the pre-determination of limits for the allowable differences between duplicates before an investigation into the cause of the large differences is made. For example, the warning level, or the level of discrepancy between duplicates which triggers an investigation, may be set at a 5% probability. This level is a difference between duplicates that is so large that, when compared with previous precision errors, should only be observed 5% of the time. A control limit, where further measurements should cease until the problem is corrected, may be set at 1% probability.

A control chart for duplicates for a check source is not as simplified as a control chart used to monitor instrument performance. This is because the instrument's response to a check source should be fairly constant over time. Duplicates are performed at various radon concentrations, however, and the total difference between two measurements is expected to increase as radon levels increase.

The use of statistics, such as the relative percent difference (RPD: the difference divided by the mean), or the coefficient of variation (COV: standard deviation divided by the mean), can be used in a control chart for duplicate measurements at radon concentrations where the expected precision error is fairly constant in proportion to the mean (e.g., at levels greater than around 4 pCi/L or 0.02 WL). At lower concentrations, for example, between 2 pCi/L (or 0.01 WL) and 4 pCi/L (or 0.02 WL), a control chart may be developed by plotting these same statistics; however, the proportion of the precision error to the mean will be greater than that proportion at levels above 4 pCi/L (or 0.02 WL). At concentrations less than about 2 pCi/L (or 0.01 WL), the lower limit of detection may be approached, and the precision error may be so large as to render a control chart not useful.

(Examples of control charts using three different statistics follow.)

2. Examples of Control Charts for Precision Error

Before a control chart can be developed, it is necessary to know, from a history of making reliable quality measurements using the exact measurement system (detectors, analysis equipment and procedures), the level of precision that is routinely encountered when the system is operating well or "in control." It is that in-control precision error that forms the basis of the control chart, and upon which all the subsequent duplicate measurements will be judged. There are two ways of initially determining this in-control level. The preferred method is to perform at least 20 duplicate pairs of measurements at each range of radon concentration for which a control chart is to be prepared. For example, if the tester will assess only precision at concentrations greater than 4 pCi/L (or 0.02 WL), s/he will need at least 20 pairs of measurements at concentrations greater than 4 pCi/L (or 0.02 WL) to assess the in-control level. The average precision error (RPD or CV) should be the in-control level.

The second way to initially set the in-control precision error level is to use a level that has been used by others and that is recognized by the industry and the EPA as a goal for precision (for example, a 10% CV corresponding to a 14% RPD). After at least 20 pairs of measurements are plotted, it will become apparent whether the 10% CV (or 14% RPD) is appropriate for the system. If it is not, a new control chart (using the guidelines to follow) should be prepared so that the warning and control limits are set at the correct probability limits for the testing system.

2.1 Sequential Control Chart Based on Coefficient of Variation

It can be demonstrated that when the expected precision is a constant function of the mean, control limits can be expressed in terms of the CV (CV = S/Xm , where S is the variance or the square of the standard deviation, and Xm is the mean or average of the two measurements). One method for obtaining percentiles for the distribution of the CV is to apply a X-squared (X^2) test:

EXAMPLE EQUATION 1: $X^2_{n-1} = B[(n-1)CV_n^2/(n+(n-1)CV_n^2)]$

where $B = n[(1 + (1/CV^2)]$;

CV_n = the observed CV of the n^{th} pair (the pair that is to be evaluated); and

CV = the in-control CV (e.g., 10% at levels greater than 4 pCi/L).

For duplicates, where n = 2, *Example Equation 1* becomes:

EXAMPLE EQUATION 2: $X^2 = [2 + (2/CV^2)][CV_n^2/(2 + CV_n^2)]$

For a value of 0.10 for CV, it further reduces to

EXAMPLE EQUATION 3: $X^2 = 202[CV_n^2/(2 + CV_n^2)]$

Referring to a X^2 chart, we learn that the probability of exceeding a X^2 of 3.84 is only 5%. Inserting this value of 3.84 for X^2 and solving for CV_n produces a CV_n of 0.20. This level of probability forms the warning level shown in Exhibit 2-1. The control limit corresponds to a X^2 of 6.63 and a CV_n of 0.26, where the probability of exceeding those values is only 1%.

This sequential control chart should be used by plotting results from each pair on the Y-axis, and noting the date and measurement numbers on the X-axis.

2.2 Sequential Control Chart Based on Relative Percent Difference

The relative percent difference, or RPD, is another expression of precision error, and is given as:

EXAMPLE EQUATION 4: $RPD = [100|x_1-x_2|]/[(x_1+x_2)/2]$

For n = 2,

EXAMPLE EQUATION 5: RPD = CV SQRT 2

The control limits for RPD can be obtained simply by multiplying the control limits for CV by the square root of two, or 1.41. These limits are shown in Exhibit 2-2. This sequential control chart for RPD should be used in the same way as the control chart for CV -- that is, with the vertical scale in units of RPD, and the horizontal scale in units of date and measurement numbers.

A control chart using the statistic RPD based on an in-control level of 25% RPD is shown in Exhibit 2-3. The warning level and control limit are set at 50% and 67%, respectively. Use of these limits may be appropriate for measured radon concentrations less than 4 pCi/L.

Exhibit 2-1:

Control Chart for Coefficient of Variation (CV) Based on an In-Control Level of 10% (for duplicates where the average >4 pCi/L or 0.02 WL):

CV or COV = standard deviation of two measurements divided by their average.

Example: Detector A = 5 pCi/L, B=6 pCi/L, CV=13%

If the CV exceeds the control limit, cease measurements until the problem is identified and corrected.

If the CV exceeds the warning level, follow guidance in #3 and see Exhibit 3-1.

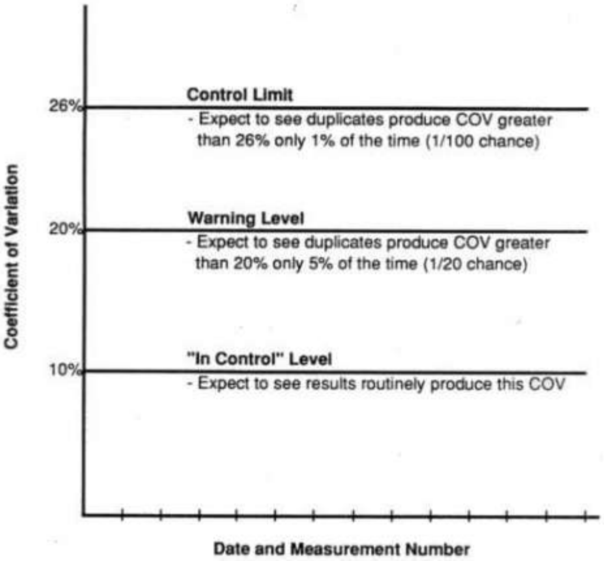
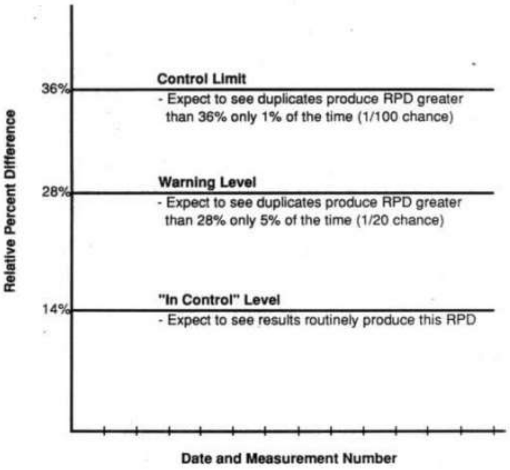


Exhibit 2-2:

Control Chart for Relative Percent Difference (RPD) Based on an In-Control Level of 14% or CV of 10% (for duplicates where average >4 pCi/L or 0.02 WL):



RPD = difference between two measurements divided by their average.

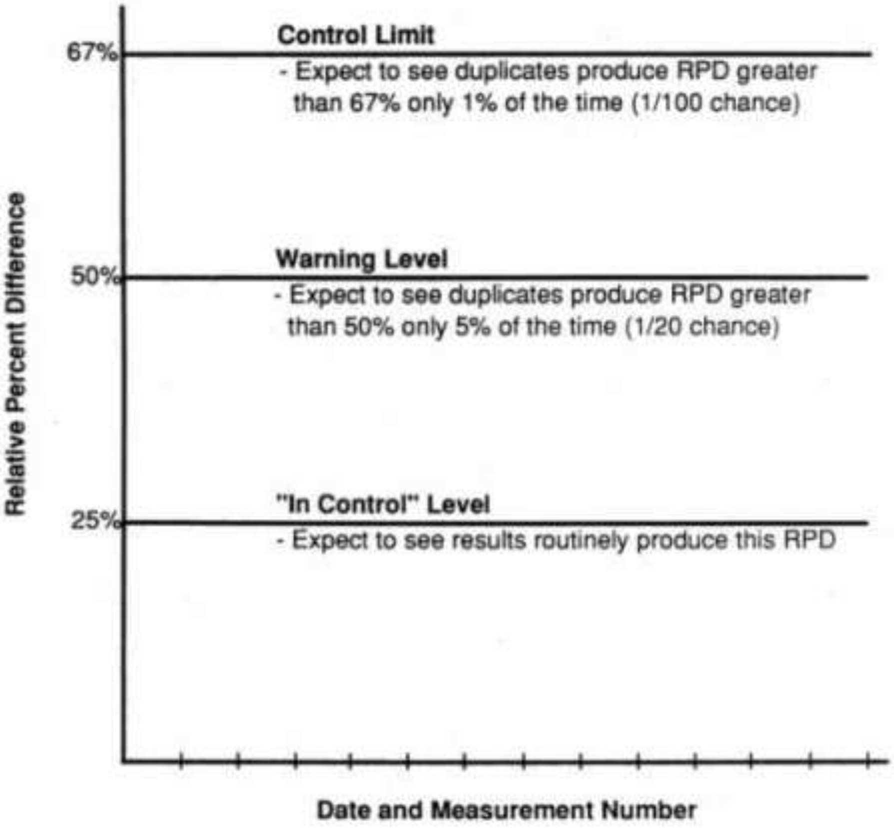
Example: Detector A = 5 pCi/L, B = 6 pCi/L, RPD = 18%

If RPD exceeds the control limit, cease measurements until the problem is identified and corrected.

If RPD exceeds the warning level, follow guidance in #3 and see Exhibit 3-1.

Exhibit 2-3:

Control Chart* for Relative Percent Difference (RPD) Based on an In-Control Level of 25% = CV of 18% (for duplicates where average <4 pCi/L or 0.02 WL):



RPD = difference between two measurements divided by their average.

Example: Detector A = 2 pCi/L, B = 3 pCi/L, RPD = 40%

If RPD exceeds the control limit, cease measurements until the problem is identified and corrected.

If RPD exceeds the warning level, follow guidance in Section #3 and see Exhibit 3-1.

2.3. Range Control Chart

A range control chart can be constructed to evaluate precision using the statistics of the range (difference between two measurements) plotted against the average of the two measurements. The control limits are, again, based on the variability of the measurements, as decided upon from previous results or using an industry standard (e.g., 10%).

In this type of control chart, the limits are expressed in terms of the mean range (Rm) where, for n=2,

EXAMPLE EQUATION 6: Rm = 1.128 s(x)

where s(x) is the standard deviation of a single measurement which reflects counting and other precision errors. The limits can be expressed as follows:

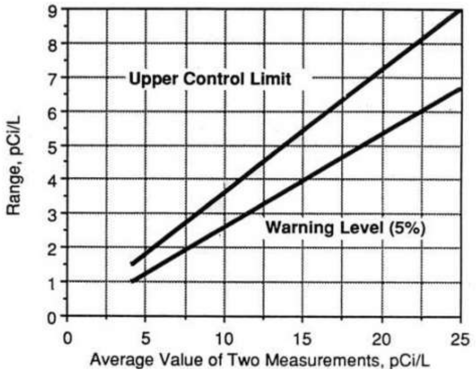
EXAMPLE EQUATION 7: Control limit = 3.69 s(x)

EXAMPLE EQUATION 8: Warning level = 2.53 s(x)

An example range control chart using an assumed s(x) equal to 10% of the mean concentration is shown in Exhibit 2-4. The chart is used by plotting the range versus average concentration as duplicate measurements are analyzed.

Exhibit 2-4:

Range Control Chart to Evaluate Precision Limits Based on s(x) = 0.1xm)



If results exceed the control limit, cease measurements until the problem is identified and corrected.

If results exceed the warning level, follow guidance in Section #3 and see Exhibit 3-1.

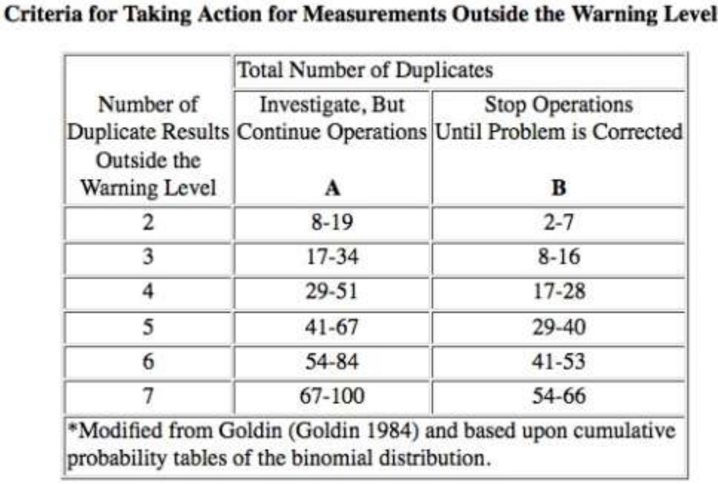
3. Interpretation of Precision Control Charts

The control chart should be examined carefully every time a new duplicate result is plotted. If a duplicate result falls outside the control limit, repeat the analyses, if possible. If the repeated analyses also fall outside the control limit, stop making measurements and identify and correct the problem.

If any measurements fall outside the warning level, use the table in Exhibit 3-1. Refer to the row showing the number of duplicate results outside the warning level. If the total number of duplicate results accumulated in the control chart is contained in Column A, investigate the cause of the high level of precision error, but continue making measurements. If the total number of duplicate results on the chart is contained in Column B, stop making measurements until the cause for the high precision error is found, and it is determined that subsequent measurements will not suffer the same high level of precision error.

Note that the example control charts shown are simplifications of actual conditions because they are premised on the assumption that the precision error is a constant fraction of the mean concentration. In fact, the total precision error may best be represented by a different function of the mean concentration -- for example, the square root of the concentration. The most accurate control chart can be rendered by a range control chart using the measurement uncertainty expressed as the standard deviation, s(x) expected at the concentrations where measurements are made. If the precision error is not a constant fraction of the mean, the control limits will not appear as straight lines, but may exhibit changing slope. However, methods discussed here present a conservative way to monitor, record and evaluate precision error and are very useful for comparing observed precision errors with an industry standard.

Exhibit 3-1:



Criteria for Taking Action for Measurements Outside the Warning Level*

Number of Duplicate Results Outside the Warning Level	Total Number of Duplicates Investigate, But Continue Operations A	 Stop Operations Until Problem is Corrected B
2	8-19	2-7
3	17-34	8-16
4	29-51	17-28
5	41-67	29-40
6	54-84	41-53
7	67-100	54-66

*Modified from Goldin (Goldin 1984) and based upon cumulative probability tables of the binomial distribution.

Note: Charts and calculations are based on guidance provided in the EPA's *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume I.*

Glossary

- **accuracy:** the degree of agreement of a measurement (X) with an accepted reference or true value (T); usually expressed as the difference between the two values (X – T), or the difference as a percentage of the reference or true value (100[X – T]/T), and sometimes expressed as a ratio (X/T).
- **active radon / radon decay product (RDP) measurement device:** a radon or radon decay product measurement system which uses a sampling device, detector and measurement system integrated as a complete unit or as separate but portable components. Active devices include continuous radon monitors, continuous working-level monitors, and grab-radon gas and grab working-level measurement systems, but does not include devices such as electret ion chamber devices, activated-carbon or other adsorbent systems, or alpha-track devices.
- **alpha particle:** two neutrons and two protons bound as a single particle that is emitted from the nucleus of certain radioactive isotopes in the process of decay.
- **background instrument (analysis system or laboratory) count rate:** the nuclear counting rate obtained on a given instrument with a background counting sample. Typical instrument background measurements are:
  - unexposed carbon, for activated-carbon measurement systems;

- scintillation vial containing scintillant and sample known to contain no radioactivity, for scintillation counters;
- background measurements made with continuous radon monitors exposed only to radon-free air (aged air or nitrogen).

- **background fields measurements (blanks):** measurements made by analyzing unexposed (closed) detectors that accompanied exposed detectors to the field. The purpose of field background measurements is to assess any exposure to the detector caused by radon exposure other than from the concentration in the environment to be measured. Results of background field measurements are subtracted from the actual field measurements before calculating the reported concentration. Background levels may be due to electronic noise of the analysis system, leakage of radon into the detector, detector response to gamma radiation, or other causes.

- **background radiation:** radiation arising from radioactive material other than that under testing. Background radiation due to cosmic rays and natural radioactivity are always present; background radiation may also be due to the presence of radioactive substances in building materials.

- **becquerel (Bq):** the International System of Units' (SI) definition of Activity. 1 Bq = 1 disintegration per second.

- **calibrate:** to determine the response or reading of an instrument relative to a series of known values over the range of the instrument; results are used to develop correction or calibration factors.

- **check source:** a radioactive source, not necessarily calibrated, which is used to confirm the continuing satisfactory operation of an instrument.

- **client:** the individual or parties who hire(s) the radon tester.

- **closed-house/building conditions:** During any short-term test, closed-house conditions should be maintained as much as possible while the test is in progress. In tests of less than four days' duration, closed-house conditions should be maintained for at least 12 hours before starting the test, as well as for the duration of the test. While closed-house conditions are not required before the start of tests that are between four and 90 days, closed-house conditions should be maintained as much as possible.

- **coefficient of variation (CV** or **COV), relative standard deviation (RSD):** a measure of precision calculated as the standard deviation of a set of values divided by the average, and usually multiplied by 100 to be expressed as a percentage:

CV = RSD = / x 100 for a sample,

CV' = RSD' = / x 100 for a population

Also see **relative percent difference.**

- **curie (Ci):** a standard measurement for radioactivity; specifically, the rate of decay for a gram of radium at 37 billion decays per second; a unit of radioactivity equal to 3.7×10^{10} disintegrations per second.
- **duplicate measurements:** two measurements made concurrently and in the same location, or side-by-side; used to evaluate the precision of the measurement method.
- **efficiency or intrinsic detector:** the relationship between the number of events recorded (counts, voltage lost, tracks) and the number of radioactive particles incident on the sensitive element of the detector per unit time. Efficiencies for radon detectors are commonly expressed in terms of the calibration factor, which is the number of events (counts) per time (hour or minute) per radon concentration (pCi/L). Methods with high efficiencies will exhibit more counts (signal) per time in response to a given radon level than will a method with a low efficiency.
- **equilibrium ratio** (for radon)**:** equilibrium ratio = WL(100)/(pCi/L). At complete equilibrium (i.e., at an equilibrium ratio of 1), 1 WL of RDPs would be present when the radon concentration was 100 pCi/L. The ratio is never 1 in a house. Due to ventilation and plate-out, the RPDs never reach equilibrium in a residential environment. A commonly assumed equilibrium ratio is 0.5 (i.e., the decay products are halfway toward equilibrium), in which case, 1 WL would correspond to 200 pCi/L. However, equilibrium ratios vary with time and location, and ratios of 0.3 to 0.7 are commonly observed.
- **equilibrium equivalent concentration (EEC):** the radon concentration in equilibrium with its short-lived progeny that has the same potential alpha energy per volume as exists in the environment being measured (also see **working level**).
- **exposure time:** the length of time a specific mail-in device must be in contact with radon or radon decay products to get an accurate radon measurement; also called **exposure period**, **exposure parameters**, and **duration of exposure**.
- **gamma radiation:** short-wavelength electromagnetic radiation of nuclear origin with energies between 10 keV to 9 MeV.
- **integrating device:** a device that measures a single average concentration value over a period of time; also called a **time-integrating device**.
- **lower limit of detection (LLD):** the smallest amount of sample activity which will yield a net count for which there is confidence at a pre-determined level that activity

is present. For a 5% probability of concluding falsely that activity is present, the LLD is approximately equal to 4.65 times the standard deviation of the background counts (assuming large numbers of counts where Gaussian statistics can be used).

- **lowest level suitable for occupancy:** the lowest level currently lived in, or a lower level not currently used (such as a basement) which a prospective buyer could use for living space without renovations. This includes a basement that could be used regularly (for example, a recreation room, bedroom, den or play room).

- **lowest lived-in level:** the lowest level or floor of a home that is used regularly, including areas such as a family room, living room, den, playroom and bedroom.

- **passive radon/radon decay product (RDP) measurement device:** a radon or radon decay product measurement system in which the sampling device, detector and measurement system do not function as a complete, integrated unit. Passive devices include electret ion chamber devices, activated-carbon or other adsorbent systems, or alpha-track devices, but do not include continuous radon/RDP monitors, or grab-radon/RDP measurement systems.

- **picocurie (pCi):** one pCi is one-trillionth of a curie, 0.037 disintegrations per second, or 2.22 disintegrations per minute.

- **picocurie per liter (pCi/L):** a unit of radioactivity corresponding to an average of one decay every 27 seconds in a volume of one liter, or 0.037 decays per second a liter of air or water.
  1 pCi/L = 37 becquerels per cubic meter (Bq/m^3).

- **precision** (or **precision error**): a measure of mutual agreement among individual measurements of the same property, usually under prescribed and similar conditions, most desirably expressed in terms of the standard deviation, but can be expressed in terms of the variance, pooled estimate of variance, range, relative percent difference, or other statistic.

- **quality assurance:** a complete program designed to produce results which are valid, scientifically defensible, and of known precision, bias and accuracy; includes planning, documentation, and quality control activities.

- **quality control:** the system of activities to ensure a quality product, including measurements made to ensure and monitor data quality; includes calibrations, duplicate, blank and spiked measurements, inter-laboratory comparisons and audits.

- **radon (Rn):** a colorless, odorless, naturally occurring, radioactive, inert, gaseous element formed by radioactive decay of radium (Ra) atoms. The atomic number is 86. Although other isotopes of radon occur in nature, radon occurring in indoor air is primarily Rn-222.

- **radon chamber:** an airtight enclosure in which operators can induce and control different levels of radon gas and radon decay products. Volume is such that samples can be taken without affecting the levels of either radon or its decay products within the chamber.

- **relative percent difference (RPD):** a measure of precision, calculated by:

  $RPD = (|X_1 - X_2|)/X_{avg} \times 100$

  where:

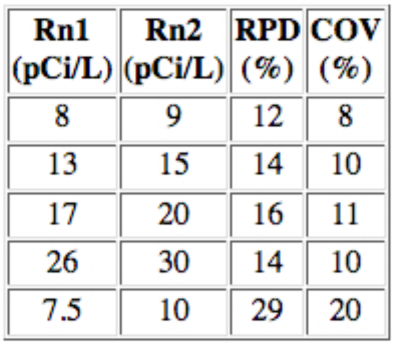
  X_1 = concentration observed with the first detector or equipment;

  X_2 = concentration observed with the second detector, equipment or absolute value;

  $|X_1 - X_2|$ = absolute value of the difference between X_1 and X_2; and

  X_{avg} = average concentration = $((X_1 + X_2) / 2)$

  The relative percent difference (RPD) and coefficient of variation (CV) provide a measure of precision, but they are not equal. Below are examples of duplicate radon results, and the corresponding values of relative percent difference and coefficient of variation:



Rn1 (pCi/L)	Rn2 (pCi/L)	RPD (%)	COV (%)
8	9	12	8
13	15	14	10
17	20	16	11
26	30	14	10
7.5	10	29	20

Note that the RPD divided by the square root of 2 = CV

Also see **coefficient of variation (CV)**.

- **relative standard deviation:** see **coefficient of variation.**

- **sensitivity:** the ability of a radon or WL measurement method to produce reliable measurements at low concentrations. This ability is dependent upon the variability of the background signal (counts not due to radon or WL exposure) which the method records, as well as its efficiency. Methods with stable background rates and high efficiencies will be able to produce reliable measurements at lower concentrations than methods with variable background rates and low efficiencies. Sensitivity can be expressed in terms of the lower limit of detection or minimum detectable activity.

- **signal-to-noise ratio:** for radon and WL detectors, this term expresses the proportion of the number of counts due to exposure to radon or WP (signal) to the number of counts due to background (noise). Measurement methods with high signal-to-noise ratios will produce more counts due to radon or WL exposure (signal) in proportion to the background counts (noise) than will methods with low signal-to-noise ratios. A method with a high signal-to-noise ratio is more likely to exhibit pronounced sensitivity (i.e., be able to produce reliable measurements at low concentrations).

- **spiked measurements**, or **known exposure measurements:** quality control measurements in which the detector or instrument is exposed to a known concentration and submitted for analysis; used to evaluate accuracy.

- **standard deviation:** a measure of the scatter of several sample values around their average. For a sample, the standard deviation *(s)* is the positive square root of the sample variance:

$$s = \frac{\sqrt{\sum_{i=1}^{n} (X_i - X_{ave})^2}}{\sqrt{n - 1}}$$

For a finite population, the standard deviation *(s)* is:

$$\sigma = \frac{\sqrt{\sum_{i=1}^{N} (X_i - \mu)^2}}{\sqrt{N}}$$

where μ is the true arithmetic mean of the population, and *N* is the number of values in the population. The property of the standard deviation that makes it most practically meaningful is that it is in the same units as the observed variable *X.* For example, the upper 95% probability limit on differences between two values is 2.77 times the sample standard deviation.

- **standard operating procedure (SOP):** a written document which details an operation, analysis or action whose mechanisms are prescribed thoroughly and which is commonly accepted as the method for performing certain routine or repetitive tasks.

- **statistical control chart** or **Shewhart control chart:** a graphical chart with statistical control limits and plotted values (for some applications, in chronological order) of some measured parameter for a series of samples. Use of the charts provides a visual display of the pattern of the data, enabling the early detection of time trends and shifts in level. For maximum usefulness in control, such charts should be plotted in a timely manner (i.e., as soon as the data are available).

- **statistical control chart limits:** the limits on control charts that have been derived by statistical analysis and are used as criteria for action, or for judging whether a set of data does or does not indicate lack of control. On a means control chart, the warning level may be two standard deviations above and below the mean, and the control limit may be three standard deviations above and below the mean.

- ***Systeme Internationale* (SI):** the International System of Units as defined by the Conference of Weights and Measures in 1960.

- **test interference:** the altering of test conditions prior to or during the measurement in order to change the radon or radon decay product concentrations, or the altering of the performance of the measurement equipment.

- **time-integrated measurement:** a measurement conducted over a specific time period (e.g., from two days to a year or more) producing results representative of the average value for that period.

- **uncertainty:** the estimated bounds of the deviation from the mean value, expressed generally as a percentage of the mean value, taken ordinarily as the sum of: (1) the random errors (errors of precision) at the 95%-confidence level; and (2) the estimated upper bound of the systematic error (errors of accuracy).

- **working level (WL):** any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of 1.3 x 105 MeV of potential alpha energy. This number was chosen because it is approximately the alpha energy released from the decay products in equilibrium with 100 pCi of Rn-222. Exposures are measured in working level months (WLM).

- **working level months (WLM):** (working level x hours or exposure)/(170 hours/working month). In SI units, 1 WLM = 6 x 105 Bq-h/m^3 (EEC).

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Quiz on Sections 12 & 13

T/F: Long-term measurements are typically three to 12 months in duration.

- True
- False

T/F: Testing durations of less than two days (48 hours) are never acceptable to determine radon concentrations for purposes of assessing the need for mitigation.

- True
- False

_________ is the preferred method of treatment for radon in water.

- Aeration
- Water storage
- UV-light
- Hydro-filtering

A _________ on the lower level may be a good choice for a radon test location because most people generally spend more time there than in any other room in the house.

- bedroom
- kitchen
- workshop
- dining room

The measurement location should not be within ______ feet of the doors and windows or other potential openings to the outdoors.

- 3
- 4
- 2 to 3
- 10

The detector should be at least _____ inches from the floor, and at least ______ inches from other objects.

- 20..... 4
- 20..... 2
- 24..... 20
- 4..... 20

T/F: Because radon measurements, like any other types of measurements, typically produce exactly the same results, especially for simultaneous testing, there will usually be no difference between the two results.

- False
- True

Before starting a short-term test lasting less than four days, make sure the active system has been operating for at least ____ hours before beginning the test.

- 24
- 48 to 72
- 12
- six

Duplicate measurements for both active and passive detectors should be side-by-side measurements made in at least _____ % of the total number of measurement locations, or 50 each month, whichever is smaller.

- 10
- 12
- 75

- 25

An electret ion chamber device is a ________ device.

- passive
- active
- central
- continuous

T/F: As of May 2006, the EPA's Radon Mitigation Standards are no longer recommended or available.

- True
- False

T/F: The primary method for temporarily reducing radon levels is to ventilate the test area with outdoor air.

- True
- False

Section 14: EPA Protocols for Indoor Radon Measurement Devices

Table of Contents

EPA

Indoor Radon And Radon
Decay Product Measurement
Device Protocols

EPA Publication 402-R-92-004 (July 1992; revised):

Indoor Radon and Radon Decay Product Measurement Device Protocols

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This document represents the cumulative efforts of many dedicated individuals within the radon measurement community and the U.S. Environmental Protection Agency. Several key components of this document were prepared by the authors acting as interpreters of the substantial field experience and technical knowledge provided by these individuals, and their assistance is gratefully acknowledged.

SIGNIFICANT CHANGES IN THIS REVISION

This protocol document updates and supersedes the U.S. Environmental Protection Agency (EPA) document entitled *Indoor Radon and Radon Decay Product Measurement Protocols,* issued in March 1989. The updating reflects new information, new procedures and new measurement devices, including a new interim protocol for unfiltered track detectors. The EPA's testing recommendations are summarized in Part 1.2. This measurement strategy reflects the changes made in the most recent edition of *A Citizen's Guide to Radon* (1992). More information is also provided in the EPA measurement guidance document, *Protocols for Radon and Radon Decay Product Measurements in Homes* (1992). Guidance on radon measurements in schools and for real estate transactions is also available.

This edition contains some clarifications and new information on quality assurance. The addition of a Glossary provides definitions and formulas for several of the technical terms used in the document, including accuracy, precision, and the values used to quantify these parameters.

The two previous editions of these protocols (1986, 1989) used the value *coefficient of variation (CV),* defined as the standard deviation divided by the mean, as the expression used for the goal (at 4 pCi/L or 0.02 WL) of 10% for precision. The CV should decrease with increasing concentration. This edition explains that there is a variety of ways to calculate and express precision, including the CV and the *relative percent difference,* defined as the difference between two duplicates divided by their mean. It is important to monitor precision over the entire range of radon levels that are encountered routinely in the measurement program, and that a systematic and documented method for evaluating changes in precision be part of the standard operating procedures. While a limited precision error is desirable (e.g., CV of < 10% at 4 pCi/L), it is most important to maintain the total error of any individual device (including both errors in precision and accuracy) to within ± 25% of the "true" radon or decay product concentration for concentrations at or above 4 pCi/L (0.02 working levels, when the equilibrium ratio is 0.5).

To limit errors in accuracy, this edition recommends that users calibrate their measurement systems at least once every 12 months. Participation in the former National Radon Measurement Proficiency (RMP) Program did not satisfy the need for annual calibration, as this Program was a performance test, not a calibration procedure.

The 1986 and 1989 versions of the measurement protocols recommended that known exposure measurements, or spikes, be conducted at a rate of a few percent of the total number of measurements. These measurements are those for which the detectors are exposed to a known radon concentration in a calibration chamber and analyzed routinely. The results are used to monitor the accuracy of the entire system. This edition clarifies this recommendation, specifying that spikes be conducted at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. This reduces the number of spikes necessary for large users and clarifies the need for spikes by all users.

A significant change in this version of the Measurement Protocols is the requirement that all devices used for measurements in homes, schools and workplaces be deployed for a minimum of 48 contiguous hours. It is important to understand that this minimum measurement period applies to all cases when the result of the measurement is given to a homeowner or building official to determine the need for further measurements or remedial action. The exceptions to the 48-hour measurement period are for those cases when the results will not be reported to a homeowner or building official, but will be used by a mitigator or researcher within the context of their project or research. For example, in-progress diagnostic measurements made in the process of performing mitigation can help to determine points of radon influx. Results of these measurements will be used to assist the contractor to better understand the dynamics of radon within that building, and will be part of a series of measurements, including pre- and post-mitigation 48-hour measurements. Radon researchers testing the effects of mitigation techniques, measurements methods or strategies may also need to perform measurements of flexible durations.

The Agency has implemented a requirement for a minimum measurement period for several reasons. First, it will help ensure consistency among measurement programs, thereby ensuring that measurement results of at least a minimum quality become the basis for decisions by homeowners, school officials, and others responsible for authorizing further measurements or mitigation. This will become increasingly important as radon is measured in more and different types of buildings, and as a more diverse group of people, many without technical backgrounds, find the need to compare and understand these results. Second, a minimum measurement period will guarantee that a certain number of hours, including daily radon cycles, will be incorporated into the result reported to the persons responsible for making a decision about that building.

A period of 48 hours for the minimum measurement period is a policy decision that was arrived at after careful scrutiny of the possible options. It is important that the complete measurement result includes the effects of daily fluctuations in radon levels, so the minimum period needed to be a multiple of a 24-hour day. The Agency deems a single 24-hour period as too short because of the possibility of unforeseen circumstances occurring during the 24 hours; this possibility is diminished if two 24-hour periods form the duration of the measurement. One possible unforeseen circumstance is the improper implementation of closed-building conditions. A longer measurement period increases the chance of identifying such occurrences and helps minimize their impact. Finally, it was deemed important to include two daily cycles so that periods of low and high radon concentrations are well-represented in the overall result.

There may be some situations when it is impossible to terminate the measurement at exactly 48 hours; therefore, a grace period of two hours will be allowed. A measurement made over a period of at least 46 hours is sufficient and is considered a two-day measurement. This grace period applies to all measurement methods.

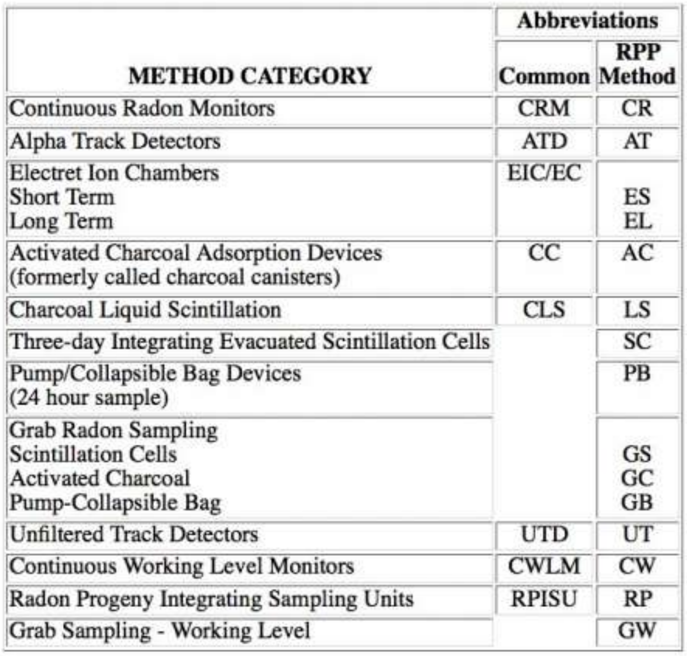
Concerns have been raised regarding the requirement of a minimum distance of 30 inches from the floor for placement of detectors. The change from 20 inches to 30 inches was made in the March 1989 protocols. This distance is not thought to be critical, so this version again recommends a minimum distance of at least 20 inches. In addition, the 1989 edition was not specific regarding the minimum distance between the measurement location and an exterior wall; this revision clarifies that distance to be about 3 feet, or 1 meter. Suspended detectors should also be about 6 to 8 feet above the floor (i.e., within the general breathing zone).

Parts 2.6 (Evacuated Scintillation Cells), 2.7 (Pump/Collapsible Bags), and 2.8 (Radon Grab-Sampling) of the previous protocol document describe methods that share common features. For this reason, the three measurement methods are combined into one section in this revision. In addition, Appendices A and B of the previous document are now part of their corresponding protocols. The radon grab-sampling and pump/collapsible bag methods are not appropriate for purposes of determining the need for further measurements or for mitigation because they do not comply with the 48-hour minimum measurement period.

This revision also reflects the method designations used in the former National Radon Proficiency (RPP) Program. A two-letter code for each method has been adopted, although ATDs (AT), RPISUs (RP), and EICs/ECs (ES or EL) may still be referred to by their traditional acronyms. The current designations are as follows:

Exhibit 1-2

Radon and Radon Decay Product Measurement Method Abbreviations



	Abbreviations	
METHOD CATEGORY	**Common**	**RPP Method**
Continuous Radon Monitors	CRM	CR
Alpha Track Detectors	ATD	AT
Electret Ion Chambers Short Term Long Term	EIC/EC	 ES EL
Activated Charcoal Adsorption Devices (formerly called charcoal canisters)	CC	AC
Charcoal Liquid Scintillation	CLS	LS
Three-day Integrating Evacuated Scintillation Cells		SC
Pump/Collapsible Bag Devices (24 hour sample)		PB
Grab Radon Sampling Scintillation Cells Activated Charcoal Pump-Collapsible Bag		 GS GC GB
Unfiltered Track Detectors	UTD	UT
Continuous Working Level Monitors	CWLM	CW
Radon Progeny Integrating Sampling Units	RPISU	RP
Grab Sampling - Working Level		GW

(Photos courtesy of Keith Braun, Signature Property Inspection, www.brauninspection.com)

Part 1: General Considerations

1.1 Introduction and Background
1.2 General Guidance on Measurement Strategy, Measurement Conditions, Device Location Selection and Documentation
1.3 Quality Assurance

1.1 Introduction and Background

The risk of lung cancer due to exposure to radon and its decay products is of concern to state and federal health officials. There is increased awareness that indoor radon concentrations may pose a significant health threat, and that there are areas in the country where some indoor levels are such that even short-term exposures can cause a significant increase in risk. It is extremely important that homes and other buildings be tested to determine if elevated radon levels are present indoors. However, in the process, the collection of unreliable or misleading data must be avoided.

There are many federal, state, university and private organizations now performing measurements or planning measurement programs. It is important for these different groups to follow consistent procedures to assure accurate and reproducible measurements, and to enable valid inter-comparison of measurement results from different studies.

The objective of this document is to provide information, recommendations and technological guidance for anyone providing measurement services using 15 radon and radon decay product measurement methods. The EPA has evaluated these techniques and found them to be satisfactory. However, the Agency has not conducted large-scale field tests using the unfiltered track-detection technique, and an interim protocol has been prepared with the assistance of researchers who have field experience with this method. As the EPA and others acquire more experience with this interim technique, the guidelines may be revised.

These protocols provide method-specific technological guidance that can be used as the basis for standard operating procedures. In keeping with good laboratory practices, each radon measurement company should develop its own detailed, instrument-specific procedures that incorporate recommendations found in this and other radon-related EPA protocol and guidance documents. Mere duplication of sections of this report will not constitute an adequate standard operating procedure.

The recommendations contained in this report are similar to those being developed by industry and other groups (e.g., the American Society of Testing and Materials [ASTM 1991] and the American Association of Radon Scientists and Technologists [AARST 1991a]). This report is a guidance document; however, one condition of participation in the EPA's National Radon Proficiency Program (RPP) was conformance with these protocols.

1.2 General Guidance on Measurement Strategy, Measurement Conditions, Device Location Selection and Documentation

1.2.1 Measurement Strategy

The choice of measurement strategy depends upon the purpose of the radon measurement and the type of building where the measurement is made, such as a home, school or workplace. The EPA's recommendations for measuring radon in various situations are outlined in documents such as the second edition of *A Citizen's Guide to Radon* (1992), the EPA's *Home Buyer's and Seller's Guide to Radon* (1992), the *Protocols for Radon and Radon Decay Product Measurements in Homes* (1992), and in *Radon Measurements in Schools* (EPA Document #402-R-92-014, revised July 1993). The following discussion on measurement conditions, device location selection and documentation apply to measurements made in all types of buildings.

1.2.2 Measurement Conditions

The following conditions should exist prior to and during a measurement period to standardize the measurement conditions as much as possible. This list may be applied to each of the measurement methods discussed in Parts 2 and 3. However, there may also be method-specific conditions that are mentioned in the applicable protocol.

Short-term measurements lasting 90 days or less should be made under closed-building conditions. To the extent reasonable, all windows, outside vents and external doors should be closed (except for normal entrance and exit) for 12 hours prior to and during the measurement period. Normal entrance and exit include opening and closing a door, but an external door should not be left open for more than a few minutes. These conditions are expected to exist as normal living conditions during the winter in northern climates. For this reason, short-term measurements should be made during winter periods whenever possible.

In addition to maintaining closed-building conditions during the measurement, closed-building conditions for 12 hours prior to the initiation of the measurement are required for measurements lasting less than four days, and are recommended prior to measurements of up to a week.

Internal-external air exchange systems (other than a furnace), such as high-volume attic and window fans, should not be operating during measurements and for at least 12 hours before measurements are initiated. Air-conditioning systems that recycle interior air may be operating. Normal operation of permanently installed air-to-air heat exchangers may also continue during closed-building conditions.

In buildings where permanent radon mitigation systems have been installed, these systems should be functioning during the measurement period.

Short-term tests lasting just two or three days should not be conducted if severe storms with high winds (greater than 30 mph) or rapidly changing barometric pressure are predicted during the measurement period. Weather predictions available on local news stations can provide sufficient information to determine if these conditions are likely.

In southern climates, or when measurements must be made during a warm season, the closed-building conditions are satisfied by meeting the criteria listed above. The closed-building conditions must be verified and maintained more rigorously, however, when they are not the normal living conditions.

1.2.3 Measurement Device Location Selection

The following criteria should be applied to select the location of the detector within a room. For further guidance on selecting an appropriate area in a building in which to place the measurement device, refer to the relevant documents mentioned in Part 1.2.1. The following list may be applied to each of the measurement methods discussed in Parts 2 and 3. However, there may be method-specific location criteria that will be mentioned in the applicable protocol.

A position should be selected where the detector will not be disturbed during the measurement period and where there is adequate room for the device.

The measurement should not be made near drafts caused by heating, ventilating and air-conditioning vents, doors, fans or windows. Locations near excessive heat, such as fireplaces or in direct sunlight, and areas of high humidity should be avoided.

The measurement location should not be within 3 feet (90 centimeters) of windows or other potential openings in the exterior wall. If there are no potential openings (e.g., windows) in the exterior wall, then the measurement location should not be within 1 foot (30 centimeters) of the exterior walls of the building.

The detector should be at least 20 inches (50 centimeters) from the floor, and at least 4 inches (10 centimeters) from other objects. For those detectors that may be suspended, an optimal height for placement is in the general breathing zone, such as 6 to 8 feet (2 to 2.5 meters) from the floor.

In general, measurements should not be made in kitchens, laundry rooms, closets or bathrooms.

1.2.4 Documentation

The operator of the measurement device must record enough information about the measurement in a permanent log so that data interpretation and comparison can be made.

The results of radon decay product measurements should be reported in working levels (WL). If the WL value is converted to a radon concentration, which is also reported to the homeowner, it should be stated that this approximate conversion is based on a 50% equilibrium ratio. In addition, the report should indicate that this ratio is typical of the home environment, but any indoor environment (especially in schools and workplaces) may have a different and varying relationship between radon and decay products.

The following list may be applied to each of the measurement methods discussed in Parts 2 and 3 (however, there may be method-specific documentation requirements that will be mentioned in the applicable protocol):

- the start and stop times and dates of the measurement;
- whether the standardized measurement conditions (as discussed in Part 1.2.2) are satisfied;
- the exact location of the device, on a diagram of the room and building, if possible;
- easily obtained information that may be useful, such as the type of building and heating system, the existence of a crawlspace or basement, the occupants' smoking habits, and the operation of humidifiers, air filters, electrostatic precipitators and clothes dryers;
- the serial number and manufacturer of the detector, along with the code number or description which uniquely identifies customer, building, room and sampling position; and
- the condition (open or closed) of any crawlspace vents.

1.3 Quality Assurance

The objective of quality assurance is to ensure that data are scientifically sound and of known precision and accuracy. This section discusses the four general categories of quality control measurements; specific guidance is provided for each method in the relevant section.

Anyone providing measurement services using radon and radon decay product measurement devices should establish and maintain quality assurance programs. These programs should include written procedures for attaining quality assurance objectives, and a system for recording and monitoring the results of the quality assurance measurements described below. The EPA offers general guidance on preparing quality assurance plans (U.S. EPA 1980); a draft standard prepared by a radon industry group is also available (AARST 1991b). The quality assurance program should include the maintenance of control charts and related statistical data, as described by Goldin (Goldin 1984) and by the EPA (U.S. EPA 1984).

1.3.1 Calibration Measurements

Calibration measurements are samples collected or measurements made in a known radon environment, such as a calibration chamber. Detectors requiring analysis, such as charcoal canisters, alpha-track detectors, electret ion chambers, and radon progeny integrating samplers, are exposed in a calibration chamber and then analyzed. Instruments providing immediate results, such as continuous working-level and radon monitors, should be operated in a chamber to establish individual instrument calibration factors.

Calibration measurements must be conducted to determine and verify the conversion factors used to derive the concentration results. These factors are determined normally for a range of concentrations and exposure times, and for a range of other exposure and/or analysis conditions pertinent to the particular device. Determination of these calibration factors is a necessary part of the laboratory analysis, and is the responsibility of the analysis laboratory. These calibration measurement procedures, including the frequency of tests and the number of devices to be tested, should be specified in the quality assurance program maintained by manufacturers and analysis laboratories.

Known exposure measurements or spiked samples consist of detectors that have been exposed to known concentrations in a radon calibration chamber. These detectors are labeled and submitted to the laboratory in the same manner as ordinary samples to preclude special processing. The results of these measurements are used to monitor the accuracy of the entire measurement system. Suppliers and analysis laboratories should provide for the blind introduction of spiked samples into their measurement processes, and the monitoring of the results in their quality assurance programs. Providers of passive measurement devices should conduct spiked measurements at a rate of three per 100 measurements, with a minimum of three per year, and a maximum required of six per month. Providers of measurements with active devices are required to re-calibrate their instruments at least once every 12 months. Participation in the EPA's former National Radon Proficiency Program (RPP) did not satisfy the need for annual calibration, as this program was a performance test, not a calibration procedure.

1.3.2 Background Measurements

Background measurements are required both for continuous monitors and for passive detectors requiring laboratory analysis. Users of continuous monitors must perform sufficient instrument background measurements to establish a reliable instrument background, and to act as a check on instrument operation.

Passive detectors requiring laboratory analysis require one type of background measurement made in the laboratory and another in the field. Suppliers and analysis laboratories should routinely measure the background of a statistically significant number of unexposed detectors from each batch or lot to establish the laboratory background for the batch and the entire measurement system. This laboratory blank value is subtracted routinely (by the laboratory) from the field sample results reported to the user, and should be made available to the users for quality assurance purposes. In addition to these background measurements, the organization performing the measurements should calculate the lower limit of detection (LLD) for its measurement system. This LLD is based on the detector and analysis system's background and can restrict the ability of some measurement systems to measure low concentrations.

Providers of passive detectors should employ field controls (called blanks) equal to approximately 5% of the detectors that are deployed, or 25 each month, whichever is smaller. These controls should be set aside from each detector shipment, kept sealed and in a low-radon environment, labeled in the same manner as the field samples to preclude special processing, and returned to the analysis laboratory along with each shipment. These field blanks measure the background exposure that may accumulate during shipment and storage, and the results should be monitored and recorded. The recommended action to be taken if the concentrations measured by one or more of the field blanks is significantly greater than the LLD is dependent upon the type of detector and is discussed in the section for each method.

1.3.3 Duplicate (Collocated) Measurements

Duplicate measurements provide a check on the quality of the measurement result, and allow the user to make an estimate of the relative precision. Large precision errors may be caused by detector manufacture, or improper data transcription or handling by suppliers, laboratories or technicians performing placements. Precision error can be an important component of the overall error, so it is important that all users monitor precision.

Duplicate measurements should be side-by-side measurements made in at least 10% of the total number of measurement locations, or 50 each month, whichever is smaller. The locations selected for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurements to homeowners can do this by providing two measurements, instead of one, to a random selection of purchasers, with the measurements made side-by-side. As with spiked samples introduced into the system as blind measurements, the precision of duplicate measurements should be monitored and recorded in the quality assurance records. The analysis of data from duplicates should follow the methodology described by Goldin in Part 5.3 of his report, and plotted on range control charts (Goldin 1984, U.S. EPA 1984). If the precision estimated by the user is not within the precision expected of the measurement method, the problem should be reported to the analysis laboratory and the cause investigated.

1.3.4 Routine Instrument Performance Checks

Proper functioning of analysis equipment and operator usage require that the equipment and measurement system be subject to routine checks. Regular monitoring of equipment and operators is vital to ensure consistently accurate results. Performance checks of analysis equipment include the frequent use of an instrument check source. In addition, important components of the device (such as a pump, battery and electronics) should be checked regularly, and the results noted in a log. Each user should develop methods for regularly monitoring their measurement system (preferably daily), and for recording and reviewing results.

The EPA established the National RMP Program (now the National Radon Proficiency Program, or RPP) under the Indoor Radon Abatement Act (IRAA) of 1988 to enable participants to demonstrate their proficiency at measuring radon and radon decay product concentrations. One condition of successful participation in the former RPP was that the total error of any individual device (including errors in both precision and accuracy) be within ±25% of the "true" radon or radon decay product concentration at or above 4 pCi/L. For further information on the former RPP and the two private proficiency programs run by NEHA and the NRSB, visit the EPA's web site at: http://www.epa.gov.

Part 2: Indoor Measurement Device Protocols

2.1 Protocol for Using Continuous Radon Monitors (CR) to Measure Indoor Radon Concentrations

2.1.1 Purpose

This protocol provides guidance for using continuous radon monitors (CR) to measure indoor radon concentrations accurately and to obtain reproducible results. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid comparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in *Protocols for Radon and Radon Decay Product Measurements in Homes* (1992) or other appropriate EPA measurement guidance documents.

2.1.2 Scope

This protocol covers, in general terms, the sample collection and analysis method, the equipment needed, and the quality control objectives of measurements made with CRs. It is not meant to replace an instrument manual but, rather, to provide guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to:

U.S. Environmental Protection Agency
Office of Radiation and Indoor Air, Indoor Environments Division (6609J)
401 M Street SW
Washington, DC 20460

phone: (202) 564-9370; fax: (202) 565-2038.

2.1.3 Method

There are three general types of CR monitors covered by this protocol. In the first type, ambient air is sampled for radon in a scintillation cell after passing through a filter that removes radon decay products and dust. As the radon in the cell decays, the radon decay products plate out on the interior surface of the scintillation cell. Alpha particles produced by subsequent decays, or by the initial radon decay, strike the zinc-sulfide coating on the inside of the scintillation cell, thereby producing scintillations. The scintillations are detected by a photomultiplier tube in the detector, which generates electrical pulses. These pulses are processed by the detector's electronics and the data are usually stored in the memory of the monitor where results are available for recall or transmission to a data logger or printer.

This type of CR monitor uses either a flow-through cell or a periodic-fill cell. In the flow-through cell, air is drawn continuously through the cell by a small pump. In the periodic-fill cell, air is drawn into the cell once during each pre-selected time interval; then, the scintillations are counted, and the cycle repeated. A third variation operates by radon diffusion through a filter area with the radon concentration in the cell varying with the radon concentration in the ambient air, after a small diffusion time lag. The concentrations measured by all three variations of cells lag the ambient radon concentrations because of the inherent delay in the radon decay product disintegration process.

A second type of CR monitor operates as an ionization chamber. Radon in the ambient air diffuses into the chamber through a filtered area so that the radon concentration in the chamber follows the radon concentration in the ambient air with some small time lag. Within the chamber, alpha particles emitted during the decay of radon atoms produce bursts of ions, which are recorded as individual electrical pulses for each disintegration. These pulses are processed by the monitor electronics; the number of pulses counted is usually displayed on the monitor, and the data are available for processing by an optional data logger/printer.

A third type of CR monitor functions by allowing ambient air to diffuse through a filter into a detection chamber. As the radon decays, the alpha particles are counted using a solid-state silicon detector. The measured radon concentration in the chamber follows the radon concentration in the ambient air by a small time lag.

2.1.4 Equipment

Equipment required depends on the type and model of CR monitor used. Aged air or nitrogen must be available for introduction into the CR monitor to measure the background count rate during calibration. For scintillation cell-type CRs, sealed scintillation cells with a measured low background should be available as spare cells.

2.1.5 Pre-Deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The CR measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

2.1.5.1 Pre-Sampling Testing

Before and after each measurement, the CR monitor should be tested carefully, according to manufacturer's directions, to verify that the correct input parameters and the unit's clock or timer are set properly, and verify the operation of the pump. Flow rates within the range of the manufacturer's specifications are satisfactory.

After every 1,000 hours of operation of scintillation cell-type CRs, the background count rate should be checked by purging the unit with clean, aged air or nitrogen, in accordance with the procedures identified in the operating manual for the instrument. In addition, the background count rate of all CR types should be monitored more frequently by operating the instrument in a low-radon environment.

Participation in a laboratory inter-comparison program should be conducted initially, and at least once every 12 months thereafter, and after equipment repair, to verify that the conversion factor used by the CR monitor is accurate. This is done by comparing the unit's response to a known radon concentration. At this time, the correct operation of the pump should be verified. (Participation in the EPA's National Radon Proficiency Program [RPP] did not satisfy the need for annual calibration, as this program was a performance test rather than an internal calibration.)

2.1.6 Measurement Criteria

Refer to Part 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.1.7 Deployment and Operation

2.1.7.1 Location Selection

Refer to Part 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.1.7.2 Operation

The CR monitor should be programmed to run continuously, recording periodically the radon concentration for at least 48 hours. Longer measurements may be required, depending on the CR type and radon level being measured. An increase in operating time decreases the uncertainty associated with using the measurement result to represent a longer-term average concentration.

Care should be taken to account for data that are produced before equilibrium conditions have been established in a flow-through cell. Generally, conditions stabilize after the first four hours. Measurements made prior to this time are low and should either be discarded or used to estimate radon concentrations using pre-established system constants. If the first four hours of data from a 48-hour measurement are discarded, the remaining hours of data can be averaged and are sufficient to represent a two-day measurement.

2.1.8 Retrieval of Monitors

When the measurement is terminated, the operator should document the stop date and stop time, and whether the closed-building conditions are still in effect.

2.1.9 Documentation

Refer to Part 1.2.4 for the list of standard information that must be documented.

The serial numbers of the CR monitor, scintillation cells and other equipment must also be recorded.

2.1.10 Results

2.1.10.1 Sensitivity

Most CR monitors are capable of a lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) of 1 picocurie per liter (pCi/L) or less.

2.1.10.2 Precision

Most CR monitors can achieve a coefficient of variation of less than 10% at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.1.11 Quality Assurance

The quality assurance program for CR measurements includes four parts: (1) calibration; (2) background measurements; (3) duplicate measurements; and (4) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements, and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.1.11.1 Calibration

Every CR monitor should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. (Note that an inherent element in the calibration process is a thorough determination of the background count rate using clean, aged air or nitrogen.) Subsequent re-calibrations and background checks should be done at least once every 12 months, with cross-checks to a recently calibrated instrument at least semi-annually. All cells need individual calibration factors.

2.1.11.2 Background Measurements

After every 1,000 hours of operation of scintillation cell-type CRs (about every 20th 48-hour measurement), and whenever any type of CR is calibrated, the background should be checked by purging the monitor with clean, aged air or nitrogen. In addition, the background count rate should be monitored more frequently by operating the instrument in a low-radon environment. Cells which develop a high background after prolonged use should be re-conditioned by the manufacturer.

2.1.11.3 Duplicate Measurements

When two or more CR monitors of the same type are available (e.g., scintillation cell, ionization chamber or silicon detector types), the precision of the measurements can be estimated by operating the monitors side-by-side. The analysis of duplicate results should follow the methodology described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.1.11.4 Routine Instrument Checks

Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check cell (for scintillation cell-type CRs) prior to beginning each measurement. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

If a check source is unavailable or incompatible with the type of CR monitor being used, an informal inter-comparison with another measurement method that has proven reliability (for example, in the EPA's National RMP Program) should be conducted at least every 10th measurement. In addition, it is important to regularly check all components of the equipment that affect the result, including battery and electronics, and to document these checks.

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

2.2 Protocol for Using Alpha-Track Detectors (AT or ATD) to Measure Indoor Radon Concentrations

2.2.1 Purpose

This protocol provides guidance for using alpha-track detectors (AT or ATD) to obtain accurate and reproducible measurements of indoor radon concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid inter-comparison of results. The investigator should also follow guidance provided by the EPA in *Protocols for Radon and Radon Decay Product Measurements in Homes*, or other appropriate EPA measurement guidance documents.

2.2.2 Scope

This protocol covers, in general terms, the equipment, procedures and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, to provide guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the EPA.

2.2.3 Method

An AT consists of a small piece of plastic or film enclosed in a container with a filter-covered opening or similar design for excluding radon decay products. Radon diffuses into the container, and alpha particles emitted by the radon and its decay products strike the detector and produce sub-microscopic damage tracks. At the end of the measurement period, the detectors are returned to a laboratory. Plastic detectors are placed in a caustic solution that accentuates the damage tracks so they can be counted using a microscope or an automated counting system. The number of tracks per unit area is correlated to the radon concentration in air using a conversion factor derived from data generated at a calibration facility. The number of tracks per unit of analyzed detector area produced per unit of time (minus the background) is proportional to the radon concentration. AT detectors function as true integrators and measure the average concentration over the exposure period.

Many factors contribute to the variability of AT results, including differences in the detector responses within and between batches of plastic, non-uniform plate-out of decay products inside the detector holder, differences in the number of background tracks, and variations in etching conditions. Since the variability in AT results decreases with the number of net tracks counted, counting more tracks over a larger area of the detector, particularly at low exposures, will reduce the uncertainty of the result.

2.2.4 Equipment

ATs are available from commercial suppliers. These suppliers offer contract services in which they provide the detector and subsequent analysis and reporting for a fixed price. Establishing an in-house capability to provide packaged detectors, a calibration program, and an analysis program would probably not be practical or economically advantageous for most users. Therefore, details for establishing the analytical aspects of an AT program are omitted from this protocol. Additional details concerning AT programs have been reviewed elsewhere (Fleischer et al. 1965, Lovett 1969).

Assuming ATs are obtained from a commercial supplier, the following equipment is needed to initiate a measurement:

- an AT in an individual, sealed container (such as an aluminized plastic bag) to prevent extraneous exposure before deployment;
- a means to attach the AT to its measurement location, if it is to be hung from the wall or ceiling;
- an instruction sheet for the occupant, a sample log sheet, and a shipping container (along with a prepaid mailing label, if appropriate);
- manufacturer's instructions for re-sealing the detector at the time of retrieval and prior to returning it to the supplier for analysis; and
- a data collection log, if appropriate.

2.2.5 Pre-Deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The AT measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The AT should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

2.2.6 Measurement Criteria

Refer to Part 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

A 12-month AT measurement provides information about radon concentrations in a building during an entire year, so the closed-building conditions do not have to be satisfied to perform a valid year-long measurement.

2.2.7 Deployment

2.2.7.1 Location Selection

Refer to Part 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

If the detector is installed during a site visit, the final site selected should be shown to the building occupant to be certain it is acceptable for the duration of the measurement period.

2.2.7.2 Timely Deployment

A group of ATs should be deployed into houses as soon as possible after delivery from the supplier. In order to minimize chances of high background exposures, users should not order more ATs than they can reasonably expect to install within the following few months. If the storage time exceeds more than a few months, the background exposures from a sample of the stored detectors should be assessed to determine if they are different from the background of detectors that are not stored for long periods. The supplier's instructions regarding storage and background determination should be followed. This background assessment of detectors stored for long periods is not necessary if the analysis laboratory routinely measures the background of stored detectors, and if the stored detectors remain tightly sealed.

The sampling period begins when the protective cover or bag is removed. The edge of the bag must be cut carefully, or the cover removed, so that it can be reused to re-seal the detector at the end of the exposure period. The detector and the radon-proof container should be inspected to make sure that they are intact and have not been physically damaged in shipment or handling.

2.2.8 Retrieval of Detectors

At the end of the measurement period (usually 90 days for short-term tests, and one year for long-term measurements), the detector should be inspected for damage or deviation from the conditions entered in the log book at the time of deployment. Any changes should be noted in the log book. The time and date of removal should be entered on the data form for the detector and in the log book, if used. The detector should then be re-sealed following the instructions provided by the supplier. After retrieval, the detectors should be stored in a low-radon environment and returned as soon as possible to the analytical laboratory for processing. In many cases, attempts at re-sealing ATs have not been totally successful, resulting in some continued exposure of the detectors beyond the deployment period. This extra exposure could bias the results high if the detectors are held for a significant length of time prior to analysis.

2.2.9 Documentation

Refer to Part 1.2.4 for the list of standard information that should be documented.

2.2.10 Analysis Requirements

2.2.10.1 Sensitivity

The lower limit of detection (LLD) is dependent upon the stability of the number of background tracks. Depending upon the system used, the background may be less variable if a greater area is analyzed. With present ATs, routine counting can achieve an LLD of 1 pCi/L-month, and an LLD of 0.2 pCi/L-month may be achieved by counting additional area.

2.2.10.2 Precision

The precision should be monitored using the results of the duplicate detectors described in Part 2.2.11.3 of this protocol, rather than a precision quoted by the manufacturer. The precision of an AT system is dependent upon the total number of tracks counted on the flank and test detector and, therefore, the area of the detector that is analyzed. If few net tracks are counted, poor precision is obtained. Thus, it is important that the organization performing the measurement with an AT arranges for counting an adequate area or number of net tracks.

2.2.11 Quality Assurance

The quality assurance program for AT measurements involves five separate parts: (1) calibration; (2) known exposure measurements; (3) duplicate (collocated) detectors; (4) control detectors; and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements, and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.2.11.1 Calibration

Every AT laboratory system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of a calibration factor requires exposure of ATs to a known radon concentration in a radon exposure chamber. These calibration exposures are to be used to obtain or verify the conversion factor between net tracks per unit area and radon concentration. (Participation in th EPA's former National Radon Proficiency Program [RPP] did not satisfy the need for annual calibration, as this program was a proficiency test rather than an internal calibration.) The following guidance is provided to manufacturers and suppliers of AT services as minimum requirements in determining the calibration factor:

- ATs should be exposed in a radon chamber at several different radon concentrations or exposure levels similar to those found in the tested buildings (a minimum of three different concentrations).
- A minimum of 10 detectors should be exposed at each level.
- A calibration factor should be determined for each batch or sheet of detector material received from the material supplier. Alternatively, calibration factors may be established from several sheets, and these factors extended to detectors from sheets exhibiting similar sensitivities (within pre-established tolerance limits).

2.2.11.2 Known Exposure Measurements

Anyone providing measurement services with AT devices should submit ATs with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) detectors should be labeled in the same manner as field detectors to ensure identical processing. The results of the spiked detector analyses should be monitored and recorded. Any significant deviation from the known concentration to which they were exposed should be investigated.

2.2.11.3 Duplicate (Collocated) Detectors

Anyone providing measurement services with AT devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10% of the number of detectors deployed each month, or 50, whichever is smaller. The pair of detectors should be treated identically in every respect. They should be shipped, stored, opened, installed, removed and processed together, and not identified as duplicates to the processing laboratory. The samples selected for duplication should be distributed systematically throughout the entire population of measurements. Groups selling measurements to homeowners can accomplish this by providing two detectors instead of one to a random selection of purchasers, with instructions to place the detectors side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. Data from duplicate detectors should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.2.11.4 Control Detectors

2.2.11.4.1 Laboratory Control Detectors

The laboratory background level for each batch of ATs should be established by each laboratory or supplier. Suppliers should measure the background of a statistically significant number of unexposed ATs that have been processed according to their standard operating procedures. Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.2.11.4.2 Field Control Detectors

Field control detectors must be a component of any AT measurement program. Field control ATs (field blanks) should consist of a minimum of 5% of the devices that are deployed every month, or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed and in a low-radon environment (less than 0.2 pCi/L), label them in the same manner as the field ATs to assure identical processing, and send them back to the supplier with the field ATs for analysis. These control devices are necessary to measure the background exposure that accumulates during shipment and storage. The results should be monitored and recorded. If one or a few field blanks have concentrations significantly greater than the LLD established by the supplier, it may indicate defective packaging or handling. If the average value from the field control devices (field blanks) is significantly greater than the LLD established by the supplier, this average value should be subtracted from the individual values reported for the other devices in the exposure group.

It may be advisable to use three sets of detectors (pre-exposure, field, and post-exposure background) in order to allow the most thorough and complete evaluation of radon levels. For example, one group of detectors (pre-exposure detectors) may be earmarked for background measurement, and returned for processing immediately after the other detectors are deployed. The results from these detectors determine if the number of tracks acquired before deployment is significant and should be subtracted from the gross result. The second set of background detectors (post-exposure background detectors) are obtained just before the field monitors are to be collected, and are opened and kept in the same location as the returning field monitors for the same duration, and returned with them. Finally, this "post-exposure background" is subtracted from the field results, if found to be significant. In general, a value of 1 pCi/L or greater for any blank AT indicates a significant level that should be investigated, and potentially subtracted from the field AT results.

2.2.11.5 Routine Instrument Checks

Proper functioning of the analysis instruments and proper response by their operators require that the equipment be subject to routine checks. Daily or more frequent monitoring of equipment and operators is vital to ensuring consistently accurate results.

2.3 Protocol for Using Electret Ion Chamber Radon Detectors (EC or ES, EL) to Measure Indoor Radon Concentrations

2.3.1 Purpose

This protocol provides guidance for using electret ion chamber radon detectors (EC) to obtain accurate and reproducible measurements of indoor radon concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid inter-comparison of results. Measurements made in accordance with this protocol can produce either short-term or long-term measurements, depending on the type of EC employed. The investigator should also follow guidance provided by the EPA in *Protocols for Radon and Radon Decay Product Measurements in Homes*, or other appropriate EPA measurement guidance documents.

2.3.2 Scope

This protocol covers, in general terms, the equipment, procedures and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, to provide guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the EPA.

2.3.3 Method

Short-term (ES) and long-term (EL) ECs have been described elsewhere (Kotrappa et al. 1988, 1990). They require no power, and function as true integrating detectors, measuring the average concentration during the measurement period.

The EC contains a charged electret (an electrostatically-charged disk of TeflonR) which collects ions formed in the chamber by radiation emitted from radon and radon decay products. When the device is exposed, radon diffuses into the chamber through filtered openings. Ions which are generated continuously by the decay of radon and radon decay products are drawn to the surface of the electret and reduce its surface voltage. The amount of voltage reduction is related directly to the average radon concentration and the duration of the exposure period. ECs can be deployed for exposure periods of two days (one day for research purposes) to 12 months, depending on the thickness of the electret and the volume of the ion chamber chosen for use. These deployment periods are flexible, and valid measurements can be made with other deployment periods, depending on the application.

The electret must be removed from the EC chamber and the electret voltage measured with a special surface voltmeter both before and after exposure. To determine the average radon concentration during the exposure period, the difference between the initial and final voltages is divided first by a calibration factor, and then by the number of exposure days. A background radon concentration equivalent of ambient gamma radiation is subtracted to compute radon concentration. Electret voltage measurements can be made in a laboratory or in the field.

2.3.4 Equipment

The following equipment is required to measure radon using the EC detection method:

- an EC of the type recommended for the anticipated exposure period and radon concentration (ES or EL);
- an instruction sheet for the user, and a shipping container with a label for returning the detector(s) to the laboratory, if appropriate;
- a specially-built surface voltmeter for measuring electret voltages before and after exposure; and

- a data collection log.

2.3.5 Pre-Deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The ES or EL measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The ES or EL should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

The ES or EL should be inspected prior to deployment to see that it has not been damaged during handling and shipping.

2.3.6 Measurement Criteria

Refer to Part 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

A 12-month EL measurement provides information about radon concentrations during an entire year, so the closed-building conditions do not have to be satisfied to perform a valid year-long measurement.

2.3.7 Deployment

2.3.7.1 Location Selection

Refer to Part 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.3.7.2 Timely Deployment

Both ESs and ELs should be deployed as soon as possible after their initial voltage is measured. Until an ES or EL is deployed, an electret cover should remain in place over the electret to minimize voltage loss due to background radon and gamma radiation.

2.3.8 Retrieval of Detectors

The recommended deployment period for the very short-term ESs is two days (one day for research or special circumstances), two to seven days for the short-term ESs, and for the long-term ELs, one to 12 months. If the occupant is terminating the sampling, the instructions should inform the occupant of when and how to terminate the sampling period. EC units integrate the radon (ion) signal permanently, so variations from these recommended measurement periods are acceptable to accommodate special circumstances as long as the final electret voltage for any measurement remains above 150 volts. In addition, the occupant also should be instructed to send the ES or EL to the laboratory as soon as possible, preferably within a few days following exposure termination.

At the end of the monitoring period, the ES or EL should be inspected for any deviation from the conditions described in the log book at the time of deployment. Any changes should be noted. The electret should be covered again using the mechanism provided.

2.3.9 Documentation

Refer to Part 1.2.4 for the list of standard information that must be documented.

In addition, the serial number, type and supplier of the chamber and electret, along with a code number or description which uniquely identifies customer, building, room and sampling position, must be documented. If the temperature of the room in which the EC is analyzed after exposure is significantly different from the temperature of the room in which the EC was analyzed prior to exposure (more than 10° F), those temperatures need to be recorded.

2.3.10 Analysis Requirements

In general, all ESs or ELs should be analyzed in the field or in the laboratory as soon as possible following removal from buildings. A background correction must be made to the radon concentration value obtained because electret ion chambers have a small response to background gamma radiation. If the temperature at the time of analysis is significantly different than at the time when the pre-exposure voltage was determined (more than 10° F), a temperature correction factor may be necessary (consult the manufacturer). It is therefore advisable to measure voltages after the temperatures of the reader and detector have stabilized to a room temperature in which both pre- and post-exposure voltages have been measured.

2.3.10.1 Sensitivity

For a seven-day exposure period using an ES, the lower level of detection or LLD (as defined by Thomas 1971) as the concentration that can be measured with a 50% error, is about 0.2 pCi/L. For an EL, the LLD is about 0.3 pCi/L or less for a three-month measurement. Note that this definition of LLD is different from that for radiation counting instruments, as defined for other methods (Altshuler and Pasternack 1963).

2.3.10.2 Precision

Precision should be monitored by using the results of duplicate detector analyses described in Part 2.3.11.3 of this protocol. This method can produce duplicate measurements with a coefficient of variation of 10% or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations, and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.3.11 Quality Assurance

The quality assurance program for measurements with ES or EL detectors includes five parts: (1) calibration; (2) known exposure detectors; (3) duplicate (collocated) detectors; (4) control detectors; and (5) routine instrument checks. The purpose of a quality assurance program is to assure and document the accuracy and precision of the measurements and assure that the measurements are not influenced by exposure from sources outside the environment to be measured.

2.3.11.1 Calibration

Every ES or EL detector system (detectors plus reader) should be calibrated in a radon calibration chamber at least once every 12 months. Initial calibration for the system is provided by the manufacturer. Determination of calibration factors for ES or EL detectors requires exposure of detectors to known concentrations of Radon-222 in a radon exposure chamber. Since ESs and ELs are also sensitive to exposure to gamma radiation (see Part 2.3.11.4), a gamma exposure-rate measurement in the test chamber is also required.

The following guidance is provided to manufacturers and suppliers of EC services as minimum requirements in determining the calibration factor:

- Detectors should be exposed in a radon chamber at several different radon concentrations or exposure levels similar to those found in the tested buildings (a minimum of three different concentrations).

- A minimum of 10 detectors should be exposed at each level.
- The period of exposure should be sufficient to allow the detector to achieve equilibrium with the chamber atmosphere.

2.3.11.2 Known Exposure Detectors

Anyone providing measurement services with ES or EL detectors should subject detectors with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Blind calibration detectors should be labeled in the same manner as the field detectors to ensure identical processing. The results of the spiked detector analysis should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.3.11.3 Duplicate (Collocated) Detectors

Anyone providing measurement services with EC devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10% of the number of detectors deployed each month or 50, whichever is smaller. The duplicate devices should be shipped, stored, exposed and analyzed under the same conditions, and not identified as duplicates to the processing laboratory. The samples selected for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can accomplish this by providing two detectors instead of one to a random selection of purchasers, with instructions to place the detectors side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. The analysis of duplicate data should follow the methodology described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.3.11.4 Control Detectors for Background Gamma Exposure and Electret Stability Monitoring

Electrets should exhibit very little loss in surface voltage due to internal electrical instabilities. Anyone providing measurement services with ES or EL detectors should set aside a minimum of 5% of the electrets or 10, whichever is smaller, from each shipment and evaluate them for voltage drift. They should be kept covered with protective caps in a low-radon environment and analyzed for voltage drift over a time period similar to the time period used for those deployed in homes. Any voltage loss found in the control electrets of more than one volt per week over a three-week test period for ESs, or one volt per month over a three-month period for ELs, should be investigated.

ECs are sensitive to background gamma radiation. The equivalent radon signal in picocuries per liter (pCi/L) per unit background radiation in micro roentgens per hour (μR/hr) is determined by the manufacturer for three different types of EC chambers currently available. This is specific to the chamber and not to the electret used in the chamber. These parameters are 0.07, 0.087 and 0.12 for H, S and L chambers, respectively. Depending on the type of chamber employed in EC, one of these values must be multiplied by the gamma radiation level at the site (in μR/hr) and the product (in equivalent pCi/L) subtracted from the apparent radon concentration. The gamma radiation at the measurement site is usually taken from the EPA list of average background by the state, as provided by the manufacturer. However, it can also be measured with an EC unit that is sealed in a radon-proof bag available from the manufacturer, or measured directly using appropriate radiation detection instruments. The latter step is necessary for accurate radon measurements at very low levels, such as those encountered in the outdoor environment.

2.3.11.5 Routine Instrument Checks

Proper operation of the surface voltmeter should be monitored following the manufacturer's procedures for zeroing the voltmeter, and analyzing a reference electret. These checks should be conducted at least once a week while the voltmeter is in use.

2.4 Protocol for Using Activated-Charcoal Adsorption Devices (AC) to Measure Indoor Radon Concentrations

2.4.1 Purpose

This protocol provides guidance for using activated-charcoal adsorption devices (AC) to obtain accurate and reproducible measurements of indoor radon concentrations. As referred to in this document, ACs are those charcoal adsorption devices that are analyzed by gamma scintillation (including open-faced canisters, diffusion barrier canisters, and diffusion bags). Charcoal detectors analyzed by liquid scintillation are covered under a separate protocol (see Part 2.5). Adherence to this protocol will help ensure uniformity among measurement programs and allow valid inter-comparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability, and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in *Protocols for Radon and Radon Decay Product Measurements in Homes*, or other appropriate EPA measurement guidance documents.

2.4.2 Scope

This protocol covers, in general terms, the sample collection and analysis method, the equipment needed, and the quality control objectives of measurements. It is not meant to replace an instrument manual but, rather, to provide guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. EPA's Office of Radiation and Indoor Air.

2.4.3 Method

ACs are passive devices requiring no power to function. The passive nature of the activated charcoal allows continual adsorption and desorption of radon. During the measurement period (typically two to seven days), the adsorbed radon undergoes radioactive decay. Therefore, the technique does not uniformly integrate radon concentrations during the exposure period. As with all devices that store radon, the average concentration calculated using the mid-exposure time is subject to error if the ambient radon concentration varies substantially during the measurement period.

The AC technique is described in detail elsewhere (Cohen and Cohen 1983, George 1984, George and Weber 1990). A device commonly used by several groups consists of a circular, 6- to 10-centimeter diameter container that is approximately 2.5 cm deep and filled with 25 to 100 grams of activated charcoal. One side of the container is fitted with a screen that keeps the charcoal in but allows air to diffuse into the charcoal.

In some cases, the charcoal container has a diffusion barrier over the opening. For longer exposures, this barrier improves the uniformity of response to variations of radon concentration with time. Desiccant is also incorporated in some containers to reduce interference from moisture adsorption during longer exposures. Another variation of the charcoal container has charcoal packaged inside a sealed bag, allowing the radon to diffuse through the bag. All ACs are sealed with a radon-proof cover or outer container after preparation.

The measurement is initiated by removing the cover to allow radon-laden air to diffuse into the charcoal bed where the radon is adsorbed onto the charcoal. At the end of a measurement period, the device is re-sealed securely and returned to a laboratory for analysis.

At the laboratory, the ACs are analyzed for radon decay products by placing the charcoal, still in its container, directly on a gamma detector. Corrections may be needed to account for the reduced sensitivity of the charcoal due to adsorbed water. This correction may be done by weighing each detector when it is prepared, and then re-weighing it when it is returned to the laboratory for analysis. Any weight increase is attributed to water adsorbed on the charcoal. The weight of water gained is correlated to a correction factor, which is derived empirically by using a method discussed elsewhere (George 1984). This correction factor is used to correct the analytical results.

This correction is not needed if the configuration of the AC is modified to reduce significantly the adsorption of water, and if the user has demonstrated experimentally that, over a wide range of humidity, there is a negligible change in the collection efficiency of the charcoal within the specified exposure period.

AC measurement systems are calibrated by analyzing detectors exposed to known concentrations of radon in a calibration facility.

2.4.4 Equipment

ACs made specifically for ambient radon-monitoring can be obtained from suppliers or can be manufactured using readily available components. Some charcoal canisters designed for use in respirators or in active air sampling may be adapted for use in ambient radon monitoring, as described elsewhere (Cohen and Cohen 1983, George 1984).

The following equipment is required to measure radon using ACs:

- a charcoal container sealed with a protective cover;
- an instruction sheet and sampling data sheet for the occupant, and a shipping container (along with a prepaid mailing label, if appropriate; and
- a data collection log.

Laboratory analysis of the exposed devices is performed using a sodium-iodide gamma scintillation detector to count the gamma rays emitted by the radon decay products on the charcoal. The detector may be used in conjunction with a multi-channel gamma spectrometer, or with a single-channel analyzer with the window set to include the appropriate gamma energy window. The detector system and detector geometry must be the same used to derive the calibration factors for the device.

2.4.5 Pre-Deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The AC measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The devices should not be deployed if the occupant's schedule prohibits terminating the measurement at the time selected for sealing the device and returning it to the laboratory.

2.4.6 Measurement Criteria

Refer to Part 1.2.2 for general conditions that must be adhered to in order to ensure standardization of measurement conditions.

2.4.7 Deployment

2.4.7.1 Location Selection

Refer to Part 1.2.3 for standard criteria to use when choosing a measurement device location.

2.4.7.2 Timely Deployment

ACs should be deployed within the shelf-life specified by the supplier. Until ACs are deployed, they should remain tightly sealed to maintain maximum sensitivity and low background.

For charcoal canisters, the sealing tape and protective cover should be removed from the canister to begin the sampling period. The cover and tape must be saved to re-seal the canister at the end of the measurement. For the diffusion bags, there is a radon-proof mailing container that is sealed at the end of the deployment period. This container may be separate from the radon-proof packaging. The device should be inspected to see that it has not been damaged during handling and shipping. It should be intact, with no charcoal leakage. For canisters, the device should be placed with the open side up toward the air. Nothing, apart from the device, should impede air flow around the device.

2.4.8 Retrieval of Detectors

The detectors should be deployed for a two- to seven-day measurement period, as specified in the supplier's instructions. If the occupant is terminating the sampling, the instructions should inform the occupant of when to terminate the sampling period, and should indicate that a deviation from the schedule may be acceptable if the time of termination is documented on the device. In addition, the occupant should also be instructed to send the device to the laboratory as soon as possible, preferably the day of termination. The analysis laboratory should be calibrated to permit accurate analysis of devices deployed for some reasonable time beyond the recommended sampling period. For example, a detector deployed for 24 hours beyond the recommended sampling time may not present an analysis problem to the measurement laboratory.

At the end of the monitoring period, the detector should be inspected for any deviation from the conditions described in the log book at the time of deployment. Any changes should be noted. The detector should be re-sealed using the original protective cover.

After the device is retrieved, it must be returned to the laboratory as soon as possible for analysis. The detector should be analyzed at least three hours after the end of sampling to allow for in-growth of decay products.

2.4.9 Documentation

Refer to Part 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

In addition, the test location temperature may need to be recorded, depending on the device configuration.

2.4.10 Analysis Requirements

ACs should be analyzed in the laboratory as soon as possible following removal from the houses. The maximum allowable delay time between the end of sampling and analysis will vary with the radon concentration and background experienced in each laboratory and should be evaluated, especially if sensitivity is of prime consideration. Corrections for the Radon-222 decay during sampling, during the interval between sampling and counting, and during counting should be made. If the device does not have a moisture barrier, the detector should be weighed, and, if necessary, a correction should be applied for the increase in weight due to moisture adsorbed. A description of the procedure used to derive the moisture correction factor is provided elsewhere (George 1984).

2.4.10.1 Sensitivity

For a two- to seven-day exposure period, the lower level of detection (LLD) should be 0.5 pCi/L or less. This LLD can normally be achieved with a counting time of up to 30 minutes. The LLD should be calculated using the results of the laboratory background determination that is described in Part 2.4.11.4.1 of this protocol.

2.4.10.2 Precision

Precision should be monitored using the results of the duplicate detector analyses described in this protocol (Part 2.4.11.3). This method can produce measurements with a coefficient of variation of 10% or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations, and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.4.11 Quality Assurance

The quality assurance program for ACs includes five parts: (1) calibration; (2) known exposure detectors; (3) duplicate (collocated) detectors; (4) control detectors; and (5) routine instrument checks. The purpose of this program is to identify the accuracy and precision of the measurements, and to assure that the measurements are not influenced by extraneous exposures. The quality assurance program should include the maintenance of control charts (section 5.3 of Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.4.11.1 Calibration

Every AC system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of calibration factors for ACs requires exposure of the detectors to known concentrations of Radon-222 in a radon exposure chamber. The calibration factors depend on the exposure time and may also depend on the amount of water adsorbed by the charcoal container during exposure. These calibration factors should be determined using the procedures described previously (George 1984). Calibration factors should be determined for each AC measurement system (container type, amount of charcoal, gamma detector type, etc.).

2.4.11.2 Known Exposure Detectors

Anyone providing measurement services with AC detectors should submit charcoal detectors with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) detectors should be labeled in the same manner as the field detectors to assure identical processing. The results of the spiked detector analysis should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.4.11.3 Duplicate (Collocated) Detectors

Anyone providing measurement services with AC devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10% of the number of detectors deployed each month, or 50, whichever is smaller. The duplicate detectors should be shipped, stored, exposed and analyzed under the same conditions, and not identified as duplicates to the processing laboratory. The locations selected to receive duplicates should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can do this by providing two detectors instead of one to a random selection of purchasers, with instructions to place them side-by-side. Consideration should be given to providing some means to ensure that the duplicate detectors are not separated during the measurement period. Data from duplicate detectors should be evaluated using the procedures described by Goldin (Section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.4.11.4 Control Detectors

2.4.11.4.1 Laboratory Control Detectors

The laboratory background level for each batch of ACs should be established by each laboratory or supplier. Suppliers should measure the background of a statistically significant number of unexposed detectors that have been processed according to their standard operating procedures (laboratory blanks). Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.4.11.4.2 Field Control Detectors

Field control detectors (field blanks) should consist of a minimum of 5% of the devices that are deployed every month, or 25, whichever is smaller. Large users of ACs should set these aside from each shipment, keep them sealed and in a low-radon (less than 0.2 pCi/L) environment, label them in the same manner as the field detectors to ensure identical processing, and send them back to the supplier with one shipment each month for analysis. These control devices measure the background exposure that may accumulate during shipment or storage, and results should be monitored and recorded. If one or a few of the field control detectors have concentrations significantly greater than the LLD established by the supplier, it may indicate defective devices or poor procedures. If most of the controls have concentrations significantly greater than the LLD, the average value of the field controls should be subtracted from the reported field detector concentrations and the supplier notified of a possible problem.

2.4.11.5 Routine Instrument Checks

Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., geometry, type of radiation emitted, etc.) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

2.5 Protocol for Using Charcoal Liquid Scintillation (LS) Devices to Measure Indoor Radon Concentration

2.5.1 Purpose

This protocol provides guidance for using charcoal liquid scintillation (LS) devices to obtain accurate and reproducible measurements of indoor radon concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.5.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Indoor Environments Division (6609J), 401 M Street S.W., Washington, D.C. 20460, (202) 564-9370, (202) 565-2038 (fax).

2.5.3 Method

LS devices are passive detectors requiring no power to function. The passive nature of the activated charcoal allows continual adsorption and desorption of radon, and the adsorbed radon undergoes radioactive decay during the measurement period. Therefore, the technique does not integrate uniformly radon concentrations during the exposure period. As with all devices that store radon, the calculated average concentration is subject to error if the ambient radon concentration adsorbed during the first half of the sampling period is substantially higher or lower than the average over the period.

The LS technique is described elsewhere (Prichard and Marien 1985). Several companies now provide a type of LS device that is a capped, 20-ml liquid scintillation vial that is approximately 25 mm in diameter by 60 mm and contains one to three grams of charcoal (other designs are also feasible). In some cases, the vial contains a diffusion barrier over the charcoal, which improves the uniformity of response of the device to variations of radon concentration with time, particularly for longer exposures. Some LS devices include a few grams of desiccant, which reduces interference from moisture adsorption by the charcoal (Perlman 1989). All LS devices are sealed with a radon-proof closure after preparation.

A measurement with the LS device is initiated by removing the radon-proof closure to allow radon-laden air to diffuse into the charcoal where the radon is adsorbed. At the end of the exposure (typically two to seven days), the device is resealed securely and returned to the laboratory for analysis.

At the laboratory, the devices are prepared for analysis by radon desorption techniques. This technique transfers reproducibly a major fraction of the radon adsorbed on the charcoal into a vial of liquid scintillation fluid. The vials of liquid scintillation fluid containing the dissolved radon are placed in a liquid scintillation counter and counted for a specified number of minutes (e.g., 10 minutes) or until the standard deviation of the count is acceptable (e.g., less than 10 percent).

2.5.4 Equipment

LS devices made specifically for ambient radon monitoring are supplied and analyzed by several laboratories.

The following equipment is required to measure radon with an LS device:

- LS devices properly sealed by the supplier;
- An instruction sheet for the occupant, and a shipping container (along with a prepaid mailing label, if appropriate; and
- A data collection log.

2.5.5 Pre-deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The LS measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The LS device should not be deployed if the occupant's schedule prohibits terminating the measurement at the time selected for closing the device and returning it to the laboratory.

2.5.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.5.7 Deployment

2.5.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.5.7.2 Timely Deployment. LS devices should be deployed into buildings within the shelf life specified by the supplier. Until they are deployed, they should remain tightly sealed to maintain low background.

The protective cap should be removed from the device to begin the sampling period. The cap must be saved to reseal the device at the end of the measurement. The device should be inspected to assure that it has not been damaged during handling and shipping. It should be intact, with no charcoal leakage. The device should also be placed with the open vial mouth up. Nothing should impede airflow around the device.

2.5.8 Retrieval of Devices

The device should be deployed for the measurement period (usually between two days and one week) specified in the instructions supplied by the analytical laboratory. If the occupant is terminating the sampling, the instructions should inform the occupant of when to terminate the sampling period and should indicate that the actual time of termination must be documented on the device. In addition, the occupant also should be instructed to send the device to the laboratory as soon as possible, preferably the day of sample termination. The analysis laboratory should be calibrated to permit accurate analysis of devices deployed for some reasonable time beyond the recommended sampling period. For example, a detector deployed for 24 hours beyond the recommended sampling time may not present an analysis problem to the measurement laboratory.

At the end of the monitoring period, the device should be inspected for any deviation from the conditions described in the logbook at the time of deployment. Any changes should be noted. The device should be resealed using the original protective cap.

2.5.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

2.5.10 Analysis Requirements

LS devices should be returned to the supplier's analysis laboratory as soon as possible following removal from the houses. The maximum allowable delay time between the end of sampling and analysis should not exceed the time specified by the supplier's instructions, especially if the radon concentration measured was expected to be low. Corrections for radon-222 decay during sampling, during the interval between sampling and counting, and during counting, will be made by the analysis laboratory. The procedures followed by an individual supplier's analysis laboratory may include a correction for moisture as measured by weight gain if this is significant for their device configuration. Other correction or calibration factors applied by the analysis laboratory must include factors accounting for the transfer of radon from the charcoal to the scintillation fluid under rigorously controlled conditions, and for the counting efficiency achieved with the specified scintillation mixture and liquid scintillation counting system.

2.5.10.1 Sensitivity. The lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) should be specified by individual suppliers for LS devices exposed and shipped according to their directions. It is estimated that LLDs of a few tenths of a picoCurie per liter (pCi/L) are achievable for some LS devices (Cohen 1988, Grodzins 1988, Perlman 1988, Prichard 1988). The LLD should be calculated using the results of the laboratory control devices discussed in Section 2.5.11.4.1 of this protocol.

2.5.10.2 Precision. Precision should be monitored and recorded periodically using the results of the duplicate device analyses described in Section 2.5.11.3 of this protocol.

Measurements made with this method can produce duplicate results with a coefficient of variation of 10 percent or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.5.11 Quality Assurance

The quality assurance program for an LS system includes five parts: (1) calibration, (2) known exposure devices, (3) duplicate (collocated) devices, (4) control devices, and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.5.11.1 Calibration. Every LS laboratory system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of calibration factors for LS devices requires exposure of calibration devices to known concentrations of radon-222 in a radon exposure chamber at carefully measured radon concentrations. The calibration factors depend on the exposure time and may also depend on the amount of water adsorbed by the device during exposure. Calibration factors should be determined for a range of different exposure times and, if appropriate, humidities.

2.5.11.2 Known Exposure Devices. Anyone providing measurement services with LS devices should submit devices with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) devices should be labeled in the same manner as the field devices to ensure identical processing. The results of the spiked device analysis should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.5.11.3 Duplicate (Collocated) Devices. Anyone providing measurement services with LS devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. Each pair of duplicate devices should be shipped, stored, exposed, and analyzed under the same conditions. The samples for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can do this by providing two detectors instead of one to a random selection of purchasers with instructions to place them side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. Data from duplicate devices should be evaluated using procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA

1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.5.11.4 Control Devices

2.5.11.4.1 Laboratory Control Devices. The laboratory background level for each batch of LS devices should be established by each laboratory or supplier. Suppliers should measure the background of a statistically significant number of unexposed LS devices that have been processed according to their standard operating procedures (laboratory blanks). Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.5.11.4.2 Field Control Devices. Field control devices (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Large users of LS detectors should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field devices, and send them back to the supplier with one shipment each month for analysis. These control devices measure the background exposure that may accumulate during shipment or storage, and the results should be monitored and recorded. If one or a few of the field control detectors have concentrations significantly greater than the LLD established by the supplier, it may indicate defective devices or procedures. If most of the controls have concentrations significantly greater than the LLD, the average value at the field controls should be subtracted from the reported field device concentration and the supplier notified of a possible problem.

2.5.11.5 Routine Instrument Checks. Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., type of radiation emitted) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

2.6 Protocol for Using Grab Radon Sampling (GB, GC, GS) Pump/Collapsible Bag Devices (PB), and Three-day Integrating Evacuated Scintillation Cells (SC) to Measure Indoor Radon Concentrations

2.6.1 Purpose

This protocol provides guidance for three similar methods that measure indoor radon air concentrations: grab radon-sampling techniques (GB, GC, GS), pumps with collapsible bags as devices (PB), and three-day integrating evacuated scintillation cells (SC). Adherence to this protocol will help obtain accurate and reproducible measurements, ensure uniformity among measurement programs, and allow valid comparisons of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled.

Results of grab sampling are influenced greatly by conditions that exist in the building during and for up to 12 hours prior to the measurement. It is therefore especially important when making grab measurements to conform to closed-building conditions for 12 hours before the measurement. Grab sampling techniques are not recommended for measurements made to determine the need for remedial action. The reader should also refer to the EPA guidance document entitled, "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.6.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Indoor Environments Division (6609J), 401 M Street S.W., Washington, D.C. 20460, (202) 564-9370, (202) 565-2038 (fax).

2.6.3 Methods

2.6.3.1 Grab Radon Sampling Techniques. There are three grab radon-sampling methods covered by this protocol. In the first method, known as grab radon/scintillation cell (GS), a sample of air is drawn into and sealed in a flask or cell that has a zinc sulfide phosphor coating on its interior surfaces. One surface of the cell is fitted with a clear window that is put in contact with a photomultiplier tube to count light pulses (scintillations) resulting from alpha disintegrations from the air sample interacting with the zinc sulfide coating. The number of pulses is proportional to the radon concentration in the cell. The cell is counted about four hours after filling to allow the short-lived radon decay products to reach equilibrium with the radon. After the cells are placed in the counters, the counting system should be allowed to dark-adapt for two minutes. Correction factors (see Section 2.6.13, Exhibit 2-1) are applied to the counting results to compensate for decay during the time between collection and counting and for decay during counting if the counting time is long (> one hour). Supplementary information on this technique is provided in Section

2.6.13. In a variation of this method, used in some portable instruments, air is pumped continuously through a flow-through-type scintillation cell for just a few minutes. Alpha particles resulting from the decay of radon gas and decay products are counted as the gas is swept through.

A second grab method covered by this protocol, known as grab radon/activated charcoal (GC), uses air pumped through activated charcoal to collect the sample. A charcoal-filled cartridge is placed into a sampler and air is pumped through the carbon cartridge. The pump with a charcoal cartridge is not flow-dependent but must remain operational at the sampling location until the charcoal collects enough radon to be in equilibrium with the radon at the sampling location. A sampling duration of one hour has been found to be optimal for most systems. The cartridge must be weighed prior to and after sampling in order to correct for the reduced sensitivity of the charcoal due to adsorbed water. The cartridges are analyzed by placing them on a sodium iodide gamma scintillation system or a germanium gamma detector. The GC system must be calibrated by analyzing cartridges pumped with known concentrations of radon in a qualified facility.

The third grab method, known as grab radon pump/collapsible bag (GB), uses the same technology described in Section 2.6.3.2 for pump/collapsible bag devices (PB). The GB method covered in this section differs only in that the bag is filled over a much shorter collection period than in the PB method described below.

2.6.3.2 Pump/Collapsible Bag Devices (PB). One of the older and simpler methods of making an integrated measurement of the concentration of radon over a period of time is to collect a sample of ambient air in a radon-proof container over the desired sampling time period and measure the resulting radon concentration in the container.

One practical method is to use a small pump with a very low and uniform flow rate to pump ambient air into an inflatable and collapsible radon-proof bag (Sill 1977). After the desired sampling period (typically 24 hours), the concentration of radon in the bag can be analyzed by any of the standard methods such as the GS protocol (Section 2.6.3.1) using the appropriate radon decay correction factors (Section 2.6.13, Exhibit 2-1). For this method, the counting system should be allowed to dark-adapt for two minutes after the cells are placed in the counters. The main purpose of the collapsible bag is to avoid variation in pump flow rate due to build up of backpressure in a container. Bags that have been measured to have a very low loss of radon by diffusion through the bag have been made of laminated Mylar, aluminized laminated Mylar, and TedlarR. The pump flow rate is not critical as long as it is suitable for the size of the bag and the sample duration, but variation of the flow rate over the collection time period of the sample will affect the accuracy of the measurement. A number of suitable battery- and/or charger-operated pumps with controlled flow rates are available commercially.

Although this PB method accumulates radon over a period of time for subsequent analysis, it should not be considered a true integrating method. Radon peaks occurring early in the sampling period will leave less radon for analysis than the same size peak occurring toward the end of the sampling period.

2.6.3.3 Three-Day Integrating Evacuated Scintillation Cells (SC). This method typically uses Lucas-type scintillation cells that have been outfitted with a restrictor valve attached to the main valve. Samples are collected by opening the valve on an evacuated cell. The restrictor valve is set so that the cell fills from a 30-inch mercury (Hg) vacuum to about 80 percent of its capacity over a three-day period. At the end of the measurement period, the valve is closed and returned to the analysis laboratory. Since the volume of the cell is known, the exact volume of filtered air collected over the three-day measurement period can be calculated from the vacuum gauge reading at the end of the sampling period.

The sample is analyzed on an alpha scintillation counter. Prior to counting, the pressure in the cell is brought to one atmosphere by adding radon-free (aged) air so that the sample is analyzed under the same conditions that prevailed during calibration of the cell. To allow radon and radon decay products to grow into equilibrium and to allow any radon decay products that may have been collected to decay, the sample should be counted no sooner than four hours after the end of the measurement period. After the cells are placed in the counters, the counting system should be allowed to dark-adapt for two minutes.

During the three-day sampling period, some of the radon that has been collected decays. The midpoint of the sampling period cannot be used for the decay correction factor because the airflow into the cell is greater during the initial time of sampling. The fraction of radon that decays must therefore be calculated from the shape of a plot of percent fill versus time. This must be measured for each cell. This factor should be applied as a correction during data reduction.

Since this method accumulates radon over a period of time for subsequent analysis, it is not a true integrating method. Radon peaks occurring early in the sampling period will leave less radon for analysis than the same size peak occurring toward the end of the sampling period.

2.6.4 Equipment

2.6.4.1 Grab Radon Sampling Techniques

2.6.4.1.1 Grab Radon/Scintillation Cell Method (GS). The equipment needed for this method includes the following:

- A scintillation cell (flask) or cells to be filled at the site;
- A pump to flow air through the cell or to evacuate the cell (depending on the valve arrangement on the cell);
- A clock to measure time from collection to counting;
- A filter and filter holder to attach to the air inlet valve of the cell; and
- A data collection log.

The equipment required for analyzing the air sample includes the following:

- A photomultiplier tube and high-voltage assembly in a light-tight chamber;
- A scaler-timer for registering pulses from the photomultiplier tube assembly and timing the counting interval;
- A National Institute of Standards and Technology (NIST)-traceable alpha check source and scintillation disc;
- A calibration flask or cell;
- A vacuum pump and cell flushing apparatus; and
- Aged air or nitrogen for flushing counting cells.

2.6.4.1.2 Grab Radon/Activated Charcoal (GC). The equipment needed for this method includes the following:

- A charcoal cartridge with both apertures sealed with protective metallic or other impermeable covers;
- A pump to pull air through the cartridge;
- A data collection log;
- A sodium iodide gamma scintillation detector and analyzer; and
- An analytic scale capable of weighing small differences in weight (up to several grams) due to water adsorbed by the charcoal.

Laboratory analysis of the saturated charcoal cartridge is performed using a sodium iodide gamma scintillation detector to count the gamma rays emitted by the radon decay products adsorbed on the carbon. The detectors may be used in conjunction with a multi-channel gamma spectrometer or with a single-channel analyzer calibrated to include the appropriate gamma energies.

2.6.4.1.3 Grab Radon Pump/Collapsible Bag Sampling (GB). The equipment requirements for this method are similar to those for the PB method of Section 2.6.4.2.

2.6.4.2 Pump/Collapsible Bag Devices (PB). The following equipment is required to conduct measurements using the PB method:

- A pump with a suitable uniform flow rate. The materials of the pump should not absorb or off-gas any substantial amount of radon;
- A collapsible bag of tested, low radon-loss material; and
- A data collection log.

2.6.4.3 Three-Day Integrating Evacuated Scintillation Cells (SC). The following equipment is required to measure radon with an evacuated cell:

- An evacuated cell with the restrictor valve and vacuum gauge prepared by the supplier;
- An instruction sheet and a shipping container (along with a prepaid mailing label, if appropriate; and
- A data collection log.

2.6.5 Pre-deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The measurement devices should not be deployed if the occupant's schedule prohibits terminating the measurement at the time selected.

Prior to collection of the grab radon sample, proper operation of the counting equipment must be verified, and counter efficiency and background must be determined. In addition, a background for each cartridge or cell should be determined prior to sampling. This may be done using the procedures described in Section 2.6.13 for flask counting.

For highly accurate cell measurements, it is necessary to standardize cell pressure prior to counting because the path lengths of alpha particles are a function of air density. For example, a cell calibrated at sea level and used to count a sample collected at Grand Junction, Colorado (1,370 meters above sea level) would overestimate the radon activity of the sample by about nine percent (George 1983). This error probably approaches the maximum that would be encountered; therefore, it may not be necessary to make this correction if this error can be tolerated. Correction procedures are given elsewhere (George 1983).

2.6.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.6.7 Deployment

2.6.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

2.6.7.2 Sampling with GB, GC, and GS. All air samples drawn into scintillation cells or flasks must be filtered to remove radon decay products and other airborne radioactive particulates. The sampling hose should be short so as to draw room air (not hose air) into the cell. Filters may be reused many times as long as they remain undamaged and functional.

For collection of a sample using a single-valve cell (Lucas-type), the cell is evacuated to at least 25 inches of mercury, the filter is attached to the cell, and the valve is opened allowing the cell to fill with air. At least 10 seconds should be allowed for the cell to fill completely. To ensure a good vacuum at the time of sampling, the cell may be evacuated using a small hand-operated pump in the room being sampled. It is good practice to evacuate the cell at least five times, allowing it to fill completely with room air each time. The air to be sampled must flow through the filter each time. If it can be demonstrated that the cells and valves do not leak, it is acceptable to evacuate the cells in the laboratory and simply attach the filter and open the valve in the building to collect a sample.

To sample using the double-valve, flow-through type cell, the filter should be attached to the inlet valve and a suitable vacuum pump should be attached to the other valve. The pump may be motor-driven or hand-operated. To begin sampling, both valves should be opened and the pump operated to flow at least 10 complete air exchanges through the cell. The pump is then stopped and both valves are closed.

Sampling using the GC or GB method is accomplished by opening and attaching a prepared sealed cartridge or collapsible bag to the sampling pump. For charcoal cartridges, the pump should draw air through the cartridge at approximately the same rate as that used in calibrating the system. Sampling should continue until the charcoal collects enough radon to be in equilibrium with the radon at the sampling site. A one-hour sampling period is typical for most GC systems. For the GB method, the pump should have a known uniform flow rate and the system should be leak-proof.

2.6.7.3 Timely Deployment of SCs. SC devices should be deployed within the period specified by the supplier. Until they are deployed, they should remain tightly sealed to maintain maximum sensitivity and accuracy.

To deploy the SC device, the reading of the attached vacuum gauge must be recorded on the log sheet along with the start-date and -time for the sample. The sample collection is started by opening the main valve according to the supplier's instructions.

2.6.8 Retrieval of Devices

2.6.8.1 Grab Radon Sampling Techniques. All pertinent sampling information (discussed in Sections 1.2.4 and 2.6.7) should be recorded after completing the measurement. The detectors should be packaged carefully for return to the counting location so that the samples will not be lost due to breakage, valves being opened, or loss of cartridge integrity.

2.6.8.2 Three-Day Integrating Evacuated Scintillation Cells (SC). The SC device should be deployed for the measurement period specified in the instructions supplied by the analytical laboratory (typically three days). If the occupant is terminating the sampling, the instructions should inform the occupant of when and how to terminate the sampling period and should indicate that the actual time of termination must be documented on the data form. In addition, the vacuum gauge reading must be recorded on the data form after the sampling valve is closed. The occupant should also be instructed to send the device to the laboratory as soon as possible, preferably on the day of sample termination.

At the end of the monitoring period, the device should be inspected for any deviation from the conditions described in the logbook at the time of deployment. Any changes should be noted.

2.6.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made. In addition to this list, the following are method-specific details of documentation requirements.

For GBs, GCs, and GSs, the serial numbers of cells, cartridges, bags, pumps, and counting equipment should also be recorded.

For PBs, the serial numbers of bags, pumps, and equipment used for analysis of the radon concentration should also be recorded.

For SCs, the start-time and stop-time vacuum gauge readings should also be recorded, along with the serial numbers of the cells and counting equipment.

2.6.10 Counting and Calculations

2.6.10.1 Grab Radon Sampling Techniques

2.6.10.1.1 Grab Radon/Scintillation Cell Sampling (GS). Cells should not be counted for at least four hours following the time of collection. Background and check sources should be counted as described in Section 2.6.13. The cell to be counted is placed on the photomultiplier tube, the cover placed over the cell, and the system allowed to dark-adapt. The cell may then be counted for a sufficient period to collect an adequate number of counts for good counting statistics in relation to the system background counts.

2.6.10.1.2 Grab Radon/Activated Charcoal Sampling (GC). Cartridges should not be analyzed for at least four hours after the end of sampling to allow for ingrowth of the radon decay products. Cartridges should then be analyzed in a laboratory following removal from the sampling location. The cartridge should be weighed, and if necessary, a correction should be applied for the increase in weight due to moisture adsorption. The maximum allowable delay time between the end of sampling and analysis will vary with the background experienced in each laboratory and should be evaluated, especially if sensitivity is of prime consideration. The cartridge should be analyzed on a calibrated sodium iodide gamma scintillation system or a germanium gamma detector.

2.6.10.1.3 Grab Radon Pump/Collapsible Bag Sampling (GB). After a four-hour waiting period, the concentration of radon in the bag can be analyzed by any of the standard methods including the GS method described above (Section 2.6.10.1.1).

2.6.10.1.4 Cell Flushing and Storage. After the cells have been counted and data are satisfactorily recorded, the cells must be flushed with aged air or nitrogen to remove the sample. Flow-through cells are flushed with at least 10 volume exchanges at a flow of about two liters per minute. Cells with single valves are evacuated and refilled with aged air or nitrogen at least five times. The cells are left filled with aged air or nitrogen and allowed to sit overnight before being counted for background. If an acceptable background is obtained, the cell is ready for reuse.

2.6.10.2 Pump/Collapsible Bag Devices (PB). If the radon concentration in the collapsible bag is to be analyzed on site, the appropriate grab radon sampling protocol (Section 2.6.10.1) should be followed.

If the radon concentration is to be measured by an analysis laboratory, the bag should be delivered to the laboratory as soon as possible following completion of sampling, especially if low concentrations are being measured.

2.6.10.3 Three-Day Integrating Evacuated Scintillation Cells (SC). SC devices should be returned to the supplier's analysis laboratory as soon as possible following removal from the buildings. The maximum allowable delay time between the end of sampling and analysis should not exceed the time specified by the supplier's instructions, especially if sensitivity is an important consideration. Corrections for the radon-222 decay during sampling, during the interval between sampling and counting, and during counting, will be made by the analysis laboratory.

2.6.11 Analysis Requirements

2.6.11.1 Sensitivity.

2.6.11.1.1 Grab Radon Sampling Techniques. The sensitivity of the GS method is dependent on the volume of the cell being used. However, sensitivities of 0.1 picoCuries per liter (pCi/L) are achievable (George 1980, George 1983). For the GC method, the lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) should be 1.0 pCi/L or less. This can be achieved normally with a counting time of up to 30 minutes. The sensitivity of the GB method depends on the analysis method used.

2.6.11.1.2 Pump/Collapsible Bag Devices (PB). The LLD for a PB will depend on the method used to analyze the contents of the bag. If a GS method is used, an LLD of a few tenths of a pCi/L should be possible.

2.6.11.1.3 Three-Day Integrating Evacuated Scintillation Cells (SC). The LLD should be specified by individual suppliers for SC devices exposed and shipped according to their directions. It is estimated that LLDs of a few tenths of a pCi/L are achievable with these devices.

2.6.11.2 Precision. The results of duplicates (collocated measurements) should be monitored and recorded using the results of the duplicate device analyses described in Section 2.6.12.3 of this protocol. These methods can produce duplicate measurements with a coefficient of variation of 10 percent or less at 4 pCi/L or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.6.12 Quality Assurance

The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the intended structure. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

This section describes five parts of a quality assurance program: (1) calibration of the system, (2) known exposure measurements, (3) duplicate (collocated) devices, (4) background measurements/control devices, and (5) routine instrument checks. Each type of method (GB, GC, GS, PB, and SC) requires some variation of all parts of the program.

2.6.12.1 Calibration

Every device should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent recalibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually.

2.6.12.1.1 Calibration Factors. Determination of calibration factors requires exposure of calibration devices to known concentrations of radon-222 in a radon exposure chamber at carefully measured radon concentrations. Since the cells are subject to shipping and handling, they should be recalibrated periodically at radon levels similar to those found in tested buildings. Scintillation counting systems used to count exposed cells should be either the system used to calibrate the cell or one calibrated against that system.

2.6.12.1.2 Cell Calibration. If a GS method of measuring the radon concentrations is used in the PB or GB methods, the following procedure on calibration should be followed.

The cell counting system consisting of the scaler, detector, and high-voltage supply must be calibrated. The correct high voltage is determined by increasing the high voltage by increments and plotting the resultant counts. This procedure is described elsewhere (George 1983). Each counting system should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent recalibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semiannually. Also, a check source or calibration cell should be counted in each analysis system each day to demonstrate proper operation prior to counting any samples.

A separate calibration factor must be obtained for each cell in the counting system. This is done by filling each cell with radon of a known concentration and counting the cell to determine the conversion factor (in counts per minute per pCi). The known concentration of radon may be obtained from a radon calibration chamber or estimated from a bubbler tube containing a known concentration of radium. These calibration procedures are discussed in more detail elsewhere (Beckman 1975, George 1976, Lucas 1957).

2.6.12.1.3 Grab-Radon/Activated Charcoal (GC) Method Calibration. This method must be calibrated in a radon calibration chamber to establish a calibration factor for a specific cartridge model. Samples should be taken at different humidities and temperatures to establish correction factors. Calibration should be carried out at several flow rates and exposure times to verify the acceptable limits. Calibration factors must be established with the identical gamma counting system and counting geometry used in sampling.

2.6.12.2 Known Exposure Measurements. Anyone providing measurement services using these methods should submit devices with known radon exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) devices should be labeled in the same manner as the field devices to assure identical processing. The results of the known exposure analyses should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

2.6.12.3 Duplicate (Collocated) Devices. Anyone providing measurement services with these methods should place duplicate devices in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. To the greatest extent possible, care should be taken to ensure that the samples are duplicates, are taken in close proximity, and are away from drafts. The samples selected for duplication should be distributed systematically throughout the entire population of samples. The duplicate devices should be shipped, stored, exposed, and analyzed under the same conditions, and not identified as duplicates to the processing laboratory. Groups selling measurement services to homeowners can accomplish this by making two side-by-side measurements in a random selection of homes. Data from duplicate devices should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.6.12.4 Background Measurements/Control Devices

2.6.12.4.1 Background Measurements. A background count for each type of system is determined prior to measurement. When the GC method is used, the background of the charcoal should also be assessed routinely.

2.6.12.4.2 Laboratory Control Devices. The background level for each device should be established by each supplier. Suppliers should measure the background of each device before each use or periodically, with a frequency based on experience. In order to calculate the radon concentrations of the sample, the background should be subtracted from the field readings taken with that cell.

2.6.12.4.3 Field Control Devices. Field control devices (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field devices, and send them back to the supplier with one shipment each month for analyses. It may be clear to the analysis laboratory that these are blanks, however it is still important to conduct the analysis. For the SC method, careful initial and final readings of the vacuum gauges on the control cells and the cell background counts on analysis will be of some use in detecting an occasional leaking cell, but any background detected in a leaking cell is not relevant to the measured field sample concentrations.

2.6.12.5 Routine Instrument Checks. Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., geometry, type of radiation emitted, etc.) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

2.6.13 Supplementary Information for the Grab Radon Sampling/ Scintillation Cell (GS) Method

2.6.13.1 Procedure. The procedure described below is that used by the EPA Office of Radiation and Indoor Air Program in its field measurement programs. It is designed for measurements made using specific cell counters and their associated cells. Equipment is available from several suppliers, and it may be necessary to modify the procedure slightly to accommodate these differences. For example, the correct cell volume must be used in calculating the activity in the cell. The following is a general procedure for equipment used by the EPA:

1. The cells to be used are flushed with aged air or nitrogen to remove traces of the previous sample. It may be necessary to store cells for 24 hours prior to reuse if the cell had contained a high activity sample. Each cell is placed in the counter, and allowed two minutes for the system to become dark-adapted. The background of the cell is then counted for ten minutes. Background data are recorded for each cell.

2. At the survey site, the sample is collected by flowing air into the longer tube in the top of the double-valve cell for a period sufficient to allow 10 air exchanges. For the single-valve cells, it is only necessary to open the valve on the evacuated cells and allow 10 to 15 seconds for complete filling. Cells must be filled with air forced through a filter to prevent entry of airborne particulates.

3. The filled cells must be allowed to equilibrate for four hours prior to counting. The cells should not be exposed to bright light prior to counting.

4. The cells are placed in the counters, and the systems are allowed to dark-adapt for two minutes. The cells are then counted. Counting time will vary based on the activity in the cell; however, at least 1,000 counts are desirable to provide good statistics.

5. The activity in the sample is calculated and corrected for ingrowth and decay as described below.

2.6.13.2 Calculation of Results. The radon concentration in pCi/L is determined using the following formula:

$$\text{pCi/L} = \text{cpm(s)} - \text{cpm (bkg)}/E \times C/A \times 1/V$$

Where:

cpm(s) = Counts per minute for the sample

cpm(bkg) = Counts per minute for background

E = Efficiency of the system determined for each cell. For the cells used by the EPA, the factor is typically 4-5 cpm/pCi.

C = Radon correction factor for decay during counting (from Exhibit 2-1)

A = Radon correction factor for decay of radon from time of collection to start of counting (from Exhibit 2-1)

V = Volume of counting cell in liters (L),

2.6.13.3 Sample Calculation. The following sample calculation demonstrates the procedure for calculating results:

Background count for system = 10 counts in 10 minutes, or 1 cpm

Sample count for 120 minutes = 1200 counts, or 10 cpm

System efficiency (E) from cell calibration = 4.62 cpm/pCi

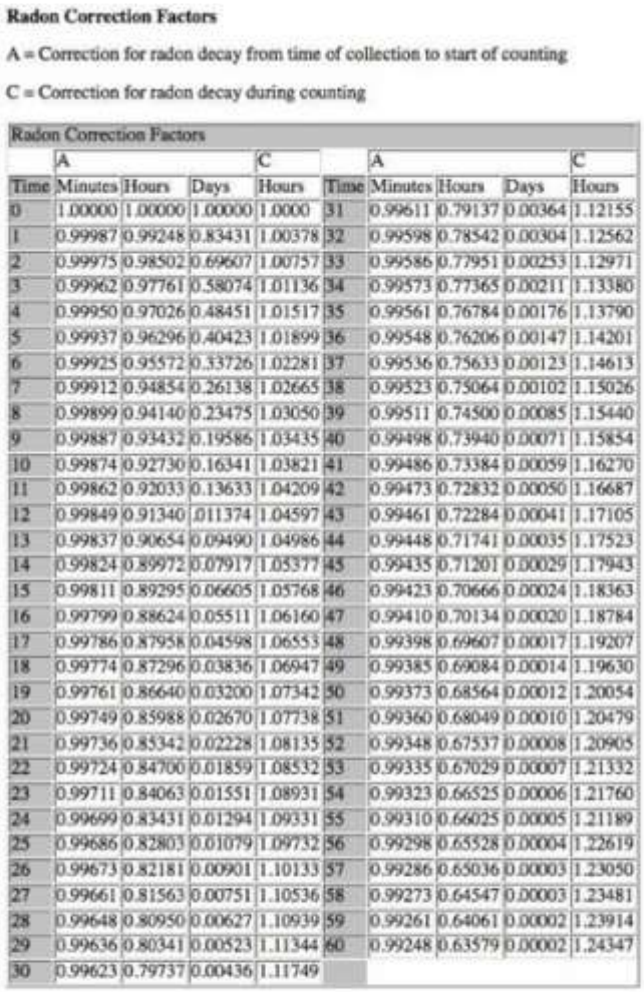
Count time correction (C) for 120 minutes = 1.00757

Delay time correction (A) for 4 hours = 0.97026

Volume correction (V) for cell = 0.170 L

pCi/L = 10 cpm - 1 cpm/4.62 cpm/pCi x 1.00757/0.97026 x 1/0.170 L = 11.9

Exhibit 2-1



Radon Correction Factors

A = Correction for radon decay from time of collection to start of counting

C = Correction for radon decay during counting

Radon Correction Factors									
	A			C		A			C
Time	Minutes	Hours	Days	Hours	Time	Minutes	Hours	Days	Hours
0	1.00000	1.00000	1.00000	1.0000	31	0.99611	0.79137	0.00364	1.12155
1	0.99987	0.99248	0.83431	1.00378	32	0.99598	0.78542	0.00304	1.12562
2	0.99975	0.98502	0.69607	1.00757	33	0.99586	0.77951	0.00253	1.12971
3	0.99962	0.97761	0.58074	1.01136	34	0.99573	0.77365	0.00211	1.13380
4	0.99950	0.97026	0.48451	1.01517	35	0.99561	0.76784	0.00176	1.13790
5	0.99937	0.96296	0.40423	1.01899	36	0.99548	0.76206	0.00147	1.14201
6	0.99925	0.95572	0.33726	1.02281	37	0.99536	0.75633	0.00123	1.14613
7	0.99912	0.94854	0.26138	1.02665	38	0.99523	0.75064	0.00102	1.15026
8	0.99899	0.94140	0.23475	1.03050	39	0.99511	0.74500	0.00085	1.15440
9	0.99887	0.93432	0.19586	1.03435	40	0.99498	0.73940	0.00071	1.15854
10	0.99874	0.92730	0.16341	1.03821	41	0.99486	0.73384	0.00059	1.16270
11	0.99862	0.92033	0.13633	1.04209	42	0.99473	0.72832	0.00050	1.16687
12	0.99849	0.91340	.011374	1.04597	43	0.99461	0.72284	0.00041	1.17105
13	0.99837	0.90654	0.09490	1.04986	44	0.99448	0.71741	0.00035	1.17523
14	0.99824	0.89972	0.07917	1.05377	45	0.99435	0.71201	0.00029	1.17943
15	0.99811	0.89295	0.06605	1.05768	46	0.99423	0.70666	0.00024	1.18363
16	0.99799	0.88624	0.05511	1.06160	47	0.99410	0.70134	0.00020	1.18784
17	0.99786	0.87958	0.04598	1.06553	48	0.99398	0.69607	0.00017	1.19207
18	0.99774	0.87296	0.03836	1.06947	49	0.99385	0.69084	0.00014	1.19630
19	0.99761	0.86640	0.03200	1.07342	50	0.99373	0.68564	0.00012	1.20054
20	0.99749	0.85988	0.02670	1.07738	51	0.99360	0.68049	0.00010	1.20479
21	0.99736	0.85342	0.02228	1.08135	52	0.99348	0.67537	0.00008	1.20905
22	0.99724	0.84700	0.01859	1.08532	53	0.99335	0.67029	0.00007	1.21332
23	0.99711	0.84063	0.01551	1.08931	54	0.99323	0.66525	0.00006	1.21760
24	0.99699	0.83431	0.01294	1.09331	55	0.99310	0.66025	0.00005	1.21189
25	0.99686	0.82803	0.01079	1.09732	56	0.99298	0.65528	0.00004	1.22619
26	0.99673	0.82181	0.00901	1.10133	57	0.99286	0.65036	0.00003	1.23050
27	0.99661	0.81563	0.00751	1.10536	58	0.99273	0.64547	0.00003	1.23481
28	0.99648	0.80950	0.00627	1.10939	59	0.99261	0.64061	0.00002	1.23914
29	0.99636	0.80341	0.00523	1.11344	60	0.99248	0.63579	0.00002	1.24347
30	0.99623	0.79737	0.00436	1.11749					

2.7 Interim Protocol for Using Unfiltered Track Detection (UT) to Measure Indoor Radon Concentrations

2.7.1 Purpose

This interim protocol provides guidance for using unfiltered track detection (UT) to obtain accurate and reproducible measurements of indoor radon concentrations. The Agency has not conducted large-scale field tests using the UT technique, and this interim protocol has been prepared with the assistance of researchers who have field experience with this method. As the EPA and others acquire more experience with this interim technique, the guidelines may be revised. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid intercomparison of results. The investigator should also follow guidance provided by the EPA in "Protocols for Radon and Radon Decay Product Measurements in Homes" (U.S. EPA 1992c) or other appropriate EPA measurement guidance documents.

2.7.2 Scope

This protocol covers, in general terms, the equipment, procedures, and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Indoor Environments Division (6609J), 401 M Street S.W., Washington, D.C. 20460, (202) 564-9370, (202) 565-2038 (fax).

2.7.3 Method

A UT detector consists of a piece of cellulose nitrate film packaged in a shielded container. Alpha particles emitted by radon and its decay products in air strike the detector and produce submicroscopic damage tracks. Cellulose nitrate is sensitive to alpha energies between about 1.5 MeV and 4.8 MeV (Damkjaer 1986, Jonsson 1987). It is not sensitive to radon decay products that plate out on the detector since their energies are above 5 MeV. Because the device detects (with different sensitivities) both radon and radon decay products, the equilibrium ratio (calculated as [working level X 100] per pCi/L of radon) between radon decay products and radon can affect the device's ability to measure accurately the concentration of radon gas. While the effect may not be pronounced at values found typically in homes (estimated usually in the range from 20 to 60 percent [Nazaroff and Nero 1988]), the error becomes significant when extreme values are encountered. Based on the EPA specifications, devices of this type (which are produced by several manufacturers) can be operated over an equilibrium range of about 40 percent, with the midpoint value available from the manufacturer.

At the end of the measurement period, the detectors are returned to a laboratory for processing and analysis. Detectors are placed in a caustic solution that accentuates the damage tracks so they can be counted using a microscope or an automatic spark counter. The detector may be exposed on one or both sides. The number of tracks per unit area is correlated to the radon concentration in air, using a conversion factor derived from data generated at a calibration facility. This conversion factor may vary for different ranges of equilibrium ratio because of the contribution from radon or radon decay products. Within a predetermined range, the number of tracks produced per unit of analyzed detector area per unit of time is proportional to the radon concentration.

Several factors contribute to the variability of the UT measurement results, including equilibrium ratio, differences in the detector response within and between batches of film, detector placement, differences in the number of background tracks, variations in etching conditions, and type of readout mechanism. Since the variability in UT measurement results decreases as the number of net tracks counted increases, counting more tracks over a larger area of the detector will reduce the uncertainty of the result. Whereas a counting area of a few square millimeters is typical with the filtered alpha track detector, it is more common to count one or more square centimeters with the UT detector.

2.7.4 Equipment

UT detectors are available from commercial suppliers. These suppliers offer contract services in which they provide the detector and subsequent analysis and reporting for a unit price. Establishing an in-house capability to provide packaged detectors, a calibration program, and a readout program would probably not be practical or economically advantageous for most users. Therefore, details for establishing the analytical aspects of a UT program are omitted from this protocol.

Assuming that UT detectors are obtained from a commercial supplier, the following equipment is needed to initiate monitoring in a house:

- The UT detector packaged in an individual, shielded container to prevent extraneous exposure before deployment;
- An instruction sheet for the occupant, a sample log sheet, and a shipping container (along with a mailing label, if appropriate;
- At the time of retrieval, some means for sealing the detector prior to returning it to the supplier for analysis; and
- A data collection log, if appropriate.

2.7.5 Pre-deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The UT measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The UT detector should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

2.7.6 Measurement Criteria

The reader should refer to Section 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

2.7.7 Deployment

2.7.7.1 Location Selection. The reader should refer to Section 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

If the detector is installed during a site visit, the final site selected should be shown to the building occupant to be certain it is acceptable for the duration of the measurement period.

2.7.7.2 Timely Deployment. A batch of UT detectors should be deployed into buildings as soon as possible after delivery from the supplier. To minimize chances of high background exposures, groups should not order more detectors than they can reasonably expect to install within the following few months. If the storage time exceeds more than a few months, the background exposures from a sample of the stored detectors should be assessed to determine if they are different from the background of detectors that are not stored for long periods. The supplier's instructions regarding storage and background determination should be followed. This background assessment of detectors stored for long periods is not necessary if the analysis laboratory measures routinely the background of stored detectors, and if the stored detectors remain tightly sealed.

The sampling period is initiated when the cellulose nitrate film is exposed. The detector should be inspected to ensure that it is intact and has not been physically damaged in shipment or handling.

2.7.8 Retrieval of Detectors

The device should be deployed for the measurement period specified in the instructions supplied by the analytical laboratory. If the occupant is terminating the sampling, the instructions should inform the occupant of when to terminate the sampling period and should indicate that the actual time of termination must be documented on the device. In addition, the occupant also should be instructed to send the device to the laboratory as soon as possible, preferably the day of sample termination. The analysis system should be calibrated to permit accurate analysis of devices deployed for some reasonable time beyond the recommended sampling period.

At the end of the measurement period, the detector should be inspected for damage or deviation from the conditions entered in the logbook at the time of deployment. Any changes should be noted in the logbook. The date of removal is entered on the data form for the detector and in the logbook. The detector is then resealed according to instructions supplied by the manufacturer. After retrieval, the detectors should be returned as soon as possible to the analytical laboratory for processing.

2.7.9 Documentation

The reader should refer to Section 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

2.7.10 Analysis Requirements

2.7.10.1 Sensitivity. The UT method permits analysis of large counting areas and thus can achieve high sensitivity. The lower limit of detection (LLD [calculated using methods described by Altshuler and Pasternack 1963]) and the precision of a UT system are, in part, dependent upon the total number of tracks counted. The number of tracks counted is dependent on the total area analyzed, the number of film emulsion sides exposed (one or two), the length of time of deployment, and the radon concentration being measured.

2.7.10.2 Precision. The precision should be monitored using the results of the duplicate detectors described in Section 2.7.11.3 of this protocol, rather than a precision quoted by the manufacturer. It is important that precision be monitored continuously over a range of radon concentrations and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

2.7.11 Quality Assurance

The quality assurance program for a UT system includes five parts: (1) calibration, (2) known exposure measurements, (3) duplicate (collocated) detectors, (4) control detectors, and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

2.7.11.1 Calibration. Every UT laboratory system should be calibrated in a radon calibration chamber at least once every 12 months. Determination of a calibration factor requires exposure of UT detectors to a known radon and decay product concentration in a radon exposure chamber. These calibration exposures are to be used to obtain or verify the conversion factor between net tracks per unit area and radon concentration. The following guidance is provided to manufacturers and suppliers of this device as minimum requirements in determining the calibration factor:

- UT detectors should be exposed in a radon chamber at several different radon and decay product concentrations similar to those expected in the tested buildings (a minimum of three different concentrations). Concentrations of radon decay products must be known in order to be included in the calculation of the calibration factor.
- A minimum of 10 detectors should be exposed at each level.
- A calibration factor should be determined for each batch of detector material received from the material supplier. Alternatively, calibration factors may be established from several sheets, and these factors extended to detectors from sheets exhibiting similar sensitivities (within pre-established tolerance limits).

- Altitude of the radon chamber must be known if located at more than 600 feet (200 meters) above sea level so that a correction can be included in the calculation of the calibration factor.

2.7.11.2 Known Exposure Measurements. Anyone providing measurement services with UT detectors should submit detectors with known radon and decay product exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure (spiked) detectors should be labeled in the same manner as field detectors to ensure identical processing. The results of the spiked detector analyses should be monitored and recorded. Any significant deviation from the known concentrations to which they were exposed should be investigated.

2.7.11.3 Duplicate (Collocated) Detectors. Anyone providing measurement services with UT devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10 percent of the number of detectors deployed each month or 50, whichever is smaller. The pair of detectors should be treated identically in every respect. They should be shipped, stored, opened, installed, removed, and processed together, and not identified as duplicates to the processing laboratory. The samples selected for duplication should be distributed systematically throughout the entire population of measurements. Groups selling measurements to homeowners can do this by providing two detectors (instead of one) to a random selection of purchasers, with instructions to place the detectors side-by-side. Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period. Data from duplicate detectors should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

2.7.11.4 Control Detectors

2.7.11.4.1 Laboratory Control Detectors. The laboratory background level for each batch of UT detectors should be established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed detectors that have been processed according to their standard operating procedures. Normally, the analysis laboratory or supplier calculates the net readings (which are used to calculate the reported sample radon concentrations) by subtracting the laboratory blank values from the results obtained from the field detectors.

2.7.11.4.2 Field Control Detectors. Field control UT detectors (field blanks) should consist of a minimum of five percent of the devices that are deployed every month or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed and in a low radon (less than 0.2 pCi/L) environment, label them in the same manner as the field UT detectors to assure identical processing, and send them back to the supplier with the field UT detectors for analysis. These control devices are necessary to measure the background exposure that accumulates during shipment and storage. The results should be monitored and recorded. If one or a few field blanks have concentrations significantly greater than the LLD established by the supplier, it may indicate defective packaging or handling. If the average value from the field control devices (field blanks) is significantly greater than the LLD established by the supplier, this average value should be subtracted from the individual values reported for the other devices in the exposure group.

2.7.11.5 Routine Instrument Checks. Proper functioning of the analysis instruments and proper response by their operators require that the equipment be subject to routine checks. Daily or more frequent monitoring of equipment and operators is vital to ensuring consistently accurate results.

Part 3: CWs, RPs and GWs

3.1 Protocol for Using Continuous Working-Level Monitors (CW) to Measure Indoor Radon
Decay Product Concentrations
3.2 Protocol for Using Radon Progeny Integrating Sampling Units (RPISU or RP) to Measure
Indoor Radon Decay Product Concentrations
3.3 Protocol for Using Grab Sampling-Working Level (GW) to Measure Indoor Radon Decay
Product Concentrations

3.1 Protocol for Using Continuous Working-Level Monitors (CW) to Measure Indoor Radon Decay Product Concentrations

3.1.1 Purpose

This protocol provides guidance for using continuous working-level monitors (CW) to obtain accurate and reproducible measurements of indoor radon decay product concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid inter-comparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in *Protocols for Radon and Radon Decay Product Measurements in Homes,* or other appropriate EPA measurement guidance documents.

3.1.2 Scope

This protocol covers, in general terms, the sample collection and analysis method, the equipment needed, and the quality control objectives of measurements made with CW. It is not meant to replace an instrument manual but, rather, to provide guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the EPA.

3.1.3 Method

The CW method samples the ambient air by filtering airborne particles as the air is drawn through a filter cartridge at a low flow rate of about 0.1 to one liter per minute. An alpha detector, such as a diffused-junction or surface-barrier detector, counts the alpha particles produced by the radon decay products as they decay on the filter. The detector is set normally to detect alpha particles with energies between 2 and 8 MeV. The alpha particles emitted from the radon decay products radium A (Po-218) and radium C (Po-214) are the significant contributors to the events that are measured by the detector. All CW detectors are capable of measuring individual radon and thoron decay products, while some can be adapted to measure the percentage of thoron decay products. The event count is directly proportional to the number of alpha particles emitted by the radon decay products on the filter. The unit contains typically a microprocessor that stores the number of counts and elapsed time. The CW detector can be set to record the total counts registered over specified time periods. The unit must be calibrated in a calibration facility to convert count rate to working-level (WL) values. This may be done initially by the manufacturer, and should be done periodically thereafter by the operator.

3.1.4 Equipment

In addition to the CW detector, equipment needed includes replacement filters, a read-out or programming device (if not part of the detector), an alpha-emitting check source, and an air flow-rate meter.

3.1.5 Pre-Deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The CW measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The CW detector should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

3.1.5.1 Pre-Sampling Testing

The CW detector should be tested carefully before and after each measurement in order to:

- verify that a new filter has been installed, and the input parameters and clock are set properly;
- measure the detector's efficiency with a check source, such as Am-241 or Th-230, and ascertain that it compares well with the technical specifications for the unit; and
- verify the operation of the pump.

When feasible, the unit should be checked after every fourth 48-hour measurement or week of operation to measure the background count rate using the procedures that are in the operating manual for the instrument.

In addition, participation in a laboratory inter-comparison program should be conducted initially, and at least once every 12 months thereafter, and after equipment repair, to verify that the conversion factor used by the microprocessor is accurate. This is done by comparing the unit's response to a known radon decay product concentration. At this time, the correct operation of the pump also should be verified by measuring the flow rate.

3.1.6 Measurement Criteria

Refer to Part 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

3.1.7 Deployment and Operation

3.1.7.1 Location Selection

Refer to Part 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

3.1.7.2 Operation

The CW detector should be programmed to run continuously, recording the periodic integrated WL and, when possible, the total integrated average WL. The sampling period should be 48 hours, with a grace period of two hours (i.e., a sampling period of 46 hours is acceptable if conditions prohibit terminating sampling after exactly 48 hours). The longer the operating time, the smaller the uncertainty associated with using the measurement result to estimate a longer-term average concentration. The integrated average WL over the measurement period should be reported as the measurement result. If results are also reported in pCi/L, it should be stated that this approximate conversion is based on a 50% equilibrium ratio, which is typical of the home environment, and any individual environment may have a different relationship between radon and decay products.

3.1.8 Retrieval of Detectors

When the measurement is terminated, the operator should note the stop date and stop time, and whether the standardized conditions are still in effect.

3.1.9 Documentation

Refer to Part 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

In addition, the serial number of the CW detector and calibration factor used should be recorded.

3.1.10 Analysis Requirements

3.1.10.1 Sensitivity

All known commercially available CW detectors are capable of a lower limit of detection (LLD) of 0.01 WL or less.

3.1.10.2 Precision

Precision should be monitored and recorded using the results of side-by-side measurements described in Part 3.1.11.3 of this protocol. This method can produce duplicate measurements with a coefficient of variation of 10% or less at 0.02 WL or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored frequently over a range of radon concentrations, and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

3.1.11 Quality Assurance

The quality assurance program for a CW system includes four parts: (1) calibration and known exposures; (2) background measurements; (3) duplicate measurements; and (4) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

3.1.11.1 Calibration and Known Exposures

Every CW detector should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent re-calibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semi-annually.

3.1.11.2 Background Measurements

Background count-rate checks must be conducted after at least every 168 hours (fourth 48-hour measurement) of operation, and whenever the unit is calibrated. The CW should be purged with clean, aged air or nitrogen, in accordance with the procedures given in the instrument's operating manual. In addition, the background count rate may be monitored more frequently by operating the CW in a low-radon environment.

3.1.11.3 Duplicate Measurements

When two or more CW detectors are available, the precision of the measurements can be estimated by operating the detectors side-by-side. The analysis of duplicate results should follow the methodology described by Goldin (section 5.3 in Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

3.1.11.4 Routine Instrument Checks

Checks using an Am-241 or similar-energy alpha check source must be performed before and after each measurement. In addition, it is important to regularly check all components of the equipment that affect the result.

Pump and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

3.2 Protocol for Using Radon Progeny-Integrating Sampling Units (RPISU or RP) to Measure Indoor Radon Decay Product Concentrations

3.2.1 Purpose

This protocol provides guidance for using radon progeny-integrating sampling units (RPISU or RP) to produce accurate and reproducible measurements of indoor radon decay product concentrations. Adherence to this procedure will help ensure uniformity in measurement programs and allow valid inter-comparison of results. Measurements made in accordance with this protocol will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability, and are more reproducible than measurements made when the building conditions are not controlled. The investigator should also follow guidance provided by the EPA in *Protocols for Radon and Radon Decay Product Measurements in Homes*, or other appropriate EPA measurement guidance documents.

3.2.2 Scope

This protocol covers, in general terms, the equipment, procedures, analysis and quality control objectives for measurements made with RPs. It is not meant to replace an instrument manual but, rather, provides guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the EPA.

3.2.3 Method

3.2.3.1 Thermoluminescent Dosimeter (TLD) RP

There are three types of RPs. The TLD type contains an air-sampling pump that draws a continuous, uniform flow of air through a detector assembly. The detector assembly includes a filter and at least two TLDs. One TLD measures the radiation emitted from radon decay products collected on the filter, and the other TLD is used for a background gamma correction. This RP is intended for a sampling period of 48 hours to a few weeks.

Analysis of the detector TLDs is performed in a laboratory using a TLD reader. Interpretation of the results of this measurement requires a calibration for the detector and the analysis system based on exposures to known concentrations of radon decay products.

3.2.3.2 Alpha-Track Detector (ATD) RP

A second type of RP consists of an air-sampling pump and an ATD assembly. The air-sampling pump draws a continuous, uniform flow of air through a filter in the detector assembly where the radon decay products are deposited. Opposite to the side of the filter where the radon decay products are deposited is a cylinder with three collimating cylindrical holes. Alpha particles emitted from the radon decay products on the filter pass through the collimating holes and through different thicknesses of energy-absorbing film before impinging on a disc of alpha-track detecting plastic film (LR-115 or CR-39). Analysis of the number of alpha-particle tracks in each of the three sectors of the film allows the determination of the number of alpha particles derived from radium A (Po-218) and radium C (Po-214). This feature allows the determination of the equilibrium factor for the radon decay products. This type of RP is intended for a sampling period of about 48 hours to a few weeks.

Etching and counting of the alpha-track assembly is carried out by mailing the detector film to the analysis laboratory. Interpretation of the results of this measurement requires a calibration for the detector, and the analysis system based on exposure to known concentrations of radon decay products.

3.2.3.3 Electret RP

The electret RP is similar in operation to the TLD-type RP, except that the TLD is replaced with an electret. The current model of this device contains a one-liter-per-minute constant air-flow pump and collects the decay products on an 11.4 cm2 filter. As the radon decay products that are collected on the filter decay, negatively-charged ions generated by alpha-particle radiation are collected on a positively-charged electret, thereby reducing its surface voltage. This reduction has been demonstrated to be proportional to the radon decay product concentration. For more general information on electrets, refer to Part 2.3.

RPs are true integrating instruments if the pump flow rate is uniform throughout the sampling period. The electret must be removed from the chamber, and the electret voltage measured with a special surface voltmeter both before and after exposure. To determine the average radon concentration during the exposure period, the difference between the initial and final voltages is divided first by a calibration factor, and then by the number of exposure days. A background radon concentration equivalent of ambient gamma radiation is subtracted to compute radon concentration. Electret voltage measurements can be made in a laboratory or in the field.

3.2.4 Equipment

The three types of RP sampling systems include a sampling pump and the detector assembly. Sampling with the TLD-type RP requires either a fresh detector assembly or fresh TLD chips to be inserted in the detector assembly. Using the electret-type RP requires a sufficient charge on the electret. Sampling with the ATD-type RP requires a fresh detector disc (LR-115 or CR-39). An air-flow rate meter should be available for checking flow rates with the RP, and spare filters should be available as replacements as needed.

3.2.5 Pre-Deployment Considerations

The plans of the occupant during the proposed measurement period should be considered before deployment. The RP measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The RPISU should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

Prior to installation in the building, the pump should be checked to ensure that it is operable and capable of maintaining a uniform flow through the detector assembly. Extra pump assemblies should be available during deployment in case a problem is encountered.

Arrangements should be made with the occupant of the building to ensure that entry into the building is possible at the time of installation, and to determine availability of a suitable electrical outlet near the sampling area in the selected room.

3.2.6 Measurement Criteria

Refer to Part 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

3.2.7 Deployment and Operation

3.2.7.1 Location Selection

Refer to Part 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

In addition, the air intake (sampling head) should be placed at least 20 inches (50 centimeters) above the floor, and at least 4 inches (10 centimeters) from surfaces that may obstruct flow.

3.2.7.2 Operation

The RP should be installed and, if possible, the air-flow rate checked with a calibrated flow meter. The location, date, starting time, running-time meter reading and flow rate should be recorded on the detector assembly envelope and in a log. The RP should be observed for a few minutes after initiating measurements to ensure continued operation. The occupants should also be informed about the RP and requested that they report any problems or pump shut-down. The occupants should be aware of the length of time the RP will be operated, and an appointment should be arranged to retrieve the unit. The occupants should also be informed of the criteria for the standardized measurement conditions (Part 1.2.2).

The sampling period should be at least 48 hours, and may need to be longer, depending on the type of RP head. A longer operating time decreases the uncertainty associated with the measurement result.

3.2.8 Retrieval of Devices

Prior to pump shut-down, the flow rate should be measured with a calibrated flow meter (if possible), and the unit should be observed briefly to ensure that it is operating properly. The detector assembly or detector film should be removed for processing, and the date, time, running-time meter reading and flow rate should be recorded both on the envelope and in a log book. The filter should be checked for holes or dust loading and any other observed conditions that might affect the measurement. If TLDs or film discs are to be removed from the detector assembly, removal should be delayed for at least three hours after sampling is completed to allow for decay and registration of radon decay products on the filter.

3.2.9 Documentation

Refer to Part 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

In addition, the serial numbers of the RPs, TLDs, film discs or electrets must be recorded.

3.2.10 Analysis Requirements

Analysis of the film from the ATD-type RPs requires an analysis laboratory equipped to etch and count alpha-track film.

Analysis of TLD-type RPs requires a TLD reader. The TLD reader is an instrument that heats the TLDs at a uniform and reproducible rate, and measures simultaneously the light emitted by the thermoluminescent material. The read-out process is controlled carefully, with the detector purged with nitrogen to prevent spurious emissions. Prior to analyzing the RPISU dosimeters, the TLD reader should be tested periodically using dosimeters exposed to a known level of alpha or gamma radiation. TLDs are prepared for re-use by cleaning and annealing at the prescribed temperature in an oven.

Analysis of the electret-type RPs requires a specially-built surface voltmeter for measuring electret voltages before and after exposure. For more information on analysis requirements, refer to Part 2.3.10 (Electret Ion Chamber Radon Detectors).

3.2.10.1 Sensitivity

The lower limit of detection (LLD) should be specified by individual suppliers for RP detectors exposed according to their directions. The LLD will depend on the length of the exposure and the background of the detector for materials used. The LLD should be calculated using the results of the laboratory control devices.

3.2.10.2 Precision

Precision should be monitored and recorded using the results of the duplicate detector analyses described in Part 3.2.11.3. This method may achieve a coefficient of variation of 10% at radon decay product concentrations of 0.02 WL or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations, and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

3.2.11 Quality Assurance

The quality assurance program for an RP system includes five parts: (1) calibration; (2) known exposure detectors; (3) duplicate (collocated) detectors; (4) control detectors; and (5) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements, and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

Users of electret-type RPs should follow the quality assurance guidance given for electret ion chamber devices in Part 2.3.

3.2.11.1 Calibration

Every RP should be calibrated in a radon calibration chamber before being put into service, and after any repairs or modifications. Subsequent re-calibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semi-annually. Calibration of RPs requires exposure in a controlled radon-exposure chamber where the radon decay product concentration is known during the exposure period. The detector must be exposed in the chamber using the normal operating flow rate for the RP sampling pumps. Calibration should include exposure of a minimum of four detectors exposed at different radon decay product concentrations representative of the range found in routine measurements. The relationship of TLD reader units or etched track reader units to working level (WL) for a given sample volume, and the standard error associated with this measurement should be determined. Calibration of the RPs also includes testing to ensure accuracy of the flow-rate measurement.

3.2.11.2 Known Exposure Devices

Anyone providing measurement services with RP devices should submit detectors with known decay product exposures (spiked samples) for analysis at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. Known exposure detectors should be labeled in the same manner as the field detectors to assure blind processing. The results of the known exposure detector analysis should be monitored and recorded, and any significant deviation from the known concentration to which they were exposed should be investigated.

3.2.11.3 Duplicate (Collocated) Detectors

Anyone providing measurement services with RP devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10% of the number of detectors deployed each month, or 50, whichever is smaller. The duplicate detectors should be shipped, stored, exposed and analyzed under the same conditions. The samples selected for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurement services to homeowners can do this by making two side-by-side measurements in a random selection of homes. Data from duplicate detectors should be evaluated using the procedures described by Goldin (section 5.3 in Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

3.2.11.4 Control Detectors

TLD-type RPs use a TLD that is shielded from the gamma radiation emitted by the material on the filter. This TLD is incorporated in the detector assembly to measure the environmental gamma exposure of the sampling detector. The two TLDs are processed identically and the environmental gamma exposure is subtracted from the sample reading. Electret-type RPs also require an environmental gamma background correction.

3.2.11.4.1 Laboratory Control Detectors

The laboratory background level for each batch of assembled TLDs should be established by each supplier. Suppliers should measure the background of a statistically significant number of unexposed thermoluminescent assemblies that have been processed according to their standard operating procedures. To calculate the net readings used to calculate the reported sample radon concentrations, the analysis laboratory subtracts this laboratory blank value from the results obtained from the field detectors.

Similarly, the laboratory background level for each batch of ATD-type RPs should be established by each supplier of these detectors. Suppliers should measure the background of a statistically significant number of unexposed detector films that have been processed according to their standard operating procedures. The analysis laboratory will subtract this laboratory blank value from the results obtained from the field detectors before calculating the final result.

Users of electret-type RPs should follow similar control detector procedures discussed in Part 2.3.11.1.

3.2.11.4.2 Field Control Detectors (Blanks)

Field control detectors (field blanks) should consist of a minimum of 5% of the detectors deployed each month, or 25, whichever is smaller. Users should set these aside from each shipment, keep them sealed, label them in the same manner as the field detectors, and, where applicable, send them back to the analysis laboratory as blind controls with one shipment each month. These field blank detectors measure the background exposure that may accumulate during shipment or storage. The results should be monitored and recorded. If one or a few of the field blanks have concentrations significantly greater than the LLD established by the supplier, it may indicate defective material or procedures. If the average value from the background control detectors (field blanks) is significantly greater than the LLD established by the supplier, this average value should be subtracted from the individual values reported for the other detectors in the exposure group. The cause for the elevated field blank readings should then be investigated.

3.2.11.5 Routine Instrument Checks

Proper operation of all analysis equipment requires that their response to a reference source be constant to within established limits. Therefore, analysis equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day during operation.

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

3.3 Protocol for Using Grab-Sampling Working Level (GW) to Measure Indoor Radon Decay Product Concentrations

3.3.1 Purpose

This protocol provides guidance for using the grab-sampling working-level (GW) technique to provide accurate and reproducible measurements of indoor radon decay product concentrations. Adherence to this protocol will help ensure uniformity among measurement programs and allow valid inter-comparison of results. Measurements made in accordance with this procedure will produce results representative of closed-building conditions. Measurements made under closed-building conditions have a smaller variability and are more reproducible than measurements made when the building conditions are not controlled.

The results of the GW method are influenced greatly by conditions that exist in the building during and for up to 12 hours prior to the measurement. It is, therefore, especially important when making grab measurements to conform to the closed-building conditions for 12 hours before the measurement. Grab-sampling techniques are not recommended for measurements made to determine the need for remedial action. The investigator should also follow guidance provided by the EPA in *Protocols for Radon and Radon Decay Product Measurements in Homes,* or other appropriate EPA measurement guidance documents.

3.3.2 Scope

This procedure covers, in general terms, the equipment, procedures and quality control objectives to be used in performing the measurements. It is not meant to replace an instrument manual but, rather, to provide guidelines to be incorporated into standard operating procedures by anyone providing measurement services. Questions about these guidelines should be directed to the EPA.

3.3.3 Methods

Grab-sampling measurements of radon decay product concentrations in air are performed by collecting the decay products from a known volume of air on a filter, and by counting the activity on the filter during or following collection. Several methods for performing such measurements have been developed and have been described previously (George 1980). Comparable results may be obtained using all these methods. This procedure, however, will describe two methods that have been used most widely with good results. These are the Kusnetz procedure and the modified Tsivoglou procedure.

The Kusnetz procedure (ANSI 1973, Kusnetz 1956) may be used to obtain results in working levels (WL) when the concentration of individual decay products is unimportant. Decay products from up to 100 liters of air are collected on a filter in a five-minute sampling period. The total alpha activity on the filter is counted at any time between 40 and 90 minutes after the end of sampling. Counting can be done using a scintillation-type counter to obtain gross alpha counts for the selected period. Counts from the filter are converted to disintegrations using the appropriate counter efficiency. The disintegrations from the decay products collected from the known volume of air may be converted into WLs using the appropriate "Kusnetz factor" for the counting time used see (Part 3.3.11.3., Exhibit 3-1).

The Tsivoglou procedure (Tsivoglou et al. 1953), as modified by Thomas (1972), may be used to determine WL and the concentration of the individual radon decay products. Sampling is the same as that used for the Kusnetz procedure; however, the filter is counted three separate times following collection. The filter is counted between the interval of two to five minutes, six to 20 minutes, and 21 to 30 minutes, following completion of sampling. Count results are used in a series of equations to calculate concentrations of the three radon decay products and WL. These equations and an example calculation appear in Part 3.3.11.4.1.

3.3.4 Equipment

Equipment required for radon decay product concentration determination by GW consists of the following items:

- an air-sampling pump capable of maintaining a flow rate of 2 to 25 liters per minute through the selected filter. The flow rate should not vary significantly during the sampling period;
- a filter holder (with adapters for attachment) to accept a 25- or 47-mm diameter, 0.8-micron membrane or glass fiber filter;
- a calibrated air-flow measurement device to determine the air flow through the filter during sampling;
- a stopwatch or timer for accurate timing of sampling and counting;
- a scintillation counter and a zinc-sulfide scintillation disc;
- a National Institute of Standards and Technology (NIST)-traceable alpha calibration source to determine counter efficiency; and
- a data collection log.

3.3.5 Pre-Deployment Considerations

The occupant's plans during the proposed measurement period should be considered before deployment. The GW measurement should not be made if the occupant will be moving during the measurement period. Deployment should be delayed until the new occupant is settled in the house.

The GW device should not be deployed if the user's schedule prohibits terminating the measurement at the appropriate time.

3.3.5.1 Pre-Measurement Testing

Prior to collection of the sample, proper operation of the equipment must be verified, and the counter efficiency and background must be determined. This is especially critical for the Tsivoglou procedure, in which the sample counting must begin two minutes following the end of sampling.

The air pump, filter assembly and flow meter must be tested to ensure that there are no leaks in the system. The scintillation counter must be operated with the scintillation tray (where applicable) and scintillation disc in place to determine background for the counting system. Also, the counter must be operated with a NIST-traceable alpha calibration source in place of a filter in the counting location to determine system-counting efficiency. Both the system background and system efficiency are used in the calculation of results from the actual sample.

3.3.6 Measurement Criteria

Refer to Part 1.2.2 for the list of general conditions that must be met to ensure standardization of measurement conditions.

3.3.7 Deployment

3.3.7.1 Location in Room

Refer to Part 1.2.3 for standard criteria that must be considered when choosing a measurement device location.

3.3.7.2 Sampling

A new filter should be placed in the filter holder prior to entering the building. Care should be taken to avoid puncturing the filter and to avoid leakage. The sampling is initiated by starting the pump and the clock simultaneously. The air-flow rate should be noted and recorded in a log book. The time the sampling was begun should also be recorded. The sampling period should be five minutes, and the time from the beginning of sampling to the time of counting must be recorded precisely.

3.3.8 Documentation

Refer to Part 1.2.4 for the list of standard information that must be documented so that data interpretation and comparison can be made.

3.3.9 Analysis Requirements

Analysis may be done using the Kusnetz procedure (ANSI 1973, Kusnetz 1956), the modified Tsivoglou procedure (Thomas 1972, Tsivoglou et al. 1953), or other procedures described elsewhere (George 1980). If the Tsivoglou procedure is used, the counting must be started two minutes following the end of sampling. Analysis using the Kusnetz procedure must be performed between 40 and 90 minutes following the end of sampling. A counting time of 10 minutes during this period is usually used. Refer to Parts 3.3.3 and 3.3.11 for more information.

The filter from the holder must be removed using forceps, and placed carefully facing the scintillation phosphor. The side of the filter on which the decay products were collected must face the phosphor disc. The chamber containing the filter and disc should be closed and allowed to dark-adapt prior to starting counting. For the Tsivoglou method, this procedure of placing the filter in the counting position must be done quickly, since the first of the three counts must begin two minutes following the end of sampling. If the counter used has been shown to be slow to dark-adapt, the counting should be done in a darkened environment. Additional details on the procedure and calculations are available (Kusnetz 1956, Thomas 1972, Tsivoglou et al. 1953).

3.3.9.1 Sensitivity

For a five-minute sampling period (10 to 20 liters of air) on a 25-mm filter, the lower limit of detection (LLD) using the Kusnetz or modified Tsivoglou counting procedure can be approximately 0.0005 WL (George 1980).

3.3.9.2 Precision

Precision should be monitored using the results of duplicate measurements (refer to Part 3.4.10.2). Sources of error in the procedure may result from inaccuracies in measuring the volume of air sampled, characteristics of the filter used, and measurement of the amount of radioactivity on the filter. The method can produce duplicate measurements with a coefficient of variation of 10% or less at 0.02 WL or greater. An alternate measure of precision is a relative percent difference, defined as the difference between two duplicate measurements divided by their mean; note that these two measures of precision are not identical quantities. It is important that precision be monitored continuously over a range of radon concentrations, and that a systematic and documented method for evaluating changes in precision be part of the operating procedures.

3.3.10 Quality Assurance

The quality assurance program for a GW system includes three parts: (1) calibration of the system; (2) duplicate measurements; and (3) routine instrument checks. The purpose of a quality assurance program is to identify the accuracy and precision of the measurements, and to ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. The quality assurance program should include the maintenance of control charts (Goldin 1984); general information is also available (Taylor 1987, U.S. EPA 1984).

3.3.10.1 Calibration

Pumps and flow meters used to sample air must be calibrated routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

Every GW device should be calibrated in a radon (decay product) calibration chamber before being put into service, and after any repairs or modifications. Subsequent re-calibrations should be done once every 12 months, with cross-checks to a recently calibrated instrument at least semi-annually. Grab measurements should be made in a calibration chamber with known radon decay product concentrations to verify the calibration factor. These measurements should also be used to test the collection efficiency and self-absorption of the filter material being used for sampling. A change in the filter material being used requires that the new material be checked for collection efficiency in a calibration chamber.

3.3.10.2 Duplicate Measurements

Anyone providing measurement services with GW devices should place duplicate detectors in enough houses to test the precision of the measurement. The number of duplicate detectors deployed should be approximately 10% of the number of detectors deployed each month, or 50, whichever is smaller. To the greatest extent possible, care should be taken to ensure that the samples are duplicates. The filter heads should be relatively close to each other and away from drafts. Care should also be taken to ensure that one filter is not in the discharge air stream of the other sampler. The measurements selected for duplication should be distributed systematically throughout the entire population of measurements. Data from duplicate samples should be evaluated using the procedures described by Goldin (section 5.3 of Goldin 1984), by Taylor (Taylor 1987), or by the EPA (U.S. EPA 1984). Whatever procedures are used must be documented prior to beginning measurements. Consistent failure in duplicate agreement may indicate a problem in the measurement process and should be investigated.

3.3.10.3 Routine Instrument Checks

Proper operation of all radiation counting instruments requires that their response to a reference source be constant to within established limits. Therefore, counting equipment should be subject to routine checks to ensure proper operation. This is achieved by counting an instrument check source at least once per day. The characteristics of the check source (i.e., geometry, type of radiation emitted, etc.) should, if possible, be similar to the samples to be analyzed. The count rate of the check source should be high enough to yield good counting statistics in a short time (for example, 1,000 to 10,000 counts per minute).

The radiological counters should have calibration checks run daily to determine counter efficiency. This is particularly important for portable counters taken into the field that may be subject to rugged use and temperature extremes. These checks are made using a NIST-traceable alpha calibration source such as Am-241. In addition, the system background count rate should be assessed regularly.

Pumps and flow meters should be checked routinely to ensure accuracy of volume measurements. This may be performed using a dry-gas meter or other flow measurement device of traceable accuracy.

3.3.11 Supplementary Information for the Grab-Sampling Working-Level (GW) Method

3.3.11.1 Sample Collection

Two commonly used methods are described below. There are several other methods reported in the literature. Sampling using these methods requires collection of radon decay products on a filter, and measuring the alpha activity of the sample with a calibrated detector at time intervals that are specific for each method.

The filter is installed in the filter-holder assembly and attached to the pump. The pump is then operated for exactly five minutes, pulling air through the filter. Starting time and air-flow rate should be recorded. The pump is stopped at the end of the five-minute sampling time. At this time, the stopwatch should be started or reset.

3.3.11.2 Sample Counting

Sample counting for two different techniques is described below.

3.3.11.2.1 Modified Tsivoglou Technique

The filter is transferred carefully from the filter-holder assembly to the detector. The collection side of the filter is oriented toward the face of the detector.

The counter is operated for the following time intervals (after sampling has stopped): two to five minutes, six to 20 minutes, and 21 to 30 minutes. The total counts for each time period are then recorded.

3.3.11.2.2 Kusnetz Technique

The filter is transferred carefully from the filter-holder assembly to the detector. The collection side of the filter is oriented toward the face of the detector.

The counter is operated over any 10-minute time interval between 40 minutes and 90 minutes after sampling starts. The total counts for the sample and the time (in minutes after sampling) at the midpoint of the 10-minute time interval are then recorded.

3.3.11.3 Data Analysis

Data analysis for the two different techniques is described below.

3.3.11.3.1 Modified Tsivoglou Technique

The concentration, in picocuries per liter (pCi/L), of each of the radon decay products (Po-218, Pb-214 and Po-214) can be determined by using the following calculations:

$$C2 = 1/FE\ (0.16921\ G1 - 0.08213\ G2 + 0.07765\ G3 - 0.5608\ R)$$

$$C3 = 1/FE\ (0.001108\ G1 - 0.02052\ G2 + 0.04904\ G3 - 0.1577\ R)$$

$$C4 = 1/FE\ (-0.02236\ G1 + 0.03310\ G2 - 0.03765\ G3 - 0.05720\ R)$$

It is important to note that the constants in these equations are based on a 3.04-minute half-life of Po-218. The working level (WL) associated with these concentrations can then be calculated using the following relationship:

Where:

C2 = concentration of Po-218 (RaA) in pCi/L;

C3 = concentration of Pb-214 (RaB) in pCi/L;

C4 = concentration of Po-214 (RaC') in pCi/L;

F = sampling flow rate in liters per minute (Lpm);

E = counter efficiency in counts per minute/disintegrations per minute (cpm/dpm);

G1 = gross alpha counts for the time interval of two to five minutes;

G2 = gross alpha counts for the time interval of six to 20 minutes;

G3 = gross alpha counts for the time interval of 21 to 30 minutes; and

R = background counting rate in cpm.

(Reference: Thomas 1972.)

3.3.11.3.2 Kusnetz Technique

WL is calculated as follows:

WL = C/Kt VE

Where:

C = sample cpm - background cpm;

Kt = factor determined from Exhibit 3-1 (PHS 1957) for time from end of collection to midpoint of counting;

V = total sample air volume in liters [calculated as flow rate (L/m) x sample time (m)]; and

E = counter efficiency in cpm/dpm.

3.3.11.4 Sample Problems

3.3.11.4.1 Sample Problem for the Modified Tsivoglou Technique

Given:

F = sampling flow rate = 3.5 Lpm

E = counting efficiency = 0.47 cpm/dpm

G1 = 880

G2 = 2660

G3 = 1460

R = 0.5

Calculate:

C2 = 1/3.5 x 0.47 (0.16921 x 880 - 0.08213 x 2660 + 0.07765 x 1460 - 0.05608 x 0.5)

C2 = 26.8 pCi/L

C3 = 1/3.5 x 0.47 (0.001108 x 880 - 0.02052 x 2660 + 0.04904 x 1460 - 0.1577 x 0.5)

C3 = 10.9 pCi/L

C4 = 1/3.5 x 0.47 (-0.02236 x 880 + 0.03310 x 2660 - 0.03766 x 1460 - 0.05720 x 0.5)

C4 = 8.1 pCi/L

WL = (1.028 x 10^{-3} x 26.8 + 5.07 x 10^{-3} x 10.9 + 3.728 x 10^{-3} x 8.1)

WL = 0.11

3.3.11.4.2 Sample Problem for the Kusnetz Technique

Background count = 3 counts in 5 minutes, or 0.6 cpm

Standard count = 5,985 counts in 5 minutes, or 1,197 cpm

Efficiency = 1197 cpm - 0.6 cpm/2,430 dpm = 0.49 (known source of 2,439 dpm)

Sample volume = 4.4 liter/minute x 5 minutes = 22 liters

Sample count at 45 minutes (time from end of sampling period to start of counting period) = 560 counts in 10 minutes, or 56 cpm

Kt at 50 minutes (from Exhibit 3-1) = 130

WL = 56 cpm - 0.6 cpm/130 x 22 L x 0.49

WL = 0.04

Glossary

- **accuracy:** the degree of agreement of a measurement (X) with an accepted reference or true value (T); usually expressed as the difference between the two values (X – T), or the difference as a percentage of the reference or true value (100[X – T]/T), and sometimes expressed as a ratio (X/T).

- **active radon/radon decay product measurement device:** a radon or radon decay product measurement system which uses a sampling device, detector and measurement system integrated as a complete unit or as separate but portable components. Active devices include continuous radon monitors, continuous working-level monitors, and grab-radon gas and grab working-level measurement systems, but do not include devices such as electret ion chamber devices, activated-carbon or other adsorbent systems, or alpha-track devices.

- **alpha particle:** two neutrons and two protons bound as a single particle that is emitted from the nucleus of certain radioactive isotopes in the process of decay.

- **background count rate:** the counting rate obtained on a given instrument with a background counting sample. Typical reference background counting samples are:

  - empty planchet: for G-M detectors, internal proportional counters, low-background beta counters, alpha spectrometers;
  - scintillation vial containing scintillant and sample known to contain no

radioactivity: for
liquid scintillation counters; and

- container filled with distilled water: for gamma spectrometers.

- **background measurements:** measurements made with either active instruments exposed to a radon-free gas, such as aged air or nitrogen, or for passive detectors by analyzing unexposed detectors. Results are subtracted from the actual field measurements before calculating the reported concentration. Background levels may be due to electronic noise of the analysis system, leakage of radon into the detector, detector response to gamma radiation, or other causes.

- **background radiation:** radiation arising from radioactive material other than that under consideration. Background radiation due to cosmic rays and natural radioactivity is always present; background radiation may also be due to the presence of radioactive substances in building materials.

- **bias:** a systematic (consistent) error in test results. Bias can exist between test results and the true value (absolute bias, or lack of accuracy), or between results from different sources (relative bias). For example, if different laboratories analyze a homogeneous and stable blind sample, the relative biases among the laboratories would be measured by the differences existing among the results from the different laboratories. However, if the true value of the blind sample were known, the absolute bias or lack of accuracy from the true value would be known for each laboratory. See **systematic error.**

- **blank sample:** a control sample in which the detector is unexposed and submitted for analysis; often used to determine detector background values.

- **blind spikes:** detectors exposed to known radon or decay product concentrations and submitted for analysis without being labeled as such; used to evaluate the accuracy of the measurement.

- **calibrate:** to determine the response or reading of an instrument relative to a series of known values over the range of the instrument; results are used to develop correction or calibration factors.

- **check source:** a radioactive source, not necessarily calibrated, which is used to confirm the continuing satisfactory operation of an instrument.

- **coefficient of variation (CV** or **COV)** and **relative standard deviation (RSD):** a measure of precision, calculated as the standard deviation *(s)* of a set of values divided by the average (Xave or μ), and usually multiplied by 100 to be expressed as a percentage.

CV = RSD = / x 100 for a sample,

CV' = RSD' = / x 100 for a population

See **relative percent difference.**

- **curie (Ci):** a standard measurement for radioactivity -- specifically, the rate of decay for a gram of radium: 37 billion decays per second; a unit of radioactivity equal to 3.7 x 10^{10} disintegrations per second.

- **duplicate measurements:** two measurements made concurrently and in the same location, or side-by-side; used to evaluate the precision of the measurement method.

- **electron:** an elementary constituent of an atom that orbits the nucleus and has a negative charge. Beta decay is radioactive decay in which an electron is emitted from a nucleus.

- **electron volt (eV):** one eV is equivalent to the energy gained by an electron in passing through a potential difference of one volt. One unit of energy = 1.6 x 10^{-12} ergs = 1.6 x 10^{-19} joules; 1 MeV = 106 eV.

- **equilibrium, radioactive:** a state in which the formation of atoms by decay of a parent radioactive isotope is equal to its rate of disintegration by radioactive decay.

- **equilibrium ratio, radioactive:** the total concentration of radon decay products (RDPs) present divided by the concentration that would exist if the RDPs were in radioactive equilibrium with the radon gas concentration which is present. At equilibrium (i.e., at an equilibrium ratio of 1), 1 WL of RDPs would be present when the radon concentration was 100 pCi/L. The ratio is never 1 in a house. Due to ventilation and plate-out, the RDPs never reach equilibrium in a house environment. A commonly assumed equilibrium ratio is 0.5 (i.e., the progeny are halfway toward equilibrium), in which case 1 WL corresponds to 200 pCi/L. However, equilibrium ratios vary with time and location, and ratios of 0.3 to 0.7 are commonly observed. Large buildings, including schools, often contain equilibrium ratios less than 0.5.

- **exposure time:** the length of time a specific mail-in device must be in contact with radon or radon decay products to get an accurate radon measurement; also called **exposure period**, **exposure parameters**, and **duration of exposure**.

- **gamma radiation:** short-wavelength electromagnetic radiation of nuclear origin, with energies between 10 keV to 9 MeV.

- **integrating device:** a device that measures a single average concentration value over a period of time; also called a **time-integrating device**.

- **ion:** an electrically charged atom in which the number of electrons does not equal the number of protons.

- **ionization:** the process whereby a neutral atom or molecule becomes negatively or positively charged by acquiring or losing an electron.

- **ionizing radiation:** any type of radiation capable of producing ionization in materials it contacts; includes high-energy charged particles such as alpha and beta rays, and non-particulate radiation such as gamma rays and X-rays; in contrast to wave radiation (e.g., visible light and radio waves) in which waves do not ionize adjacent atoms as they move.

- **lower limit of detection (LLD):** the smallest amount of sample activity which will yield a net count for which there is confidence at a pre-determined level that activity is present. For a 5% probability of concluding falsely that activity is present, the LLD is approximately equal to 4.65 times the standard deviation of the background counts (assuming large numbers of counts where Gaussian statistics can be used [ANSI 1989, Pasternack and Harley 1971, U.S. DOE 1990]).

- **passive radon/radon decay product measurement device:** a radon or radon decay product measurement system in which the sampling device, detector and measurement system do not function as a complete, integrated unit. Passive devices include electret ion chamber devices, activated-carbon or other adsorbent systems, or alpha-track devices, but do not include continuous radon/radon decay product monitors, or grab-radon/radon decay product measurement systems.

- **picocurie (pCi):** one pCi is one trillionth of a curie, 0.037 disintegrations per second, or 2.22 disintegrations per minute.

- **picocurie per liter (pCi/L):** a unit of radioactivity corresponding to one decay every 27 seconds in a volume of one liter, or 0.037 decays per second in every liter of air.

- **pooled estimate of variance:** an estimate of precision derived from different sets of duplicates, calculated as follows:

  S2dp = S2d1 (n1 - 1) + S2ds (n2 - 1)/(n1 - 1) + (n2 - 1)

  where:

  S2dp = pooled variance;

  S2d1 = variance observed with the first group of detectors or equipment;

  S2d2 = variance observed with the second group of detectors or equipment;

  n1 = sample size of the first group of detectors or equipment; and

  n2 = sample size of the second group of detectors or equipment.

- **precision:** a measure of mutual agreement among individual measurements of the same property, usually under prescribed and similar conditions; most desirably expressed in terms of the standard deviation, but can be expressed in terms of the variance, pooled estimate of variance, range, relative percent difference, or other statistic.

- **quality assurance:** a complete program designed to produce results which are valid, scientifically defensible, and of known precision, bias and accuracy; includes planning, documentation and quality control activities.

- **quality control:** the system of activities to ensure a quality product, including measurements made to ensure and monitor data quality; includes calibrations, duplicate, blank and spiked measurements, inter-laboratory comparisons and audits.

- **radon (Rn):** a colorless, odorless, naturally occurring, radioactive, inert, gaseous element formed by radioactive decay of radium (Ra) atoms. The atomic number is 86. Although other isotopes of radon occur in nature, radon in indoor air is almost exclusively Rn-222.

- **radon chamber:** an airtight enclosure in which operators can induce and control different levels of radon gas and radon decay products. Volume is such that samples can be taken without affecting the levels of either radon or its decay products within the chamber.

- **random error:** variations of repeated measurements that are random in nature and not predictable individually. The causes of random error are assumed to be indeterminate or non-assignable. The distribution of random errors is assumed generally to be normal (Gaussian).

- **range:** the difference between the maximum and minimum values of a set of values. When the number of values is small (eight or less), the range is a relatively sensitive (efficient) measure of variability. As the number of values increases above eight, the efficiency of the range (as an estimator of the variability) decreases rapidly. The range, or difference between two paired values, is of particular importance in air pollution measurement, since, in many situations, duplicate measurements are performed as part of the quality assurance program.

- **relative percent difference (RPD):** a measure of precision, calculated by:

  Rd% = (X1 - X2)/Xavg x 100

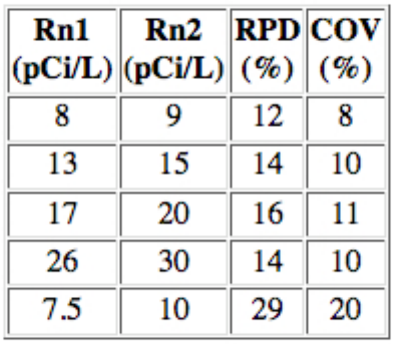
  where:

  X1 = concentration observed with the first detector or equipment;

X2 = concentration observed with the second detector, equipment or absolute value; and

Xavg = average concentration = ([X1 + X2] / 2)

The relative percent difference (RPD) and coefficient of variation (CV) provide a measure of precision, but they are not equal. Below are example duplicate radon results, and the corresponding values of relative percent difference and coefficient of variation:



Rn1 (pCi/L)	Rn2 (pCi/L)	RPD (%)	COV (%)
8	9	12	8
13	15	14	10
17	20	16	11
26	30	14	10
7.5	10	29	20

See **coefficient of variation (CV).**

- **relative standard deviation:** see **coefficient of variation.**
- **spiked measurements, known exposure measurements:** quality control measurements in which the detector or instrument is exposed to a known concentration and submitted for analysis; used to evaluate accuracy.
- **standard deviation:** a measure of the scatter of several sample values around their average. For a sample, the standard deviation *(s)* is the positive square root of the sample variance:

$$s = \frac{\sqrt{\sum_{i=1}^{n} (X_i - X_{ave})^2}}{\sqrt{n - 1}}$$

For a finite population, the standard deviation *(s)* is:

$$\sigma = \frac{\sqrt{\sum_{i=1}^{N} (X_i - \mu)^2}}{\sqrt{N}}$$

where μ is the true arithmetic mean of the population, and *N* is the number of values in the population. The property of the standard deviation that makes it most practically meaningful is that it is in the same units as the observed variable *X.* For example, the upper 95% probability limit on differences between two values is 2.77 times the sample standard deviation.

- **standard operating procedure:** a written document which details an operation, analysis or action whose mechanisms are prescribed thoroughly and which is commonly accepted as the method for performing certain routine or repetitive tasks.

- **statistical control chart, Shewhart control chart:** a graphical chart with statistical control limits and plotted values (for some applications, in chronological order) of some measured parameter for a series of samples. Use of the charts provides a visual display of the pattern of the data, enabling the early detection of time trends and shifts in level. For maximum usefulness in control, such charts should be plotted in a timely manner (i.e., as soon as the data are available).

- **statistical control chart limits:** the limits on control charts that have been derived by statistical analysis and are used as criteria for action, or for judging whether a set of data does or does not indicate lack of control. On a means control chart, the warning level may be two standard deviations above and below the mean, and the control limit may be three standard deviations above and below the mean.

- **systematic error:** the condition of a consistent deviation of the results of a measurement process from the reference or known level. The cause for the deviation, or bias, may be known or unknown, but is considered "assignable" (i.e., if the cause is unknown, it should be possible to determine the cause). See **bias.**

- **time-integrated sampling:** sampling conducted over a specific time period (e.g., from two days to a year or more) producing results representative of the average value for that period.

- **uncertainty:** the estimated bounds of the deviation from the mean value, expressed generally as a percentage of the mean value; taken ordinarily as the sum of: (1) the random errors (errors of precision) at the 95% confidence level; and (2) the estimated upper bound of the systematic error (errors of accuracy).

- **variance:** mathematically, the sample variance is the sum of squares of the differences between the individual values of a set and the arithmetic average of the set, divided by one less than the number of values:

$$s^2 = \frac{\sum_{i=1}^{n} (X_i - X_{ave})^2}{n - 1}$$

For a finite population, the variance s^2 is the sum of squares of deviations from the arithmetic mean, divided by the number of values in the population:

$$\sigma^2 = \frac{\sum_{i=1}^{N} (X_i - \mu)^2}{N}$$

where μ is the true arithmetic mean of the population.

- **working level (WL):** any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of 1.3 x 105 MeV of potential alpha energy. This number was chosen because it is approximately the alpha energy released from the decay products in equilibrium with 100 pCi of Rn-222. Exposures are measured in working level months (WLM).

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Section 15: EPA and ASTM Standards

The EPA's Revised Standards

The EPA recommends the *Standard Practice for Radon Mitigation Systems in Existing Low-Rise Residential Buildings** for residential radon mitigation. The agency initially recognized this standard in 2003 as the most appropriate guide to reducing radon in homes, as far as practicable, below the national action level of 4 pCi/L in indoor air. A single, free copy of the E-2121 standard is available from the EPA's National Service Center for Environmental Publications. Copies of the standard may be purchased from ASTMI, or from the American National Standards Institute (ANSI).

*E-2121-03 (February 10, 2003), American Society for Testing and Materials International (ASTMI); an American National Standards Institute (ANSI) approved consensus standard.

Note: As of May 2006, the EPA's *Radon Mitigation Standards* (EPA 402-R-93-078, revised April 1994) is no longer recommended or available.

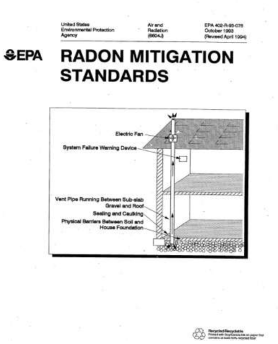
To control for radon in new residential construction, the EPA recommends the use of ASTM's *Standard Practice for Radon Control Options for the Design and Construction of New Low-Rise Residential Buildings.**

A single, free printed copy of ASTM E 1465-07a is available from the EPA upon request. Use the EPA's document number (402-K-07-010) when ordering from the National Service Center for Environmental Publications.

*ASTM E1465-07a; July 15, 2007. EPA reprints E1465-07a by permission with ASTM. Copies of E1465-07a may be purchased from ASTM International, or from the American National Standards Institute.

Section 16: The EPA's Radon Mitigation Standards

Radon Mitigation Standards



United States
Environmental Protection
Agency

Air and
Radiation
(6604J)

EPA 402-R-93-078
October 1993
(Revised April 1994)

RADON MITIGATION
STANDARDS

EPA Publication 402-R-93-078 (October 1993; revised April 1994):

Radon Mitigation Standards

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Editor's Note: The online version of this document has been modified slightly from the 1994 printed version to contain hypertext links to online versions of EPA documents, and to reflect current program terminology (particularly for the EPA's National Radon Proficiency Program). Also, it should be noted that the EPA discontinued operation of the National Radon Proficiency Program (RPP) on September 30, 1998.

Table of Contents

The Mitigation Standards

1.0 Background

The 1988 Indoor Radon Abatement Act (IRAA) required the Environmental Protection Agency (EPA) to develop a voluntary program to evaluate and provide information on contractors who offer radon control services to homeowners. The Radon Contractor Proficiency (RCP) Program was established to fulfill this portion of the IRAA. Individuals meeting the EPA's National Radon Proficiency Program (RPP) requirements are now known as Mitigation Service Providers. In December 1991, the EPA published *Interim Radon Mitigation Standards* as initial guidelines for evaluating the performance of radon mitigation contractors under the RCP Program. Over the past six years, the effectiveness of the basic radon mitigation techniques set forth in the *Interim Standards* has been validated in field applications throughout the United States. This experience now serves as the basis for the more detailed and final *Radon Mitigation Standards (RMS)* set forth in this document.

2.0 Purpose

The purpose of the RMS is to provide radon mitigation contractors with uniform standards that will ensure quality and effectiveness in the design, installation and evaluation of radon mitigation systems in detached and attached residential buildings three stories or less in height. The RMS is intended to serve as a model set of requirements which can be adopted or modified by state and local jurisdictions to fulfill objectives of their specific radon contractor certification or licensure programs.

3.0 Participants

Minimum requirements are established in the RMS for individuals nationwide who perform radon remediation work and wish to participate in the EPA's RPP as Mitigation Service Providers. To successfully participate in the EPA's RPP, the mitigation contractor shall have completed all training, examination and other program requirements, and shall agree to follow the provisions of the RMS.

4.0 Scope

The requirements addressed in the RMS include the following categories of contractor activity:

- General Practices;
- Building Investigation;
- Worker Health and Safety;

- Systems Design;
- Systems Installation;
- Materials, Monitors and Labeling;
- Post-Mitigation Testing; and
- Contracts and Documentation.

5.0 Assumption

Before applying the provisions of the RMS, it is assumed that appropriate radon/radon decay product measurements have been performed within the structure, and that the owner has decided that radon remediation is necessary.

6.0 Implementation

6.1 The RMS includes requirements for installation of radon remediation systems and provides a basis for evaluating the quality of those installations. It may be adopted by state regulatory agencies for state or local radon mitigation contractor licensure programs. It may also be used as a reference during inspection of in-progress or completed radon mitigation work.

6.2 Contractors shall personally conduct follow-up inspection of any radon mitigation systems installed by their firm or by subcontractors to insure conformance with the requirements of the RMS. This requirement shall include the post-mitigation testing prescribed in paragraph 17.0.

6.3 The EPA will evaluate reports of non-compliance with the RMS that are referred to the agency by states and other agencies that monitor radon mitigation services. Based on its evaluation, the EPA may initiate established RCP program de-listing procedures against contractors that the agency or states (with certification programs) find are in violation of the mandatory provisions of the RMS (see paragraph 6.4). In addition, the EPA or its agent may conduct inspections of radon mitigation projects. State radon program personnel or their contracted representatives are considered EPA agents for conducting such inspections.

6.4 Those provisions of the RMS that are considered to be mandatory are prefaced by the term "shall." Provisions that are considered good practice but which are not mandatory are prefaced by the terms "should" or "recommended."

6.5 The RMS will be updated as necessary, and in response to technological advances and field experience.

7.0 Limitations

7.1 Although the provisions of the RMS have been carefully reviewed for potential conflicts with other regulatory requirements, adherence to the RMS does not guarantee compliance with the applicable codes or regulations of any other federal, state or local agency having jurisdiction.

7.2 Where discrepancies exist between provisions of the RMS and local codes or regulations, local codes shall take precedence. However, where compliance with local codes necessitates a deviation from the RMS, the EPA recommends that RPP-listed Mitigation Service Providers (mitigation contractors) report the deviation in writing to the appropriate EPA Regional Office and the appropriate state regulatory official within 30 days. It should be noted that the EPA is not requiring the reporting that is recommended in this paragraph. States with radon mitigation contractor certification programs may require that contractors give prior notification of their intent to deviate from the RMS for research or other purposes.

7.3 The RMS is not intended to be used as a design manual, and compliance with its provisions will not guarantee reduction of indoor radon concentrations to any specific level.

7.4 The RMS shall not apply to radon mitigation systems installed prior to its effective date, except when a previously installed system is altered. "Altering" radon mitigation systems does not include activities such as replacing worn-out equipment, or providing new filters while leaving the remainder of the system unchanged. Mitigation systems installed prior to the effective date of the RMS should be in compliance with the requirements in force at that time (i.e. *EPA Interim Radon Mitigation Standards*, December 15, 1991, as amended by the *Addendum on Backdrafting* of October 1, 1992). If a radon mitigation system is found that does not comply with current standards, contractors should recommend to clients that the system be upgraded or altered to meet current standards.

7.5 Because of the wide variation in building design, size, operation and use, the RMS does not include detailed guidance on how to select the most appropriate mitigation strategy for a given building. That guidance is provided in the documents referenced in paragraphs 8.1, 8.2 and 8.3.

7.6 The provisions of the RMS are limited to proven technologies and methods. Publication of this standard is not intended, however, to inhibit research and evaluation of other innovative radon mitigation techniques. When such research is conducted, a performance standard shall be applied, i.e., post-mitigation radon levels shall be at or below the EPA's action level (currently 4 pCi/L), and the systems design criteria in paragraph 13.0 shall be applied. Contractors who expect to deviate from proven radon mitigation technologies and methods (as defined in the RMS and other EPA references in Part 8.0) for purposes of research on innovative mitigation techniques shall obtain prior approval from state regulatory offices, document the non-standard techniques, and inform the client of the deviation from standard procedures. In cases where radon mitigation is not regulated by the state, contractors shall obtain prior approval from a regional EPA office.

7.7 At this time, the RMS does not include standards for installing systems to mitigate radon in water. However, the EPA is currently developing a standard that will regulate radon levels in domestic water supplies. Following publication of that standard, the RMS may be revised, as appropriate, to include standards for installation of systems that are effective in reducing radon levels in water.

8.0 Reference Documents

The following documents are sources of additional radon mitigation information and are recommended reading for contractors participating in the EPA's RPP program as Mitigation Service Providers:

8.1 EPA Training Manual, "Reducing Radon In Structures (Third Edition)," January 1993.

8.2 "Radon Reduction Techniques for Detached Houses, Technical Guidance (Second Edition),"
EPA/625/5-87/019, January 1988.

8.3 "Application of Radon Reduction Methods," EPA/625/5-88/024, August 1988.

8.4 "Indoor Radon and Radon Decay Product Measurement Device Protocols," EPA 402-R-92-
004, July 1992.

8.5 "Protocols for Radon and Radon Decay Product Measurements in Homes," EPA 402-R-92-
003, June 1993.

8.6 "A Citizen's Guide To Radon (Second Edition)," EPA 402-K92-001, May 1992.

8.7 "Consumer's Guide to Radon Reduction," EPA, 402-K92-003, August 1992.

8.8 "Home Buyer's and Seller's Guide to Radon," EPA 402-R-93-003, March 1993.

8.9 "ASHRAE Standard 62-1989," Appendix B, Positive Combustion Air Supply.

8.10 "National Gas Code," Appendix H (p.2223.1-98), 1988, Recommended Procedure for Safety Inspection of an Existing Appliance Installation.

8.11 "Chimney Safety Tests User's Manual," Second Edition, January 12, 1988, Scanada Shelter
Consortium Inc., for Canada Mortgage and Housing Corp.

8.12 OSHA "Safety and Health Regulations for Construction, Ionizing Radiation," 29 CFR 1926.53.

8.13 OSHA "Occupational Safety and Health Regulations, Ionizing Radiation," 29 CFR 1910.96.

8.14 NIOSH "Guide to Industrial Respiratory Protection," DHHS (NIOSH) Publication No. 87-116, September 1987.

8.15 NCRP "Measurement of Radon and Radon Decay Daughters in Air," NCRP Report No. 97, November 1988.

8.16 EPA Handbook, "Sub-Slab Depressurization for Low Permeability Fill Material," EPA/625/6-91/029, July 1991.

8.17 "Radon Reduction Techniques for Existing Detached Houses, Technical Guidance (Third Edition) for Active Soil Depressurization Systems," EPA/625/R-93-011, October 1993.

9.0 Description of Terms

For this document, certain terms are defined in this section. Terms not defined herein should have their ordinary meaning within the context of their use. Ordinary meaning is as defined in "Webster's Ninth New Collegiate Dictionary."

9.1 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 or blockage at the chimney or flue termination.

9.2 backer rod: a semi-rigid foam material resembling a rope of various diameters, used to fill around pipes, etc., to assist in making a sealed penetration. For example, where a pipe is inserted through a concrete slab, a length of backer rod is jammed into the opening around the pipe. Caulking is then applied to the space above the backer rod and between the outside of the pipe and the slab opening. The purpose of the backer rod is to hold the semi-fluid caulk in place until it sets or hardens.

9.3 block-wall depressurization: a radon mitigation technique that depressurizes the void network within a block-wall foundation by drawing air from inside the wall and venting it to the outside.

9.4 perimeter channel drain: a means for collecting water in a basement by means of a large gap or channel between the concrete floor and the wall. Collected water may flow to aggregate beneath the slot ("French drain") or to a sump where it can be drained or pumped away.

9.5 certified: a rating applied by some jurisdictions to individuals or firms that are qualified and authorized to provide radon testing or mitigation services within the area of their jurisdiction.

9.6 client: the person, persons or company that contracts with a radon mitigation contractor to install a radon-reduction system in a building.

9.7 combination foundations: buildings constructed with more than one foundation type, e.g., basement/crawlspace or basement/slab-on-grade.

9.8 communication test: a diagnostic test designed to qualitatively measure the ability of a suction field and air flow to extend through the material beneath a concrete slab floor, and thus evaluate the potential effectiveness of a sub-slab depressurization system. This qualitative test is commonly conducted by applying suction on a centrally located hole drilled through the concrete slab, and simultaneously observing the movement of smoke downward into small holes drilled in the slab at locations separated from the central suction hole. (See also paragraph 9.16: **pressure field extension**.)

9.9 contractor: an individual listed in the EPA's RPP program, specifically one listed as a "Mitigation Service Provider," or certified by a state which requires adherence to the RMS.

9.10 crawlspace depressurization: a radon control technique designed to achieve lower air pressure in the crawlspace relative to indoor air pressure by use of a fan-powered vent drawing air from within the crawlspace. (See also paragraph 9.14: **mechanically ventilated crawlspace system**.)

9.11 diagnostic tests: procedures used to identify or characterize conditions within buildings that may contribute to radon entry or elevated radon levels, or may provide information regarding the performance of a mitigation system.

9.12 drain tile loop: a continuous length of drain tile or perforated pipe extending around all or part of the internal or external perimeter of a basement or crawlspace footing.

9.13 mitigation system: any system or steps designed to reduce radon concentrations in the indoor air of a building.

9.14 mechanically ventilated crawlspace system: a radon control technique designed to increase ventilation within a crawlspace, achieve higher air pressure in the crawlspace relative to air pressure in the soil beneath the crawlspace, or achieve lower air pressure in the crawlspace relative to air pressure in the living spaces, by use of a fan. (See also paragraph 9.10: **crawlspace depressurization**.)

9.15 pCi/L: the abbreviation for **picocuries per liter**, which is a unit of measure for the amount of radioactivity in a liter of air. The prefix "pico" means a multiplication factor of 1 trillionth. A curie is a commonly used measurement of radioactivity.

9.16 pressure field extension: the distance that a pressure change is induced in the sub-slab area, measured from a single or multiple suction points. (See also paragraph 9.8: **communication test**.)

9.17 radon: a naturally occurring radioactive element (Rn-222) which exists as a gas and is measured in picocuries per liter (pCi/L).

9.18 radon decay products (RDPs): the four short-lived radioactive elements (Po-218, Pb-214, Bi-214 and Po-214) which exist as solids and immediately follow Rn-222 in the decay chain. They are measured in working levels (WL).

9.19 re-entrainment: the unintended re-entry into a building of radon that is being exhausted from the vent of a radon mitigation system.

9.20 soil gas: the gas mixture present in soil which may contain radon.

9.21 soil-gas retarder: a continuous membrane or other comparable material used to retard the flow of soil gases into a building.

9.22 stack effect: the overall upward movement of air inside a building that results from heated air rising and escaping through openings in the building envelope, thus causing indoor air pressure in the lower portions of a building to be lower than the pressure in the soil beneath or surrounding the building foundation.

9.23 sub-membrane depressurization: a radon control technique designed to achieve lower air pressure in the space under a soil-gas retarder membrane laid on the crawlspace floor, relative to air pressure in the crawlspace, by use of a fan-powered vent drawing air from beneath the membrane.

9.24 sub-slab depressurization (active): a radon control technique designed to achieve lower sub-slab air pressure relative to indoor air pressure by use of a fan-powered vent to draw air from beneath the concrete slab.

9.25 sub-slab depressurization (passive): a radon control technique designed to achieve lower sub-slab air pressure relative to indoor air pressure by use of a vent pipe (without a fan) routed through the conditioned space of a building, and connecting the sub-slab area to the outdoor air. This system relies primarily on the convective flow of warmed air upward in the vent to draw air from beneath the concrete slab.

9.26 working level (WL): a unit of radon decay product exposure rate; numerically, any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of 130,000 MeV of potential alpha energy. This number was chosen because it is approximately the total alpha energy released from the short-lived decay products in equilibrium with 100 pCi of Rn-222 per liter of air. (See also the referenced document in paragraph 8.15.)

9.27 working-level month (WLM): a unit of exposure used to express the accumulated human exposure to radon decay products. It is calculated by multiplying the average working level to which a person has been exposed by the number of hours exposed and dividing the product by 170.

10.0 General Practices

The following general practices are required for all contacts between radon mitigation contractors and clients.

10.1 In the initial contact with a client, the contractor shall review any available results from previous radon tests to assist in developing an appropriate mitigation strategy.

10.2 Based on guidance contained in *A Citizen's Guide to Radon, Second Edition* (paragraph 8.6), or subsequent revisions of that document, the contractor shall refer the client to the discussions of interpreting indoor radon test results and the health risk associated with the radon level found in the building. The*Consumer's Guide to Radon Reduction* (paragraph 8.7) is an appropriate reference for providing advice on actions to take to reduce indoor radon levels. Similar documents developed by states and mandated for dissemination by state regulations may also be used as references.

10.3 When delays in the installation of a permanent radon control system are unavoidable due to building conditions or construction activities, and a temporary system is installed, the contractor shall inform the client about the temporary nature of the system. A label that is readable from at least 3 feet shall be placed on the system. The label shall include a statement that the system is temporary and that it will be replaced with a permanent system within 30 days. The label shall also include the date of installation, and the contractor's name, phone number and RPP Identification Number. (EXCEPTION: The 30-day limit on use of a temporary mitigation system may be extended in cases where a major renovation or change in building use necessitates a delay in installation of a permanent mitigation system that is optimized to the new building's configuration or use. The appropriate state or local building official or radon program official should be notified when this exception is being applied.)

10.4 When the selected mitigation technique requires use of sealants, caulks or bonding chemicals containing volatile solvents, prior to starting work, the contractor shall inform the client of the need to ventilate work areas during and after the use of such materials. Ventilation shall be provided as recommended by the manufacturer of the material.

11.0 Building Investigation

11.1 The contractor shall conduct a thorough visual inspection of the building prior to initiating any radon mitigation work. The inspection is intended to identify any specific building characteristics and configurations (e.g., large cracks in slabs, exposed earth in crawlspaces, open stairways to basements) and operational conditions (e.g., continuously running HVAC systems or operational windows) that may affect the design, installation and effectiveness of radon mitigation systems. As part of this inspection, clients should be asked to provide any available information on the building (e.g., construction specifications, pictures, drawings, etc.) that might be of value in determining the radon mitigation strategy.

11.2 To facilitate selection of the most effective radon control system and avoid the costs of installing systems that subsequently prove to be ineffective, it is recommended that the contractor conduct diagnostic tests to assist in identifying and verifying suspected radon sources and entry points. Radon grab-sampling, continuous radon monitoring, and use of chemical smoke sticks are examples of the types of diagnostic testing commonly used. (See paragraph 11.4.)

11.3 It is recommended that, during the building investigation, contractors routinely perform diagnostic tests to evaluate the existence of, or the potential for, back-drafting of natural-draft combustion appliances. Published procedures for conducting backdrafting tests are covered in the Reference Documents listed in Paragraphs 8.9, 8.10 and 8.11. The following checklist has been extracted from material in these references and may be used to test for existing or potential back-drafting conditions:

1. Close all windows and doors, both external and internal.
2. Open all HVAC-supply and return-air duct vents/registers.

3. Close fireplace and wood-stove dampers.
4. Turn on all exhaust and air-distribution fans and combustion appliances EXCEPT the appliance being tested for back-drafting.
5. Wait five minutes.
6. Test to determine the indoor-outdoor pressure differential in the room where the appliance being tested is located. If the pressure differential is a negative 5 Pascals or more, assume that a potential for back-drafting exists.
7. To begin a test for actual spillage of flue gases, turn on the appliance being tested. (If the appliance is a forced-air furnace, ensure that the blower starts to run before proceeding.)
8. Wait five minutes.
9. Using either a smoke tube or a carbon-dioxide gas analyzer, check for flue-gas spillage near the vent hood.
10. Repeat steps (4) through (9) for each natural-draft combustion appliance being tested for back-drafting. Seasonal and extreme weather conditions should be considered when evaluating pressure differentials and the potential for back-drafting.

If spillage is confirmed from any natural-draft combustion appliance, clients shall be advised of the back-drafting condition, and that active (fan-powered) radon mitigation systems cannot be installed until the condition has been corrected. Contractors should advise the client to contact an HVAC contractor if correcting an existing or potential backdrafting condition is necessary. (See paragraph 17.3 for post-mitigation back-drafting testing.)

11.4 If installation of a sub-slab depressurization system is contemplated and characteristics of the sub-slab material are unknown, a communication test, as defined in paragraph 9.8, is recommended.

11.5 As part of the building investigation, a floor-plan sketch shall be developed (if not already in existence and readily available) that includes illustrations of the building foundation (slab-on-grade, basement or crawlspace area). The sketch should include the location of load-bearing walls, drain fixtures and HVAC systems. It should be annotated to include suspected or confirmed radon entry points, results of any diagnostic testing, the anticipated layout of any radon mitigation system piping, and the anticipated locations of any vent fan and system warning devices for the envisioned mitigation systems. The sketch shall be finalized during installation and shall be included in the documentation. (See paragraph 18.2 and Appendix A.)

12.0 Worker Health and Safety

12.1 Contractors shall comply with all OSHA, state and local standards and regulations relating to worker safety and occupational radon exposure. Applicable references in the Code of Federal Regulations and NIOSH publications are listed in paragraphs 8.12, 8.13 and 8.14.

12.2 In addition to the OSHA and NIOSH standards, the following requirements that are specifically or uniquely applicable for the safety and protection of radon mitigation workers shall be met:

12.2.1 The contractor shall advise workers of the hazards of exposure to radon and the need to apply protective measures when working in areas of elevated radon concentrations.

12.2.2 The contractor shall have a worker protection plan on file that is available to all employees and is approved by any state or local regulating agencies that require such a plan. EXCEPTION: A worker protection plan is not required for a contractor who is a sole proprietor, unless required by state or local regulations.

12.2.3 The contractor shall ensure that appropriate safety equipment, such as hard hats, face shields, ear plugs, steel-toe boots and protective gloves, are available on the job site during cutting, drilling, grinding, polishing, demolishing or other activity associated with radon mitigation projects.

12.2.4 All electrical equipment used during radon mitigation projects shall be properly grounded. Circuits used as a power source should be protected by ground-fault circuit interrupters (GFCI).

12.2.5 When work is required at elevations above the ground or floor, the contractor shall ensure that ladders or scaffolding are safely installed and operated.

12.2.6 Work areas shall be ventilated to reduce worker exposure to radon decay products, dust or other airborne pollutants. In work areas where ventilation is impractical, or where ventilation cannot reduce radon levels to less than 0.3 WL (based on a short-term diagnostic test such as a grab-sample), the contractor shall ensure that respiratory protection conforms with the requirements in the *NIOSH Guide to Industrial Respiratory Protection*. (See paragraph 8.14.) Note: If unable to make working level measurements, a radon level of 30 pCi/L shall be used.

12.2.7 Where combustible materials exist in the specific area of the building where radon mitigation work is to be conducted, and the contractor is creating any temperatures high enough to induce a flame, the contractor shall ensure that fire extinguishers suitable for type A, B and C fires are available in the immediate work area.

12.2.8 Pending development of an approved personal radon exposure device and a protocol for its use, contractors shall record employee exposure to radon at each work site, based on:

1. the highest pre-mitigation indoor radon or working-level measurement available; and
2. the time employees are exposed (without respirator protection) at that level. (See paragraph 12.2.6.)

Note: This approach is not intended to preclude the alternative use of on-site radon or radon decay product measurements to determine exact exposure. Consistent with OSHA Permissible Exposure Limits, contractors shall ensure that employees are exposed to no more than 4 working level months (WLM) over a 12-month period. An equilibrium ratio of 50% shall be used to convert radon exposure to WLM.

12.2.9 In any planned work area where it is suspected that friable asbestos may exist and be disturbed, radon mitigation work shall not be conducted until a determination is made by a properly trained or accredited person that such work will be undertaken in a manner which complies with applicable asbestos regulations.

12.2.10 When mitigation work requires the use of sealants, adhesives, paints or other substances that may be hazardous to health, contractors shall provide employees with the applicable Material Safety Data Sheets (MSDS) and explain the required safety procedures.

13.0 Systems Design

13.1 All radon mitigation systems shall be designed and installed as permanent, integral additions to the building, except where a temporary system has been installed in accordance with paragraph 10.3.

13.2 All radon mitigation systems shall be designed to avoid the creation of other health, safety or environmental hazards to the building's occupants, such as back-drafting of natural-draft combustion appliances.

13.3 All radon mitigation systems shall be designed to maximize radon reduction and, in consideration of the need to minimize excess energy usage, to avoid compromising moisture and temperature controls and other comfort features, and to minimize noise.

13.4 All radon mitigation systems and their components shall be designed to comply with the laws, ordinances, codes and regulations of relevant jurisdictional authorities, including applicable mechanical, electrical, building, plumbing, energy and fire-prevention codes.

14.0 Systems Installation

14.1 General Requirements

14.1.1 All components of radon mitigation systems installed in compliance with provisions of the RMS shall also be in compliance with the applicable mechanical, electrical, building, plumbing, energy and fire-prevention codes, standards and regulations of the local jurisdiction.

14.1.2 The contractor shall obtain all required licenses and permits, and display them in the work areas, as required by local ordinances.

14.1.3 Where portions of structural framing material must be removed to accommodate radon vent pipes, the material removed shall be no greater than that permitted for plumbing installations by applicable building or plumbing codes.

14.1.4 Where the installation of a radon mitigation system requires pipes or ducts to penetrate a firewall or other fire resistance-rated wall or floor, penetrations shall be protected in accordance with applicable building, mechanical, fire and electrical codes.

14.1.5 When installing radon mitigation systems that use sump pits as the suction point for active soil depressurization, if sump pumps are needed, it is recommended that submersible sump pumps be used. (See paragraphs 14.5.1, 14.7.4, 15.7 and 15.8.)

14.2 Radon Vent Pipe Installation Requirements

14.2.1 All joints and connections in radon mitigation systems using plastic vent pipes shall be permanently sealed with adhesives, as specified by the manufacturer of the pipe material used. (See paragraph 14.3.7 for exceptions when installing fans, and paragraph 14.2.7 for exceptions when installing vent pipes in sumps.) Joints or connections in other vent pipe materials shall be made airtight.

14.2.2 Attic and external piping runs in areas subject to sub-freezing conditions should be protected to avoid the risk of vent pipe freeze-up.

14.2.3 Radon vent pipes shall be fastened to the structure of the building with hangers, strapping or other supports that will adequately secure the vent material. Existing plumbing pipes, ducts or mechanical equipment shall not be used to support or secure a radon vent pipe.

14.2.4 Supports for radon vent pipes shall be installed at least every 6 feet on horizontal runs. Vertical runs shall be secured either above or below the points of penetration through floors, ceilings and roofs, or at least every 8 feet on runs that do not penetrate floors, ceilings or roofs.

14.2.5 To prevent blockage of air flow into the bottom of radon vent pipes, these pipes shall be supported or secured in a permanent manner that prevents their downward movement to the bottom of suction pits or sump pits, or into the soil beneath an aggregate layer under a slab.

14.2.6 Radon vent pipes shall be installed in a configuration that ensures that any rainwater or condensation within the pipes drains downward into the ground beneath the slab or soil-gas retarder membrane.

14.2.7 Radon vent pipes shall not block access to any areas requiring maintenance or inspection. Radon vents shall not be installed in front of or interfere with any light, opening, door, window or equipment access area required by code. If radon vent pipes are installed in sump pits, the system shall be designed with removable or flexible couplings to facilitate removal of the sump pit cover for sump-pump maintenance.

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 all of the following requirements: (1) be above the eaves of the roof; (2) be 10 feet or more above ground level; (3) be 10 feet or more from any window, door or other opening into conditioned spaces of the structure that is less than 2 feet below the exhaust point; and (4) be 10 feet or more from any opening into an adjacent building. The total required distance (10 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 eaves of the building and as close to the roof's ridgeline as possible.

14.2.9 When a radon mitigation system is designed to draw soil gas from a perimeter drain tile loop (internal or external) that discharges water through a drain line to daylight or a soak-away, a one-way flow valve, water trap or other control device should be installed in or on the discharge line to prevent outside air from entering the system while allowing water to flow out of the system.

14.3 Radon Vent Fan Installation Requirements

14.3.1 Vent fans used in radon mitigation systems shall be designed or otherwise sealed to reduce the potential for leakage of soil gas from the fan housing.

14.3.2 Radon vent fans shall be sized to provide the pressure difference and air-flow characteristics necessary to achieve the radon-reduction goals established for the specific mitigation project. Guidelines for sizing vent fans and piping can be found in the references cited in paragraphs 8.1, 8.16 and 8.17.

14.3.3 Radon vent fans used in active soil depressurization or block-wall depressurization systems shall not be installed below ground nor in the conditioned (heated/cooled) space of a building, nor in any basement, crawlspace or other interior location directly beneath the conditioned spaces of a building. Acceptable locations for radon vent fans include attics not suitable for occupancy (including attics over living spaces and garages), garages that are not beneath conditioned spaces, and on the exterior of the building.

14.3.4 Radon vent fans shall be installed in a configuration that avoids condensation buildup in the fan housing. Whenever possible, fans should be installed in vertical runs of the vent pipe.

14.3.5 Radon vent fans mounted on the exterior of buildings shall be rated for outdoor use, or installed in a watertight protective housing.

14.3.6 Radon vent fans shall be mounted and secured in a manner that minimizes transfer of vibration to the structural framing of the building.

14.3.7 To facilitate maintenance and future replacement, radon vent fans shall be installed in the vent pipe using removable couplings or flexible connections that can be tightly secured to both the fan and the vent pipe.

14.3.8 The intakes of fans used in crawlspace pressurization, or in pressurizing the building itself, shall be screened or filtered to prevent ingestion of debris or personal injury. Screens or filters shall be removable to permit cleaning and replacement, and building owners shall be informed of the need to periodically replace or clean such screens and filters. This information shall also be included in the documentation. (See paragraph 18.5.)

14.4 Suction Pit Requirement for Sub-Slab Depressurization (SSD) Systems

14.4.1 To provide optimum pressure field extension of the sub-slab communication zone, adequate material shall be excavated from the area immediately below the slab penetration point of SSD system's vent pipes.

14.5 Sealing Requirements

14.5.1 Sump pits that permit entry of soil-gas or that would allow conditioned air to be drawn into a sub-slab depressurization system shall be covered and sealed. The covers on sumps that previously provided protection or relief from surface-water collection shall be fitted with a water or mechanically trapped drain. Water traps should be fitted with an automatic supply of priming water. (See paragraph 15.7 for details on sump cover and sealing materials.)

14.5.2 Openings around radon vent-pipe penetrations of the slab, the foundation walls, or the crawlspace soil-gas retarder membrane shall be cleaned, prepared and sealed in a permanent, air-tight manner using compatible caulks or other sealant materials. (See paragraph 15.5.) Openings around other utility penetrations of the slab, walls or soil-gas retarder shall also be sealed.

14.5.3 Where a block-wall depressurization (BWD) system is used to mitigate radon, openings in the tops of such walls, and all accessible openings or cracks in the interior surfaces of the walls, shall be closed and sealed with polyurethane or equivalent caulks, expandable foams, or other fillers and sealants. (See paragraphs 15.5 and 15.6.) Openings or cracks that are determined to be inaccessible or beyond the ability of the contractor to seal shall be disclosed to the client and included in the documentation.

14.5.4 Openings, perimeter channel drains, or cracks that exist where the slab meets the foundation wall (floor-wall joint) shall be sealed with urethane caulk or equivalent material. When the opening or channel is greater than 1/2-inch in width, a foam backer rod or other comparable filler material shall be inserted in the channel before application of the sealant. This sealing technique shall be done in a manner that retains the channel feature as a water control system. Other openings or cracks in slabs, or at expansion or control joints, should also be sealed. Openings or cracks that are determined to be inaccessible or beyond the ability of the contractor to seal shall be disclosed to the client and included in the documentation.

14.5.5 When installing baseboard-type suction systems, all seams and joints in the baseboard material shall be joined and sealed using materials recommended by the manufacturer of the baseboard system. Baseboards shall be secured to walls and floors with adhesives designed and recommended for such installations. If a baseboard system is installed on a block-wall foundation, the tops of the block wall shall be closed and sealed as prescribed in paragraph 14.5.3.

14.5.6 Any seams in soil-gas retarder membranes used in crawlspaces for sub-membrane depressurization systems shall be overlapped at least 12 inches and should be sealed. To enhance the effectiveness of sub-membrane depressurization systems, the membrane should also be sealed around interior piers and to the inside of exterior walls.

14.5.7 In combination basement/crawlspace foundations, where the crawlspace has been confirmed as a source of radon entry, access doors and other openings between the basement and the adjacent crawlspace shall be closed and sealed. Access doors required by code shall be fitted with airtight gaskets and a means of positive closure, but shall not be permanently sealed. In cases where both the basement and the adjacent crawlspace areas are being mitigated with active SSD and SMD systems, sealing of the openings between those areas is not required.

14.5.8 When crawlspace depressurization is used for radon mitigation, openings and cracks in floors above the crawlspace which would permit conditioned air to pass out of the living spaces of the building shall be identified, closed and sealed. Sealing of openings around hydronic heat or steam-pipe penetrations shall be done using non-combustible materials. Openings or cracks that are determined to be inaccessible or beyond the ability of the contractor to seal shall be disclosed to the client and included in the documentation.

14.6 Electrical Requirements

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 exceeds 50% of the circuit's capacity into which it will be connected, or if the total connected load on the circuit (including the radon vent fan) exceeds 80% 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 de-activation of the fan for maintenance or repair by the building's owner or servicing contractor. (Disconnect switches are not required with plugged fans.)

14.7 Drain Installation Requirements

14.7.1 If drains discharge directly into the soil beneath the slab or through solid pipe to a soak-away, the contractor should install a drain that meets the requirements in paragraph 14.5.1.

14.7.2 If condensate drains from air-conditioning units terminate beneath the floor slab, the contractor shall install a trap in the drain that provides a minimum 6-inch standing water-seal depth, re-route the drain directly into a trapped floor drain, or reconnect the drain to a condensate pump.

14.7.3 Perimeter (channel or French) drains should be sealed with backer rods and urethane or comparable sealants in a manner that will retain the channel feature as a water control system. (See paragraph 14.5.4.)

14.7.4 When a sump pit is the only system in a basement for protection or relief from excess surface water, and a cover is installed on the sump for radon control, the cover shall be recessed and fitted with a trapped drain that meets the requirements of paragraph 14.5.1.

14.8 HVAC Installation Requirements

14.8.1 Modifications to an existing HVAC system which are proposed to mitigate elevated levels of radon should be reviewed and approved by the original designer of the system (when possible), or by a licensed mechanical contractor.

14.8.2 Foundation vents installed specifically to reduce indoor radon levels by increasing the natural ventilation of a crawlspace shall be non-closeable. In areas subject to sub-freezing conditions, the existing location of water supply and distribution pipes in the crawlspace, and the need to insulate or apply heat tape to those pipes, should be considered when selecting locations for installing foundation vents.

14.8.3 Heat-recovery ventilation (HRV) systems shall not be installed in rooms that contain friable asbestos.

14.8.4 In HRV installations, supply and exhaust ports in the interior shall be located a minimum of 12 feet apart. The exterior supply and exhaust ports shall be positioned to avoid blockage by snow or leaves, and be a minimum of 10 feet apart.

14.8.5 Contractors installing HRV systems shall verify that the incoming and outgoing air flow is balanced to ensure that the system does not create a negative pressure within the building. Contractors shall inform building owners that periodic filter replacement and inlet grill cleaning are necessary to maintain a balanced air flow. This information shall also be included in the documentation.

14.8.6 Both internal and external intake and exhaust vents in HRV systems shall be covered with wire mesh or screening to prevent the entry of animals or debris, or injury to occupants.

15.0 Materials

15.1 All mitigation system electrical components shall be UL-listed, or of equivalent specifications.

15.2 As a minimum, all plastic vent pipes in mitigation systems shall be made of Schedule 20 PVC, ABS or equivalent piping material. Schedule 40 piping or its equivalent should be used in garages and in other internal and external locations subject to weathering or physical damage.

15.3 Vent-pipe fittings in a mitigation system shall be of the same material as the vent pipes. (See paragraph 14.3.7 for exceptions when installing vent fans, and paragraph 14.2.7 for exceptions when installing radon vent pipes in sump pit covers.)

15.4 Cleaning solvents and adhesives used to join plastic pipes and fittings shall be as recommended by manufacturers for use with the type of pipe material used in the mitigation system.

15.5 When sealing cracks in slabs and other small openings around penetrations of the slab and foundation walls, caulks and sealants designed for such application shall be used. Urethane sealants are recommended because of their durability.

15.6 When sealing holes for plumbing rough-in or other large openings in slabs and foundation walls that are below the ground surface, non-shrink mortar, grouts, expanding foam or similar materials designed for such application shall be used.

15.7 Sump pit covers shall be made of durable plastic or other rigid material and designed to permit airtight sealing. To permit easy removal for sump pump servicing, the cover shall be sealed using silicone or other non-permanent-type caulking materials or an airtight gasket.

15.8 Penetrations of sump covers to accommodate electrical wiring, water-ejection pipes, or radon vent pipes shall be designed to permit airtight sealing around penetrations using caulk or grommets. Sump covers that permit observation of conditions in the sump pit are recommended.

15.9 Plastic sheeting installed in crawlspaces as soil-gas retarders shall be a minimum of 6-mil (3 mil cross-laminated) polyethylene, or equivalent flexible material. Heavier gauge sheeting should be used when crawlspaces are used for storage, or when frequent entry is required for maintenance of utilities.

15.10 Any wood used in attaching soil-gas retarder membranes to crawlspace walls or piers shall be pressure-treated or naturally resistant to decay and termites.

16.0 Monitors and Labeling

16.1 All active soil depressurization and block-wall depressurization radon mitigation systems shall include a mechanism to monitor system performance and warn of system failure. The mechanism shall be simple to read or interpret, and be located where it is easily seen or heard by building occupants, and protected from damage or destruction.

16.2 Electrical radon-mitigation system monitors (whether visual or audible) shall be installed on non-switched circuits, and be designed to re-set automatically when power is restored after service or power-supply failure. Battery-operated monitoring devices shall not be used unless they are equipped with a low-power warning feature.

16.3 Mechanical radon-mitigation system monitors, such as manometer-type pressure gauges, shall be clearly marked to indicate the range or zone of pressure readings that existed when the system was initially activated.

16.4 A system description label shall be placed on the mitigation system, the electric service entrance panel, or other prominent location. This label shall be legible from a distance of at least 3 feet and include the following information: "Radon Reduction System," the installer's name, phone number and RCP Identification Number, the date of installation, and an advisory that the building should be tested for radon at least every two years or as required or recommended by state or local agencies. In addition, all exposed and visible interior radon-mitigation system vent-pipe sections shall be identified with at least one label on each floor level. The label shall read, "Radon Reduction System."

16.5 The circuit breakers controlling the circuits on which the radon vent fan and system-failure warning devices operate shall be labeled "Radon System."

17.0 Post-Mitigation Testing

17.1 After installation of an active radon control system (e.g., SSD), the contractor shall re-examine and verify the integrity of the fan mounting seals and all joints in the interior vent piping.

17.2 After installation of any active radon mitigation system, the contractor shall measure suctions or flows in system piping or ducting to assure that the system is operating as designed. (Note: When SSD systems are installed and activated, a test of pressure field extension is a good practice, particularly when there is uncertainty regarding the permeability of materials under all parts of the slab.)

17.3 Immediately after installation and activation of any active (fan-powered) sub-slab depressurization or block-wall depressurization system in buildings containing natural-draft combustion appliances, the building shall be tested for back-drafting of those appliances. Any backdrafting condition that results from installation of the radon mitigation system shall be corrected before the system is placed in operation. (Procedures and a checklist for conducting backdrafting tests are covered in the reference documents listed in paragraphs 8.9, 8.10 and 8.11, and in paragraph 11.3.)

17.4 Upon completion of radon mitigation work, a test of the mitigation system's effectiveness shall be conducted using an EPA RPP Analytical Service Provider-listed test device, and in accordance with EPA testing protocols or state requirements. This test should be conducted no sooner than 24 hours, nor later than 30 days, following completion and activation of the mitigation system(s). This test may be conducted by the contractor, by the client, or by a third-party testing firm. If this test is conducted by the mitigation contractor, and the test results are accepted by the client as satisfactory evidence of the system's effectiveness, further post-mitigation testing is not required. However, to avoid the appearance of a conflict of interest, the contractor shall recommend to the client that a mitigation system-effectiveness test be conducted by an independent EPA RPP-listed Measurement Service Provider, or state-certified testing firm, or by the client. The contractor should request a copy of the report of any post-mitigation testing conducted by the client or by an independent testing firm.

17.5 To ensure continued effectiveness of the radon mitigation system(s) installed, the contractor shall advise the client to re-test the building at least every two years, or as required or recommended by the state or local authority. Re-testing is also recommended if the building undergoes significant alteration.

18.0 Contracts and Documentation

18.1 The EPA recommends that contractors provide the following written information to clients prior to initiation of work:

1. the contractor's EPA RPP Mitigation Service Provider identification number;

2. a statement that describes the planned scope of the work that includes an estimate of the time needed to complete the work;
3. a statement describing any known hazards associated with chemicals used in or as part of the installation;
4. a statement indicating compliance with and implementation of all EPA standards and those of other agencies having jurisdiction (e.g., code requirements);
5. a statement describing any system maintenance that the building owner would be required to perform;
6. an estimate of the installation cost and annual operating costs of the system; and
7. the conditions of any warranty or guarantee.

18.2 The EPA recommends that RPP-listed mitigation contractors keep records of all radon mitigation work performed, and maintain those records for three years, or for the period of any warranty or guarantee, whichever is longer. These records should include:

1. the Building Investigation Summary and floor plan sketch (see Appendix A);
2. pre- and post-mitigation radon test data;
3. pre- and post-mitigation diagnostic test data;
4. copies of contracts and warranties; and
5. a narrative or pictorial description of mitigation system(s) installed.

18.2.1 Appendix A contains a suggested standard format for compiling mitigation project records.

18.3 Other records or bookkeeping required by local, state or federal statutes and regulations shall be maintained for the period(s) prescribed by those requirements.

18.4 The EPA recommends that health and safety records, including worker radon exposure logs, be maintained for a minimum of 20 years.

18.5 Upon completion of the mitigation project, contractors shall provide clients with an information package that includes:

1. any building permits required by local codes;
2. copies of the Building Investigation Summary and floor plan sketch (see Appendix A);
3. pre-and post-mitigation radon test data;
4. copies of contracts and warranties;
5. a description of the mitigation system installed, and its basic operating principles;
6. a description of any deviations from the RMS or state's requirements;
7. a description of the proper operating procedures of any mechanical or electrical systems installed, including the manufacturer's operation and maintenance instructions, and

warranties;

8. a list of appropriate actions for clients to take if the system-failure warning device indicates system degradation or failure; and
9. the name, telephone number and EPA RPP Mitigation Service Provider Identification Number of the contractor, and the phone number of the state radon office.

Note: Appendix A is available in the hard-copy version, which is available from state radon contacts.

Section 17: Model Standards

The EPA's Model Standards for New Residences

EPA Publication 402-R-94-009 (March 1994):

Model Standards of Techniques for Control of Radon in New Residential Buildings

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NOTE: The EPA closed its National Radon Proficiency Program on September 30,

1998. Visit http://www.epa.gov/iaq/radon/proficiency.html for to find a qualified radon measurement service provider.

FORWARD

This document is intended to serve as a model for use by the Model Code Organizations, states and other jurisdictions as they develop and adopt building codes, appendices to codes, and standards specifically applicable to their unique local and regional radon control requirements.

This document is responsive to the requirements set forth in Section 304 of Title III of the Toxic Substances Control Act (TSCA), 15 U.S.C. 2664, commonly referred to as the Indoor Radon Abatement Act (IRAA) of 1988. It is anticipated that future editions of this document will be prepared as additional experience is gained in constructing new radon-resistant residential buildings.

Table of Contents

1.0 Scope

1.1 This document contains model building standards and techniques applicable to controlling radon levels in new construction of one- and two-family dwellings and other residential buildings three stories or less in height, as defined in model codes promulgated by the respective Model Code Organizations.

1.2 The model building standards and techniques are also applicable when additions are made to the foundations of existing one- and two-family dwellings that result in extension of the building footprint.

1.3 This document is not intended to be a building code, nor is it required that it be adopted verbatim as a referenced standard.

1.4 It is intended that the building standards and techniques contained in Part 9.0 of this document, the construction method in Part 7.0, and the recommended procedures for applying the standards and construction method in Part 8.0, serve as a model for use by the Model Code Organizations and authorities within states and other jurisdictions that are responsible for regulating building construction as they develop and adopt building codes, appendices to codes, and standards and implementing regulations specifically applicable to their unique local or regional radon control requirements.

1.5 The preferential grant assistance authorized in Section 306(d) of the Indoor Radon Abatement Act of 1988 (Title III of the Toxic Substances Control Act, TSCA, 15 U.S.C. 2666) will be applied for states where appropriate authorities who regulate building construction are taking action to adopt radon-resistant standards in their building codes.

1.6 Model building standards and techniques contained in this document are not intended to supersede any radon-resistant construction standards, codes or regulations previously adopted by local jurisdictions and authorities. However, jurisdictions and authorities are encouraged to review their current building standards, codes and regulations and their unique local or regional radon control requirements, and consider modifications, if necessary.

1.7 This document will be updated and revised as ongoing and future research programs suggest revisions of standards, identify ways to improve the model construction techniques, or when newly tested products or techniques prove to be equivalent to or more effective in radon control. Updates and revisions to the model building standards and techniques contained in Part 9.0 will undergo appropriate peer review.

1.8 The EPA is committed to continuing evaluation of the effectiveness of the standards and techniques contained in Part 9.0 and to research programs that may identify other more effective and efficient methods.

2.0 Limitations

2.1 The Indoor Radon Abatement Act of 1988 (Title III of TSCA) establishes a long-term national goal of achieving radon levels inside buildings that are no higher than those found in ambient air outside of buildings. While technological, physical and financial limitations currently preclude attaining this goal, the underlying objective of this document is to move toward achieving the lowest technologically achievable and most cost-effective levels of indoor radon in new residential buildings.

2.2 Preliminary research indicates that the building standards and techniques contained in Part 9.0 can be applied successfully in mitigating radon problems in some existing non-residential buildings. However, their effectiveness when applied during construction of new non-residential buildings has not yet been fully demonstrated. Therefore, it is recommended that, pending further research, these building standards and techniques not be used at this time as a basis for changing the specific sections of building codes that cover non-residential construction.

2.3 Although radon levels below 4 pCi/L have been achieved in all types of residential buildings by using these model building standards and techniques, specific indoor radon levels for any given building cannot be predicted due to different site and environmental conditions, building design, construction practices, and variations in the operation of buildings.

2.4 These model building standards and techniques are not to be construed as the only acceptable methods for controlling radon levels, and are not intended to preempt, preclude or restrict the application of alternative materials, systems and construction practices approved by building officials under procedures prescribed in existing building codes.

2.5 Elevated indoor radon levels caused by emanation of radon from water is of potential concern, particularly in areas where there is a history of groundwater with high radon content. This document does not include model construction standards or techniques for reducing elevated levels of indoor radon that may be caused by the presence of high levels of radon in water supplies. The EPA has developed a suggested approach (see paragraph 8.3.2) that state or local jurisdictions should consider as they develop regulations concerning private wells. The EPA is continuing to evaluate the issue of radon occurrence in private wells, and the economic impacts of testing and remediation of wells with elevated radon levels.

2.6 While it is not currently possible to make a precise prediction of indoor radon potential for a specific building site, a general assessment, on a statewide, county or grouping-of-counties basis can be made by referring to the EPA's Map of Radon Zones and other locally available data. It should be noted that some radon potential exists in all areas. However, the EPA recognizes that, based on available data, there is a lower potential for elevated indoor radon levels in some states and portions of some states, and that adoption of building codes for the prevention of radon in new construction may not be justified in these areas at this time. There is language in paragraph 8.2.3 of this document recommending that jurisdictions in these areas review all available data on local indoor radon measurements, geology, soil parameters and housing characteristics as they consider whether adoption of new codes is appropriate.

3.0 Reference Documents

References are made to the following publications throughout this document. Some of the references do not specifically address radon. They are listed here only as relevant sources of additional information on building design, construction techniques, and good building practices that should be considered as part of a general radon reduction strategy.

3.1 "Building Foundation Design Handbook," ORNL/SUB/86-72143/1, May 1988.

3.2 "Building Radon Resistant Foundations -- A Design Handbook," NCMA, 1989.

3.3 "Council of American Building Officials (CABO) Model Energy Code," 1992.

3.4 "Design and Construction of Post-Tensioned Slabs on Ground," Post Tensioning Institute Manual.

3.5 "Energy-Efficient Design of New Buildings Except Low-Rise Residential Buildings," ASHRAE Standard 90.1-1989.

3.6 "Energy-Efficient Design of New Low-Rise Residential Buildings," Draft ASHRAE Standard 90.2 (under public review).

3.7 "Home Buyer's and Seller's Guide to Radon," EPA 402-R-93-003, March 1993.

3.8 "Guide to Residential Cast-in-Place Concrete Construction," ACI 332R.

3.9 "Indoor Radon and Radon Decay Product Measurement Device Protocols," EPA 402-R-92-004, July 1992.

3.10 "Protocols For Radon and Radon Decay Product Measurements in Homes," EPA 402-R-92-003, June 1993.

3.11 "Permanent Wood Foundation System - Basic Requirements, NFPA Technical Report No.7."

3.12 "Radon Control Options for the Design and Construction of New Low-Rise Residential Buildings," ASTM Standard Guide, E1465-92.

3.13 "Radon Handbook for the Building Industry," NAHB-NRC, 1989.

3.14 "U.S. EPA Map of Radon Zones," December 1993.

3.15 "Radon Reduction in New Construction: An Interim Guide," OPA-87-009, August 1987.

3.16 "Radon Reduction in Wood Floor and Wood Foundation Systems," NFPA, 1988.

3.17 "Radon-Resistant Construction Techniques for New Residential Construction: Technical Guidance," EPA/625/2-91/032, February 1991.

3.18 "Radon-Resistant Residential New Construction," EPA/600/8-88/087, July 1988.

3.19 "Guide for Concrete Floor and Slab Construction," ACI 302.1R-89.

3.20 "Ventilation for Acceptable Indoor Air Quality," ASHRAE 62-1989.

4.0 Description of Terms

For this document, certain terms are defined in this section. Terms not defined herein should have their ordinary meaning within the context of their use. Ordinary meaning is as defined in "Webster's Ninth New Collegiate Dictionary."

- **action level:** a term used to identify the level of indoor radon at which remedial action is recommended. (The EPA's current action level is 4 pCi/L.)

- **air passages:** openings through or within walls, through floors and ceilings, and around chimney flues and plumbing chases that permit air to move out of the conditioned spaces of the building.

- **combination foundations:** buildings constructed with more than one foundation type, e.g., basement/crawlspace or basement/slab-on-grade.

- **drain tile loop:** a continuous length of drain tile or perforated pipe extending around all or part of the internal or external perimeter of a basement or crawlspace footing.

- **governmental:** state or local organizations and agencies responsible for building code enforcement.

- **Map of Radon Zones:** a U.S. EPA publication depicting areas of differing radon potential in both map form and in state-specific booklets.

- **mechanically ventilated crawlspace system:** a system designed to increase ventilation within a crawlspace, achieve higher air pressure in the crawlspace relative to air pressure in the soil beneath the crawlspace, or achieve lower air pressure in the crawlspace relative to air pressure in the living spaces, by use of a fan.

- **Model Building Codes:** the building codes published by the four Model Code Organizations and commonly adopted by state and other jurisdictions to control local construction activity.

- **Model Code Organizations:** includes the following agencies and the model building codes they promulgate:

1. Building Officials and Code Administrators International, Inc. (BOCA National Building Code/1993 and BOCA National Mechanical Code/1993);

2. International Conference of Building Officials (Uniform Building Code/1991 and Uniform Mechanical Code/1991);

3. Southern Building Code Congress, International, Inc. (Standard Building Code/1991 and Standard Mechanical Code/1991); and

4. Council of American Building Officials (CABO One- and Two-Family Dwelling Code/1992 and CABO Model Energy Code/1993).

- **pCi/L:** the abbreviation for "picocuries per liter" which is used as a radiation unit of measure for radon. The prefix "pico" means a multiplication factor of one-trillionth. A curie is a commonly used measurement of radioactivity.

- **soil gas:** the gas present in soil which may contain radon.

- **soil-gas retarder:** a continuous membrane or other comparable material used to retard the flow of soil gases into a building.

- **stack effect:** the overall upward movement of air inside a building that results from heated air rising and escaping through openings in the building's super-structure, thus causing an indoor pressure level lower than that in the soil gas beneath or surrounding the building's foundation.

- **sub-slab depressurization system (active):** a system designed to achieve lower sub-slab air pressure relative to indoor air pressure by use of a fan-powered vent to draw air from beneath the slab.
- **sub-slab depressurization system (passive):** a system designed to achieve lower sub-slab air pressure relative to indoor air pressure by use of a vent pipe routed through the conditioned space of a building, and connecting the sub-slab area with outdoor air, thereby relying solely on the convective flow of air upward in the vent to draw air from beneath the slab.
- **sub-membrane depressurization system:** a system designed to achieve lower sub-membrane air pressure relative to crawlspace air pressure by use of a fan-powered vent to draw air from under the soil-gas retarder's membrane.

5.0 Principles for Construction

Principles for Construction of Radon-Resistant Residential Buildings

5.1 The following principles for construction of radon-resistant residential buildings underlie the specific model standards and techniques set forth in Part 9.0.

5.1.1 Residential buildings should be designed and constructed to minimize the entrance of soil gas into the living space.

5.1.2 Residential buildings should be designed and constructed with features that will facilitate post-construction radon removal, or further reduction of radon entry if installed prevention techniques fail to reduce radon levels below the locally prescribed action level.

5.2 As noted in the limitations part (paragraph 2.0.2), construction standards and techniques specifically applicable to new non-residential buildings (including high-rise residential buildings) have not yet been fully demonstrated. Accordingly, the specific standards and techniques set forth in Part 9.0 should not, at this time, be considered applicable to such buildings. There are, however, several general conclusions that may be drawn from the limited mitigation experience available on large non-residential construction. These conclusions are summarized below to provide some initial factors for consideration by builders of non-residential buildings.

5.2.1 HVAC systems should be carefully designed, installed and operated to avoid depressurization of basements and other areas in contact with the soil.

5.2.2 As a minimum, the use of a coarse gravel or other permeable base material beneath slabs, and effective sealing of expansion joints and penetrations in foundations below the ground surface, will facilitate post-construction installation of a sub-slab depressurization system, if necessary.

5.2.3 Limited mitigation experience has shown that some of the same radon-reduction systems and techniques used in residential buildings can be scaled up in size, number or performance to effectively reduce radon in larger buildings.

6.0 Summary of Model Building Standards

Summary of the Model Building Standards and Techniques

The model building standards and techniques listed in Part 9.0 are designed primarily for control of radon in new one- and two family dwellings and other residential buildings three stories or less in height.

6.1 Basement and Slab-on-Grade Foundations

The model building standards and techniques for radon control in new residential buildings constructed on basement and slab-on-grade foundations include a layer of permeable sub-slab material, the sealing of joints, cracks and other penetrations of slabs, floor assemblies and foundation walls below or in contact with the ground surface, providing a soil-gas retarder under floors, and installing either an active or passive sub-slab depressurization system (SSD). Additional radon-reduction techniques are prescribed to reduce radon entry caused by the heat-induced stack effect. These include the closing of air passages (also called thermal bypasses), providing adequate makeup air for combustion and exhaust devices, and installing energy-conservation features that reduce non-required air flow out of the building's super-structure.

6.2 Crawlspace Foundations

The model building standards and techniques for radon control in new residential buildings constructed on crawlspace foundations include those systems that actively or passively vent the crawlspace to outside air, that divert radon before entry into the crawlspace, and that reduce radon entry into normally occupied spaces of the building through floor openings and ductwork.

6.3 Combination Foundations

Radon control in new residential buildings constructed on a combination of basement, slab-on-grade or crawlspace foundations is achieved by applying the appropriate construction techniques to the different foundation segments of the building. While each foundation type should be constructed using the relevant portions of these model building standards and techniques, special consideration must be given to the points at which different foundation types join, since additional soil-gas entry routes exist in such locations.

7.0 Construction Methods

The model construction standards and techniques described in Part 9.0 have proved to be effective in reducing indoor radon levels when used to mitigate radon problems in existing homes and when applied in the construction of new homes. In most cases, combinations of two or more of these standards and techniques have been applied to achieve desired reductions in radon levels. Because of success achieved in reducing radon levels by applying these multiple, inter-dependent techniques, limited data have been collected on the singular contribution to radon reduction made by any one of the construction standards or techniques. Accordingly, there has been no attempt to classify or prioritize the individual standards and techniques as to their specific contribution to radon reduction. It is believed that the use of all the standards and techniques (both passive and active) will produce the lowest achievable levels of indoor radon in new homes. Levels below 2 pCi/L have been achieved in over 90% of new homes. It is also believed that use of only selected (passive) standards and techniques will produce indoor radon levels below the current the EPA action level of 4 pCi/L in most new homes, even in areas of high radon potential.

7.1 It is recommended that all the passive standards and techniques listed in Part 9.0 (including a roughed-in passive radon control system) be used in areas of high radon potential, as defined by local jurisdictions or in the EPA's Map of Radon Zones. Based on more detailed analysis of locally available data, jurisdictions may choose to apply more or less restrictive construction requirements within designated portions of their areas of responsibility. To ensure that new homes are below the locally prescribed action level, in those cases where only passive radon control systems have been installed, occupants should have their homes tested to determine if passive radon control systems need to be activated. In addition, it is recommended that periodic re-tests be conducted to confirm continued effectiveness of the radon control system.

7.2 Any radon testing referenced in this document should be conducted in accordance with EPA Radon Testing Protocols or current EPA guidance for radon testing in real estate transactions, as referenced in paragraph 3.0. It is recommended that all testing be conducted by companies listed in the EPA's Radon Measurement Proficiency Program (RMP) or comparable state-certification programs.

7.3 The design and installation of radon control systems should be performed or supervised by individuals (i.e., builders, their representatives, or registered design professionals, such as architects or engineers) who have attended an EPA-approved radon training course, or by an individual listed in the EPA Radon Contractor Proficiency Program.

[Note: The EPA discontinued its National Radon Proficiency Program on September 30, 1998. Visit www.epa.gov/iaq/radon/proficiency.html to find a qualified radon measurement service provider.]

8.0 Recommended Procedures

Recommended Implementation Procedures

The following procedures are recommended as guidelines for applying the model building standards and techniques and construction methods contained in this document. These procedures are based on the rationale that a passive radon control system and features for facilitating any necessary post-construction radon reduction should be routinely built in to new residential buildings in areas having a high radon potential.

8.1 State, county and local jurisdictions that use these model building standards and techniques as a basis for developing building codes for radon-resistant construction should classify their area by reference to the zones in the EPA's Map of Radon Zones, or by considering other locally available data. While the EPA believes that the Map of Radon Zones and accompanying state-specific booklets are useful in setting general boundaries of areas of concern, the EPA recommends that state and local jurisdictions collect and analyze local indoor radon measurements, and assess geology, soil parameters and housing characteristics -- in conjunction with referring to the EPA radon maps -- to determine the specific areas within their jurisdictions that should be classified as Zone 1.

8.2 State, county and local jurisdictions that use these model building standards and techniques as a basis for developing building codes for radon-resistant construction should specify the construction methods applicable to their jurisdictional area.

8.2.1 In areas classified as Zone 1 in the Map of Radon Zones, or by local jurisdiction, application of the construction method in paragraph 7.1 is recommended.

8.2.2 In areas classified as Zone 2, home builders may apply any of the radon-resistant construction standards and techniques that contribute to reducing the incidence of elevated radon levels in new homes and that are appropriate to the unique radon potential that may exist in their local building area.

8.2.3 In those areas where state and local jurisdictions have analyzed local indoor radon measurements, geology, soil parameters and housing characteristics, and determined that there is a low potential for indoor radon, application of radon-resistant construction techniques may not be appropriate. In these areas, radon-resistant construction techniques may not be needed, or limited use of selected techniques may be sufficient.

8.3 It is recognized that specific rules, regulations and ordinances covering implementation of construction standards and codes are developed and enforced by state and local jurisdictions. While developing the model construction standards and techniques contained in this document, the EPA also developed several approaches to regulation that states and local jurisdictions may find useful and appropriate as they develop rules and regulations that meet their unique requirements. For example:

8.3.1 In areas where the recommended construction method or comparable prescriptive methods are mandated by state or local jurisdictions, regulations would need to include, as part of the inspection process, a review of the radon-resistant construction features by inspectors who have received additional training to ensure that the radon-resistant construction features are properly installed during construction. It would also be necessary to establish requirements for those building officials who review and approve construction plans and specifications to become proficient in identifying and approving planned radon-resistant construction features.

8.3.2 In any area where surveys have shown the existence of high levels of radon in groundwater, or in areas where elevated levels of indoor radon have been found in homes already equipped with active radon control systems, well water may be the source. In such areas, authorities responsible for water regulation should consider establishing well-water testing requirements that include tests for radon.

9.0 Building Standards and Techniques

Model Building Standards and Techniques

9.1 Foundation and Floor Assemblies

The following construction techniques are intended to resist radon entry and prepare the building for post-construction radon mitigation, if necessary. These techniques, when combined with those listed in paragraph 9.2, meet the requirements of the construction method outlined in paragraph 7.1. (See also the construction methods listed in ASTM Standard Guide, E-1465-92.)

9.1.1 A layer of gas-permeable material shall be placed under all concrete slabs and other floor systems that directly contact the ground and are within the walls of the living spaces of the building to facilitate installation of a sub-slab depressurization system, if needed. Alternatives for creating the gas-permeable layer include:

a. a uniform layer of clean aggregate, a minimum of 4 inches thick. The aggregate shall consist of material that will pass through a 2-inch sieve and be retained by a ¼-inch sieve.

b. a uniform layer of sand, a minimum of 4 inches thick, overlain by a layer or strips of geotextile drainage matting designed to allow the lateral flow of soil gases.

c. other materials, systems, or floor designs with the demonstrated capability to permit depressurization across the entire sub-floor area.

9.1.2 A minimum 6-mil (or 3-mil cross-laminated) polyethylene or equivalent flexible sheeting material shall be placed on top of the gas-permeable layer prior to pouring the slab, or placing the floor assembly to serve as a soil-gas retarder by bridging any cracks that develop in the slab or floor assembly, and to prevent concrete from entering the void spaces in aggregate-base material. The sheeting should cover the entire floor area, and separate sections of sheeting should be overlapped at least 12 inches. The sheeting shall fit closely around any pipe, wire or other penetrations of the material. All punctures or tears in the material shall be sealed or covered with additional sheeting.

9.1.3 To minimize the formation of cracks, all concrete floor slabs shall be designed, mixed, placed, reinforced, consolidated, finished and cured in accordance with standards set forth in the Model Building Codes. The American Concrete Institute publications *Guide for Concrete Floor and Slab Construction*, ACI 302.1R, *Guide to Residential Cast-in-Place Concrete Construction*, ACI 332R, or the Post Tensioning Institute Manual, *Design and Construction of Post-Tensioned Slabs on Ground* are references that provide additional information on construction of concrete floor slabs.

9.1.4 Floor assemblies in contact with the soil and constructed of materials other than concrete shall be sealed to minimize soil-gas transport into the conditioned spaces of the building. A soil-gas retarder shall be installed beneath the entire floor assembly, in accordance with paragraph 9.1.2.

9.1.5 To retard soil-gas entry, large openings through concrete slabs, wood and other floor assemblies in contact with the soil, such as spaces around the bathtub, shower and toilet drains, shall be filled or closed with materials that provide a permanent airtight seal, such as non-shrink mortar, grouts, expanding foam, or similar materials designed for such application.

9.1.6 To retard soil-gas entry, smaller gaps around all pipe, wire and other objects that penetrate concrete slabs or other floor assemblies shall be made airtight with an elastomeric joint sealant, as defined in ASTM C920-87, and applied in accordance with the manufacturer's recommendations.

9.1.7 To retard soil-gas entry, all control joints, isolation joints, construction joints, and any other joints in concrete slabs or between slabs and foundation walls shall be sealed. A continuous formed gap (for example, a "tooled edge") which allows the application of a sealant that will provide a continuous, airtight seal, shall be created along all joints. When the slab has cured, the gap shall be cleared of loose material and filled with an elastomeric joint sealant, as defined in ASTM C920-97, and applied in accordance with the manufacturer's recommendations.

9.1.8 Channel-type (or French) drains are not recommended. However, if used, such drains shall be sealed with backer rods and an elastomeric joint sealant in a manner that retains the channel feature and does not interfere with the effectiveness of the drain as a water-control system.

9.1.9 Floor drains and air-conditioning condensate drains that discharge directly into the soil below the slab or into crawlspaces should be avoided. If installed, these drains shall be routed through solid pipe to daylight, or through a trap approved for use in floor drains by local plumbing codes.

9.1.10 Sumps open to soil or serving as the termination point for sub-slab or exterior drain tile loops shall be covered with a gasketed or otherwise sealed lid to retard soil-gas entry. (Note: If the sump is to be used as the suction point in an active sub-slab depressurization system, the lid should be designed to accommodate the vent pipe. If also intended as a floor drain, the lid shall also be equipped with a trapped inlet to handle any surface water on the slab.)

9.1.11 Concrete masonry foundation walls below the ground surface shall be constructed to minimize the transport of soil gas from the soil into the building. Hollow-block masonry walls shall be sealed at the top to prevent the passage of air from the interior of the wall into the living space. At least one continuous course of solid masonry, one course of masonry-grouted solid, or a poured concrete beam at or above finished ground surface-level shall be used for this purpose. Where a brick veneer or other masonry ledge is installed, the course immediately below that ledge shall also be sealed.

9.1.12 Pressure-treated wood foundations shall be constructed and installed as described in the National Forest Products Association (NFPA) Manual,*Permanent Wood Foundation System: Basic Requirements, Technical Report No. 7.* In addition, the NFPA publication, *Radon Reduction in Wood Floor and Wood Foundation Systems* provides more detailed information on construction of radon-resistant wood floors and foundations.

9.1.13 Joints, cracks and other openings around all penetrations of both exterior and interior surfaces of masonry block or wood foundation walls below the ground surface shall be sealed with an elastomeric sealant that provides an airtight seal. Penetrations of poured concrete walls should also be sealed on the exterior surface. This includes sealing of wall-tie penetrations.

9.1.14 To resist soil-gas entry, the exterior surfaces of portions of poured concrete and masonry block walls below the ground surface shall be constructed in accordance with water-proofing procedures outlined in the Model Building Codes.

9.1.15 Placing air-handling ducts in or beneath a concrete slab floor, or in other areas below grade and exposed to earth, is not recommended unless the air-handling system is designed to maintain continuous positive pressure within such ducting. If ductwork does pass through a crawlspace or beneath a slab, it should be of a seamless material. Where joints in such ductwork are unavoidable, they shall be sealed with materials that prevent air leakage.

9.1.16 Placing air-handling units in crawlspaces, or in other areas below grade and exposed to soil gas, is not recommended. However, if such units are installed in crawlspaces or in other areas below grade and exposed to soil gas, they shall be designed or otherwise sealed in a durable manner that prevents air surrounding the unit from being drawn into the unit.

9.1.17 To retard soil-gas entry, the openings around all penetrations through floors above crawlspaces shall be sealed with materials that prevent air leakage.

9.1.18 To retard soil-gas entry, access doors and other openings and penetrations between basements and adjoining crawlspaces shall be closed, gasketed or otherwise sealed with materials that prevent air leakage.

9.1.19 Crawlspaces should be ventilated in conformance with locally adopted codes. In addition, vents in passively ventilated crawlspaces shall be open to the exterior and be of a non-closeable design.

9.1.20 In buildings with crawlspace foundations, the following components of a passive sub-membrane depressurization system shall be installed during construction:

9.1.20.1 The soil in both vented and unvented crawlspaces shall be covered with a continuous layer of minimum 6-mil thick polyethylene sheeting or equivalent membrane material. The sheeting shall be sealed at seams and penetrations, around the perimeter of interior piers, and to the foundation walls. Following installation of underlayment, flooring, plumbing, wiring and other construction activity in or over the crawlspace, the membrane material shall be inspected for holes, tears or other damage, and for continued adhesion to walls and piers. Repairs shall be made as necessary.

9.1.20.2 A length of 3- or 4-inch diameter perforated pipe or a strip of geotextile drainage matting should be inserted horizontally beneath the sheeting, and connected to a 3- or 4-inch diameter T-fitting with a vertical standpipe installed through the sheeting. The standpipe shall be extended vertically through the building floors, terminate at least 12 inches above the surface of the roof, and in a location at least 10 feet away from any window or other opening into the conditioned spaces of the building that is less than 2 feet below the exhaust point, and 10 feet from any adjoining or adjacent buildings.

9.1.20.3 All exposed and visible interior radon vent pipes shall be identified with at least one label on each floor level. The label shall read: "Radon Reduction System."

9.1.20.4 To facilitate installation of an active sub-membrane depressurization system, electrical junction boxes shall be installed during construction in proximity to the anticipated locations of vent pipe fans and system-failure alarms.

EXCEPTION: Where local codes permit mechanical crawlspace ventilation or other effective ventilation systems, and such systems are operated or proven to be effective year-round, the sub-membrane depressurization system components are not required.

9.1.21 In basement and slab-on-grade buildings, the following components of a passive sub-slab depressurization system shall be installed during construction:

9.1.21.1 A minimum 3-inch diameter PVC or other gas-tight pipe shall be embedded vertically into the sub-slab aggregate or other permeable material before the slab is poured. A T-fitting or other support on the bottom of the pipe shall be used to ensure that the pipe opening remains within the sub-slab permeable material. This gas-tight pipe shall be extended vertically through the building floors, terminate at least 12 inches above the surface of the roof, and in a location at least 10 feet away from any window or other opening into the conditioned spaces of the building that is less than 2 feet below the exhaust point, and 10 feet from any adjoining or adjacent buildings.

Note: Because of the uniform permeability of the sub-slab layer prescribed in paragraph 9.1.1, the precise positioning of the vent pipe through the slab is not critical to system performance, in most cases. However, a central location shall be used, where feasible. In buildings designed with interior footings (that is, footings located inside the overall perimeter footprint of the building), or other barriers to lateral flow of sub-slab soil gas, radon vent pipes shall be installed in each isolated, non-connected floor area. If multiple suction points are used in non-connected floor areas, vent pipes are permitted to be manifolded in the basement or attic into a single vent that could be activated using a single fan.

9.1.21.2 Internal sub-slab and external footing drain tile loops that terminate in a covered and sealed sump, or internal drain tile loops that are stubbed up through the slab, are also permitted to provide a roughed-in passive sub-slab depressurization capability. The sump or stubbed-up pipe shall be connected to a vent pipe that extends vertically through the building floors, terminate at least 12 inches above the surface of the roof, and in a location at least 10 feet away from any window or other opening into the conditioned spaces of the building that is less than 2 feet below the exhaust point, and 10 feet from any adjoining or adjacent buildings.

9.1.21.3 All exposed and visible interior radon vent pipes shall be identified with at least one label on each floor level. The label shall read: "Radon Reduction System."

9.1.21.4 To facilitate installation of an active sub-slab depressurization system, electrical junction boxes shall be installed during construction in proximity to the anticipated locations of vent pipe fans and system-failure alarms.

9.1.21.5 In combination basement/crawlspace and slab-on-grade/crawlspace buildings, the sub-membrane vent described in paragraph 9.1.20.2 may be tied into the sub-slab depressurization vent to permit use of a single fan for suction, if activation of the system is necessary.

9.2 Stack Effect-Reduction Techniques

The following construction techniques are intended to reduce the stack effect in buildings and, thus, the driving force that contributes to radon entry and migration through buildings. As a basic principle, the driving force decreases as the number and size of air leaks in the upper surface of the building decrease. It should also be noted that, in most cases, exhaust fans contribute to stack effect.

9.2.1 Openings around chimney flues, plumbing chases, pipes and fixtures, ductwork, electrical wires and fixtures, elevator shafts, and other air passages that penetrate the conditioned envelope of the building shall be closed or sealed using sealant or fire-resistant materials approved in local codes for such application.

9.2.2 If located in conditioned spaces, attic access stairs and other openings to the attic from the building shall be closed, gasketed, or otherwise sealed with materials that prevent air leakage.

9.2.3 Recessed ceiling lights that are designed to be sealed and that are Type IC-rated shall be used when installed on top-floor ceilings and in other ceilings that connect to air passages.

9.2.4 Fireplaces, wood stoves, and other combustion or vented appliances, such as furnaces, clothes dryers and water heaters shall be installed in compliance with locally adopted codes, or other provisions made to ensure an adequate supply of combustion and makeup air.

9.2.5 Windows and exterior doors in the building's super-structure shall be weather-stripped or otherwise designed in conformance with the air-leakage criteria of the CABO Model Energy Code.

9.2.6 HVAC systems shall be designed and installed to avoid depressurization of the building relative to the underlying and surrounding soil. Specifically, joints in air ducts and plenums passing through unconditioned spaces, such as attics, crawlspaces and garages, shall be sealed.

9.3 Active Sub-Slab/Sub-Membrane Depressurization System

When necessary, activation of the roughed-in passive sub-membrane and sub-slab depressurization systems described in paragraphs 9.1.20 and 9.1.21 shall be completed by adding an exhaust fan in the vent pipe, and a prominently positioned visible or audible warning system to alert the building's occupants if there is loss of pressure or air flow in the vent pipe.

9.3.1 The fan in the vent pipe and all positively pressurized portions of the vent pipe shall be located outside the habitable space of the building.

9.3.2 The fan in the vent pipe shall be installed in a vertical run of the vent pipe.

9.3.3 Radon vent pipes shall be installed in a configuration and supported in a manner that ensures that any rainwater or condensation accumulating within the pipes drains downward into the ground beneath the slab or soil-gas retarder.

9.3.4 To avoid re-entry of soil gas into the building, the vent pipe shall exhaust at least 12 inches above the surface of the roof, in a location at least 10 feet away from any window and other opening into the conditioned spaces of the building that is less than 2 feet below the exhaust point, and 10 feet from any adjoining or adjacent buildings.

9.3.5 To facilitate the future installation of a vent fan, if needed, the radon vent pipe shall be routed through attics in a location that will allow sufficient room to install and maintain the fan.

9.3.6 The size and air-movement capacity of the vent pipe fan shall be sufficient to create and maintain a pressure field beneath the slab or crawlspace membrane that is lower than the ambient pressure above the slab or membrane.

9.3.7 Under conditions where the soil is highly permeable, reversing the air flow in an active sub-slab depressurization system and forcing air beneath the slab may be effective in reducing indoor radon levels.

Note: The long-term effect of active sub-slab depressurization or pressurization on the soil beneath building foundations has not been determined. Until ongoing research produces definitive data, in areas where expansive soils or other unusual soil conditions exist, the local soils engineer shall be consulted during the design and installation of sub-slab depressurization or pressurization systems.

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Section 18: Building Radon Out

EPA: Building Radon Out:

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Building Radon Out
A Step-by-Step Guide On How To Build Radon-Resistant Homes

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A Step-by-Step Guide on How to Build Radon-Resistant Homes

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Building the Framework: Introduction

Should you be concerned about radon?

Yes.

Radon is a colorless, odorless gas that can cause lung cancer. Your customers rely on you to construct a high-quality, safe home. You can easily make a difference in how much radon gets into the homes you build. By using a handful of simple building practices and common materials, you can effectively lower the radon level in the homes that you build, and build most radon problems right out of the house.

Does it make sense to build homes radon-resistant?

Absolutely. There are a number of reasons why you should consider installing radon-resistant features:

You can gain a marketing advantage.

Offering homes with radon-resistant features can attract more potential home buyers, which can translate into closing more sales, and greater profits. Consumers are becoming more aware that radon is a health risk, and building a home with radon-resistant features could give buyers one more reason to purchase a home from you. About one in every six homes is being built radon-resistant in the United States every year, averaging about 200,000 homes annually, according to annual surveys of home-builder practices conducted by the National Association of Home Builders (NAHB) Research Center over the past decade. In high radon areas, about one in every three homes is built with the features.

Industry surveys continue to demonstrate a rapidly growing market for more energy-efficient, environmentally-friendly, comfortable and healthy homes. Radon-reduction techniques are consistent with state-of-the-art, energy-efficient construction. The features can also decrease moisture and other soil gases entering the home, reducing molds, mildews, methane, pesticide gases, volatile organic compounds, and other indoor air-quality problems. When using these techniques, follow the Model Energy Code (or other applicable energy codes) for weatherization, which will result in energy savings and lower utility bills for the homeowner.

It is a good investment for a homebuyer.

It is cheaper to install a radon-reduction system during construction than to go back and fix a radon problem identified later. On average, installing radon-resistant features during construction costs about $350 to $500, or even less, if you already use some of the techniques for moisture control and energy efficiency. Many builders who use the techniques have reported actual costs of $100 or less. In contrast, retrofitting an existing home will typically cost between $800 and $2,500.

It is effective.

A basic radon-reduction system, called a passive sub-slab depressurization system, effectively reduces radon levels by an average of about 50% and, in most cases, to levels below the EPA's action level. An upgraded system, called an active sub-slab depressurization system, includes an in-line fan to provide even further reductions.

It is simple to install.

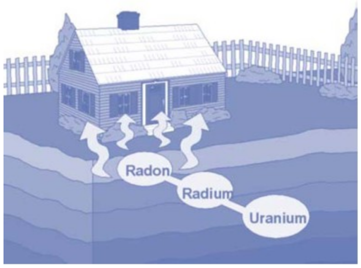
All of the techniques and materials are commonly used in construction. No special skills or materials are required.

Upgrading is easy.

After occupancy, all homes should be tested for radon, even those built with radon-resistant features. The EPA recommends that homes with radon levels at or above 4 picocuries per liter of air (pCi/L) be mitigated. Homes with a passive system can be upgraded to an active system with the simple installation of a special in-line fan to further reduce the radon level. Typically, the passive system includes a junction box in the attic to make the future installation of the fan easy. This upgrade is also used by some builders to control moisture in basements and crawlspaces.

Digging Deeper: Questions and Answers

This chapter digs deeper into some of the more commonly asked questions concerning radon-resistant new construction.



What is radon?

Radon is a radioactive gas. It comes from uranium and radium in soils, which can be found everywhere in the world. Uranium is present in rocks, such as granite, shale, phosphate and pitchblende. Uranium breaks down to radium, which then decays into radon. This gas can easily move up through the soil into the atmosphere. Natural deposits of uranium and radium, not manufactured sources, produce most of the radon present in the air.

Radon is in the soil and air everywhere in varying amounts.

People cannot see, taste, feel or smell radon. There is no way to sense the presence of radon.

Radon levels are commonly expressed in picocuries per liter of air (pCi/L), where a picocurie is a measure of radioactivity.

The national average of indoor radon levels in homes is about 1.3 pCi/L. Radon levels outdoors, where radon is diluted, average about 0.4 pCi/L.

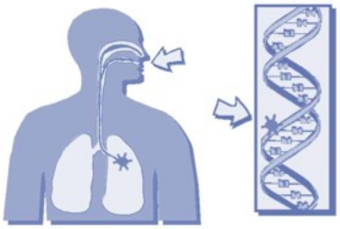
Radon in the soil can be drawn into a building and can accumulate to high levels. Every building and home has the potential for elevated levels of radon. All homes should be tested for radon, even those built with radon-resistant features. The EPA recommends taking action to reduce indoor radon levels when levels are 4 pCi/L or higher.

Is radon a significant health risk?

When radon enters a home, it decays into radioactive particles that have a static charge, which attracts them to particles in the air. These particles can get trapped in your lungs when you breathe. As the radioactive particles break down further, they release bursts of energy which can damage the DNA in lung tissue. In some cases, if the lung tissue does not repair the DNA correctly, the damage can lead to lung cancer.

Not everyone exposed to elevated levels of radon will develop lung cancer, but your risk of getting radon-induced lung cancer increases as your exposure to radon increases, either because the radon levels are higher or you live in the home longer. Smokers who have high radon levels in their homes are at an especially high risk for getting radon-induced lung cancer.

The evidence that radon causes lung cancer is extensive and based on: human data taken from studies of underground miners carried out over more than 50 years in five countries, including the United States and Canada; human data from studies in homes in many different nations, including the U.S. and Canada; and biological and molecular studies.



Radon is classified as a Class A carcinogen (known to cause cancer in humans).
Some other Class A carcinogens are arsenic, asbestos and benzene.

Energy released from radon decay products damages DNA. Radon decay particles are breathed into the lungs.

Is radon a health problem in homes?

Radon is the second-leading cause of lung cancer in the United States. Radon causes about 20,000 lung cancer deaths per year.

The following are some organizations which state that radon is a health threat in homes:

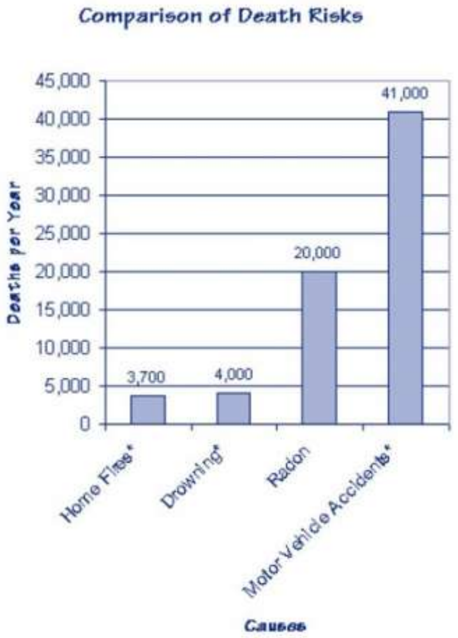
- the U.S. Surgeon General;
- the American Medical Association;
- the American Lung Association;
- the Centers for Disease Control;
- the National Cancer Institute;
- the National Academy of Sciences; and
- the Environmental Protection Agency.

The risk of developing lung cancer from radon has been clearly demonstrated in underground miners. Did you know that the average lifetime radon exposure for the general population is about the same as the levels of exposure at which increased risk has been demonstrated in underground miners?

A study released by the National Academy of Sciences on February 19, 1998 called *The Health Effects of Exposure to Indoor Radon* is the most definitive accumulation of scientific data on indoor radon. The report concludes that radon causes 15,000 to 22,000 deaths per year, making it the second-leading cause of lung cancer in the U.S., and a serious public health concern.

Have you heard of Stanley Watras?

Stanley J. Watras was a construction engineer at the Limerick Nuclear Power Plant in Pottstown, Pennsylvania. One day, on his way to work, he entered the plant and set off the radiation monitor alarms, which help protect workers by detecting exposure to radiation. Safety personnel checked him out, but could not find the source of the radiation. Interestingly, because the plant was under construction at the time, there was no nuclear fuel at the plant. They discovered the source of radiation exposure when Watras's home was tested and was measured to have very high radon levels (2,700 pCi/L). After installing a radon-reduction system, radon levels in the home tested below 4 pCi/L.



* data from the National Safety Council, 1999

Is there a safe level of radon?

There is no known safe level of radon. As your exposure to radon is increased, so is your risk for developing lung cancer. Even radon levels below 4 pCi/L pose some risk.

Homes have been found with radon levels above 20, 100, and, in rare cases, even 2,000 pCi/L. High indoor radon levels have been found in every state.

The EPA, the Surgeon General, the Centers for Disease Control, and many other health organizations recommend that action be taken to reduce indoor radon levels at or above 4 pCi/L, which is a reasonably achievable level of radon in homes using currently available, cost-effective techniques.

Radon is a significant risk. More people die from lung cancer caused by radon each year than from many other highly publicized causes of death.

How Does Radon Enter a House?

Common Radon Entry Points

There are four main factors that drive radon into homes. All of these factors exist in most homes throughout the country.

1. Uranium is present in the soil nearly everywhere in the United States.
2. The soil is permeable enough to allow radon to migrate into the home through the slab, basement or crawlspace.
3. There are pathways for the radon to enter the basement, such as small holes, cracks, plumbing penetrations or sumps. All homes have radon-entry pathways.
4. An air-pressure difference between the basement or crawlspace and the surrounding soil draws radon into the home.

How does air pressure affect radon entry?

The air pressure in a house is generally lower than in the surrounding air and soil, particularly at the basement and foundation levels. This difference in pressure causes a house to act like a vacuum, drawing air containing radon and other soil gases in through foundation's cracks and other openings. Some of the replacement air comes from the underlying soil and can contain radon.

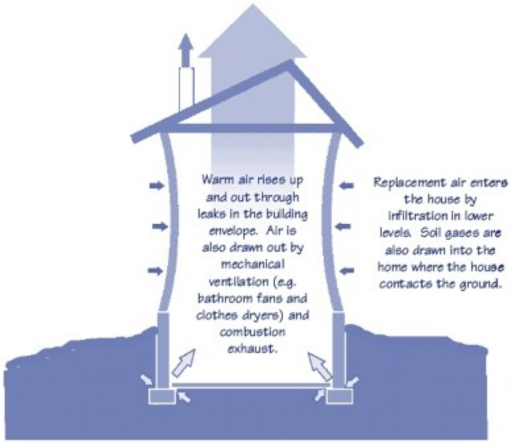
One reason why this pressure difference occurs is because exhaust fans remove air from inside the house. When this air is exhausted, outside air enters the house to replace it. Another cause for a pressure difference is that warm air rises and will leak from openings in the upper portion of the house when temperatures are higher indoors than outdoors. This condition, known as “stack effect,” causes unconditioned replacement air to enter the lower portion of the house.

Mechanical systems, such as the furnaces and central air conditioners, may also contribute to the difference in air pressure. In areas with very short, mild winters, mechanical systems can be the dominant driving force. Air handlers and leaky return ducts can not only draw in radon, but they can also distribute it throughout a home.

Warm air rises up and out through leaks in the building envelope. Air is also drawn out by mechanical ventilation (e.g., bathroom fans and clothes dryers) and combustion exhaust.

Replacement air enters the house by infiltration in lower levels. Soil gases are also drawn into the home where the house contacts the ground.

Does Foundation Type Affect Radon Entry?



Because radon can literally be sucked into a home, any home can potentially have a radon problem. All conventional house construction types have been found to have radon levels exceeding the action level of 4 pCi/L.

Basement

Radon can enter through floor-to-wall joints, control joints and cracks in the slab.

Crawlspace

The vacuums that exist within a home are exerted on the crawlspaces causing radon and other gases to enter the home from the earthen area below. Even with crawlspace vents, a slight vacuum is still exerted on the crawlspace. Measurements in homes with crawlspaces have shown elevated radon levels.

Slab-on-Grade

Radon can enter a home regardless of whether or not there is a basement. Slabs built on grade can have just as many openings to allow radon to enter as do basements.

Manufactured Homes

Unless these buildings are set up on piers without any skirting placed around them, interior vacuums can cause radon to enter these types of homes, as well.

What can you do to reduce radon in new homes?

You can easily draw radon away and help prevent radon from entering the home with the following basic steps.

You may already be employing many of these techniques in the homes that you build. All of the techniques have additional benefits associated with them, and they are very easy to install.

Install a sub-slab (or sub-membrane) depressurization system.

The objective of these systems is to create a vacuum beneath the foundation which is greater in strength than the vacuum applied to the soil by the house itself. The soil gases that are collected beneath the home are piped to a safe location to be vented directly outside.

Use mechanical barriers to soil-gas entry.

Plastic sheeting, and foundation sealing and caulking can serve as barriers to radon entry, entry of other soil gases, and moisture.

Reduce stack effect.

Sealing and caulking reduce stack effect and, thus, reduce the negative pressure in lower levels of the home.

Install air-distribution systems so that soil air is not “mined.”

Air-handling units and all ducts in basements and, especially, in crawlspaces should be sealed to prevent air (and radon) from being drawn into the system. Seamless ducts are preferred for runs through crawlspaces and beneath slabs. Any seams and joints in ducts should be sealed.

Can we keep radon out by sealing the cracks?

Sealing large cracks and openings is important to do, both in the lower portion of the home to reduce radon entry-points, and in the upper portion of the home to reduce stack effect. However, field research has shown that attempting to seal all of the openings in a foundation is both impractical and ineffective as a stand-alone technique. Radon can enter through very small cracks and openings which can often be too small to locate and effectively seal. Even if all cracks could be sealed during construction (which would be costly), building settlement may cause new cracks to occur. Therefore, sealing large cracks and openings is one of the key components of radon-resistant construction, but not the only technique that should be employed.

What pulls the soil gas through pipe?

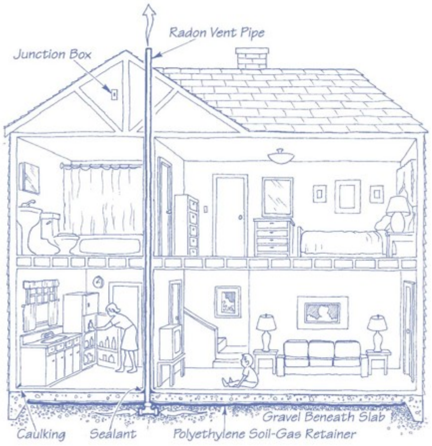
If pipe is routed through a warm space (such as an interior wall or the furnace flue chase, following local fire codes), the stack effect can create a natural draft in the pipe. Because this method requires no mechanical devices, it is called a passive soil-depressurization system.

If further reduction is necessary to bring radon levels in a home below the action level of 4 pCi/L, or even lower, an in-line fan can be installed in the pipe to activate the system. The system is then called an active soil depressurization system. The future installation of the fan can be made easier with a little planning during construction.

What are the radon-resistant features?

The techniques may vary for different foundations and site requirements, but the basic elements of the passive sub-slab depressurization system follow.

In many parts of the country, the gravel beneath the slab (the gas-permeable layer), plastic sheeting, and sealing and caulking are already employed for moisture reduction. In these cases, simply adding the vent pipe and junction box is extremely cost-effective for reducing radon, so much so that even the cost-conscious organization Habitat for Humanity, which relies on donations and grants for its funding, has been adding these features in many of its homes.



Popular and Effective Radon-Resistant Features in New Construction

Gas-Permeable Layer

Usually, a 4-inch layer of clean, coarse gravel is used beneath the slab to allow the soil gas to move freely underneath the house. Other options are to install a loop of perforated pipe or a soil-gas collection mat (also known as a drainage mat or soil-gas matting).

Plastic Sheeting

Polyethylene sheeting is placed on top of the gas-permeable layer to help prevent the soil gas from entering the home. The sheeting also keeps concrete from clogging the gas-permeable layer when the slab is poured.

Vent Pipe

A 3- or 4-inch PVC or other gas-tight pipe (commonly used for plumbing) runs from the gas-permeable layer through the house and roof to safely vent radon and other soil gases above the house. Although some builders use 3-inch pipe, field results have indicated that passive systems tend to function better with 4-inch pipe.

Junction Box

An electrical junction box is wired in case an electric venting fan is needed later to activate the system.

Sealing and Caulking

All openings in the concrete foundation floor are sealed to prevent soil gas from entering the home. Also, sealing and caulking the rest of the building envelope reduces stack effect in the home.

Is there a way to test the lot before building?

Soil testing for radon is not recommended for determining whether a house should be built radon-resistant. Although soil testing can be done, it cannot rule out the possibility that radon could be a problem in the house you build on that lot. Even if soil testing reveals low levels of radon gas in the soil, the amount of radon that may enter the finished house cannot be accurately predicted because one cannot predict the impact that the site preparation will have on introducing new radon pathways, or the extent to which a vacuum will be produced by the house. Furthermore, the cost of a single soil test for radon ranges from $70 to $150, and at least four to eight tests could be required to accurately characterize the radon in the soil at a single building site. Therefore, the cost to perform soil testing is very high when compared with installing the passive radon system in high radon-potential areas.

Why not wait to install the features until after the home is completed and a radon test is performed?

It is much easier and far less costly to prepare the sub-grade to improve soil-gas flow before the slab is cast. Also, the pipe itself can be run more easily through the house before it is finished. This significantly improves aesthetics and can reduce subsequent system operating costs by planning to route the pipe through warm space to maximize passive operation of the system.

The best way to determine the radon level in a home is to test the home for radon after occupancy.

Would I incur liability by installing the features?

New homes built in the United States are not required to meet a specified radon level. You are not required to test a home, nor to guarantee that a home will meet a specified radon level. By installing radon-resistant features, you are pro-actively offering your home buyers features designed to reduce radon levels. Adopting radon-resistant building techniques should not increase your liability risks in any jurisdiction as long as due care is exercised in following the proper construction techniques. Especially in high radon areas, radon-resistant features may actually help you market and sell the homes you build.

Once you have decided to build radon-resistant, you will want to make sure to install the features properly. If your building code includes provisions for the radon features, follow your code requirements. Otherwise, follow the guidance provided in this document, or in any of the following documents:

MODEL STANDARDS AND TECHNIQUES FOR CONTROL OF RADON IN NEW RESIDENTIAL BUILDINGS

CABO ONE and TWO FAMILY DWELLING COD

International Residential Code 2000

- EPA: *Model Standards and Techniques for Control of Radon in New Residential Buildings* (March 1994);

- Council of American Building Officials: *One- and Two-Family Dwelling Code: Appendix F* (1995 Edition);

- International Code Council: *International One- and Two-Family Dwelling Code: Appendix D* (1998 Edition);

- International Code Council: *International Residential Code: Appendix F* (2000 Edition); and

- American Society for Testing and Materials: *Standard Guide for Radon Control Options for the Design and Construction of New Low Rise Residential Buildings, E 1465-92.*

Should All New Homes Be Built Radon-Resistant

All homes could benefit from having a radon-reduction system. However, it is especially cost-effective to install the features in homes with the greatest potential for high radon levels.

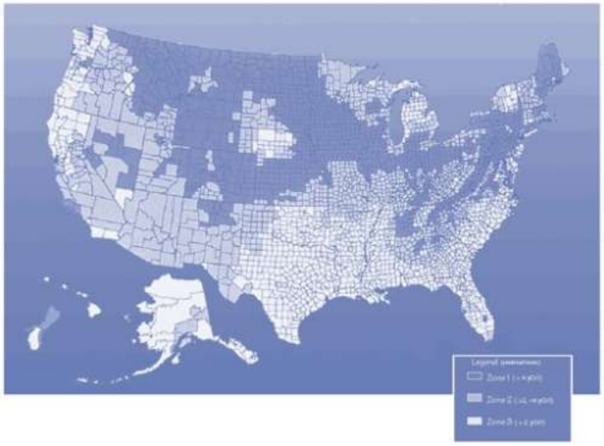
The potential for elevated radon levels is not uniform throughout the United States. The EPA and the U.S. Geological Survey have identified areas of the country with the greatest potential for high radon levels. The map to follow is based on indoor radon measurements, local geology, and population densities compiled in an effort to rank radon potentials in all counties across the U.S. The map indicates three radon-potential zones defined by the likelihood of finding radon measurements within certain ranges when a short-term closed-building radon test is performed.

The EPA recommends that all homes built in Zone 1 areas (with high radon potential) install radon-reduction systems.

The NAHB also recommends using the passive system in homes in high radon potential areas (Zone 1). Zone 1 counties are listed by state.

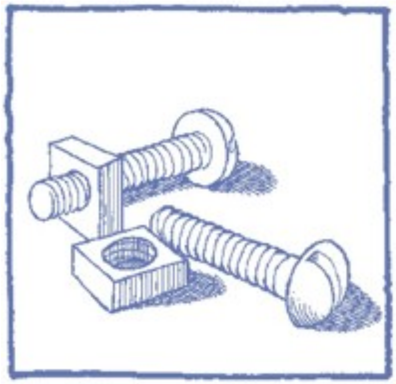
If you are building in a Zone 2 or 3 area, the homes you build could still have high radon levels, particularly if there is a radon "hot spot" in your county. According to an annual survey by the NAHB Research Center, about 60,000 homes in Zones 2 and 3 are built with radon-resistant techniques each year. You may want to consider applying the techniques in these areas, too. Since the map was developed, many states have acquired additional information on high radon areas. Contact your state radon office for more information.

Consumers have asked for the radon-reduction features in many different parts of the country and in all three radon zones.



List of Zone 1 Counties

Nuts and Bolts: Installation Guide



Installation is easy.

As you'll see in this chapter, installing radon-resistant features is simple because you use common building practices and materials.

Proper installation of the radon-resistant features is very important. Improper installation could actually increase indoor radon levels.

This section gives you step-by-step instructions -- the nuts and bolts -- on how to install radon-resistant features.

The techniques in this document apply primarily to new one- and two-family dwellings, and other residential buildings three stories or less in height.

PLANNING

Step 1: Answer These Questions

To install or not to install?

To help you answer this question, consider the following points:

Do you want to reap the benefits of installing the features?

The features not only protect your customer's health, they also affect your bottom line -- your profit. A small investment up front on your part may make a big difference in return down the road, particularly as home buyers are increasingly looking for environmentally-conscious builders and healthy homes.

Are you building in a Zone 1 area?

Check the radon potential map and the list of Zone 1 counties in the previous chapter. Some states and counties have done further research on radon potential, and you can check with your state and county governments to find out whether additional information is available.

If you are building in a Zone 1 area, you should install radon-resistant features in the homes that you build. Some builders also choose to install the features in Zone 2 and 3 areas, particularly if radon-resistant construction is a common practice in those areas.

Are you required by code to use radon-resistant techniques?

Some states and local jurisdictions have adopted Appendix F of the 1995 *CABO One- & Two-Family Dwelling Code*, Appendix D of the 1998 *International One- & Two-Family Dwelling Code,* or a similar code requiring installation of the radon-resistant features. The International Code Council's new *International Residential Code,* published in 2000, also contains a voluntary appendix for radon-resistant construction requirements that becomes effective if the appendix is adopted with the code. If you don't already know what is required in your area, check with your local code official for more information.

Are other builders in your area installing radon-resistant features?

If so, you may want to find out why they are installing the features, how much it costs to install the features in your area, and what the market response has been.

Are the home buyers in your area interested in features that improve indoor air quality and/or energy efficiency?

A sub-slab depressurization system not only helps to reduce indoor radon levels, but also may help to reduce moisture and other soil gases. The techniques also improve energy-efficiency, which can translate into energy savings for the home buyer.

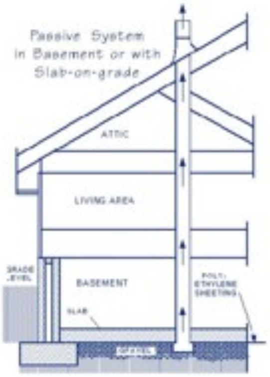
Step 2: Determine What Type of System to Install

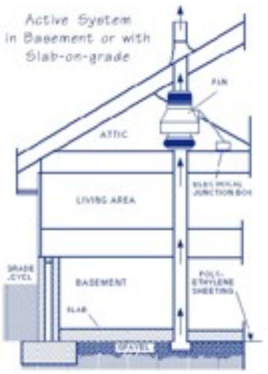
There are three general types of radon-reduction systems that builders have installed.

Recommended Option

Passive sub-slab or sub-membrane depressurization system:

It is cost-effective and recommended to install a complete passive sub-slab or sub-membrane depressurization system, which would be fully functioning as soon as construction is finished. The home should be tested after occupancy, and the passive system should be activated if post-occupancy testing reveals radon levels at or above 4 pCi/L.





Upgraded Option

Active sub-slab or sub-membrane depressurization system:

Activating a passive system by adding an in-line fan would be an effective upgrade during construction. Virtually all homes with an active system have radon levels below the 4 pCi/L action level.

Not Recommended

Passive system rough-in:

Some builders perform only the sub-slab preparation and stub the vent pipe above the slab. A vent pipe can be connected and routed through the home and roof later if radon levels are high.

It is much more cost-effective to run the vent pipe through the house during construction rather than after the walls have been closed up. However, if you elect to rough in a radon-reduction system, it is important to be clear with the home buyer that the home is not equipped with a functioning system. Be sure to seal off the riser stub so that radon is not being vented into the living space. Also, label the stub so it is not used as a plumbing waste line.

Step 3: Determine Vent Pipe Location and Size

Route pipe through warm spaces.

The vent pipe exhausts radon collected from beneath the slab or crawlspace. One objective of a radon system in a new home is to install it in such a manner that a natural draft occurs in the pipe to draw the radon from the soil without the use of a fan. To accomplish this, route the pipe up through a warm part of the house and exhaust it through the roof.

Ideally, the vent pipe should be installed in a vertical run, with the least number of elbows, which could restrict air flow. A radon vent pipe can also be run through the same chase as the furnace and water-heater flue. Do not tie them together but, rather, allow for enough room to route the radon vent pipe up alongside the flues with proper clearances consistent with local building and fire codes. This means that the riser should be brought up through the slab within the same room as the furnace or water heater. This requires a little planning on your part to identify this location before the slab is poured, and to allow for sufficient room in the chase.

In cold climates, do not route the pipe up through an outside wall. Routing the pipe up an outside wall will reduce the natural thermal stack effect in the vent pipe, reducing its effectiveness. It will also make it difficult to install a fan in the attic if it is needed later on. A better option is to route the pipe up through an interior wall.

In hot climates and predominantly air-conditioned houses, the passive stack will depend more on wind, a hot attic, and sun heating the pipe.

Discharge Location

To prevent radon from re-entering the house, or any other nearby buildings, make sure the vent pipe exhausts:

- a minimum of 12 inches above the surface of the roof;
- a minimum of 10 feet away from any windows and other openings in the building; and
- a minimum of 10 feet away from any windows and other openings in adjoining and adjacent buildings.

If you are routing the pipe through the same chase as the furnace flue, the vent pipe needs to exit the roof at least 10 feet away from the furnace flue. Plan to elbow the pipe away from the flue in the attic to maintain this separation above the roof. However, the additional elbows and horizontal pipe length will restrict air flow through the pipe if the system is activated. Use 45-degree joints to reduce friction.

(Photo courtesy of Greg Keene)

Use 4-inch pipe when possible.

When deciding between 3-inch and 4-inch pipe (PVC or ABS), the 3-inch pipe size is the minimum you should use. However, 4-inch pipe is the preferred choice for a couple of reasons. Field results have indicated that passive systems tend to function better with 4-inch pipe. A 4-inch pipe will also allow for a quieter system, if the system is activated.

Installation: Step 1

Installation

The type of system you install also depends on foundation type. Please refer to the relevant sections in the EPA guides which correspond to the type of foundation you will be using for:

Basement and Slab-on-Grade Construction:

Crawlspace:

Combination Foundation: Treat each foundation separately and use the appropriate techniques for each foundation segment. Pay special attention to the points at which different foundation types join, because soil-gas entry routes exist in such locations.

Installation: Step 1A

Basement and Slab-on-Grade Construction

If the house you are building has a slab-on-grade or basement foundation, the radon gas must be able to move laterally beneath the slab to the location where the vent pipe collects the gas. There are three basic methods for improving soil gas collection beneath slabs.

Gravel

This option is generally chosen in regions of the country where gravel is plentiful and economical, and where gravel is required by the building code for water drainage. A continuous 4-inch layer of ½-inch to ¾-inch clean gravel (no fines) placed beneath a slab provides a largely unrestricted path for radon to be collected. This size gravel provides a drainage layer and capillary break for moisture control.

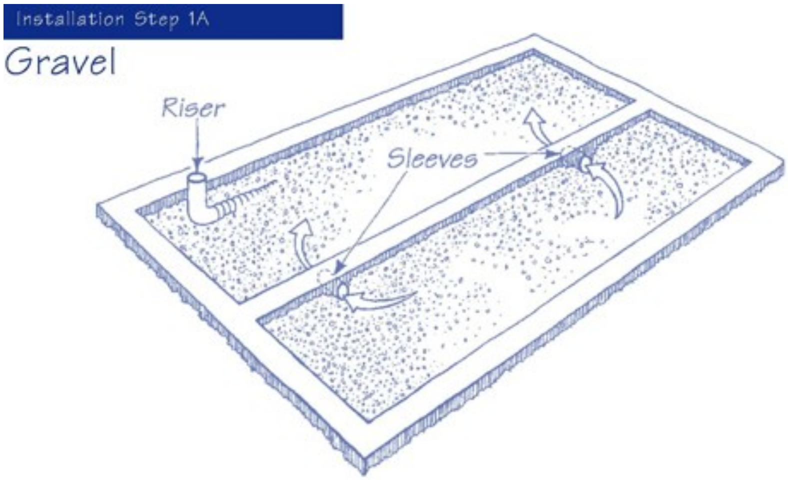
Sub-Slab Preparation

Perforated Pipe Alternative

In some regions of the country, gravel is not a feasible option, either because native soils are sufficiently permeable and gravel is not required for water drainage, or because lack of local supply makes gravel very expensive. One alternative is to use the native fills beneath the slab and lay in a loop of perforated pipe to improve soil-gas movement. This method is already employed in some homes with the use of a drain tile loop. The loop of perforated pipe works well because the soil gases need only move to the loop rather than all the way across the slab, as in the case of a single collection point.

Soil-Gas Collection Mat Alternative

In some areas, the perforated pipe option may not be feasible if the labor needed to dig a trench for the pipe loop is too expensive, or if sub-grade soils are compacted or frozen. The third option is to install interconnected strips of drainage mats (soil-gas mats) on top of the sub-grade and beneath the slab. Drain mats consist of plastic material that resembles an egg crate. Wrapped around the "egg crate" is a geotextile filter fabric that allows for the passage of air but prevents the infiltration of wet concrete. The mat can be laid directly on top of the prepared sub-grade, which should be a uniform layer of sand (native or fill), a minimum of 4 inches thick. The concrete can be poured directly over the soil-gas collection mat.



Place a uniform layer of clean aggregate under all concrete slabs or floor systems that directly contact the ground and are within the walls of the living spaces. Use a minimum 4-inch thick layer. The gravel should be about ½- to ¾-inch size. Smaller or fine gravel, or gravel that is not as uniform in size, will restrict air movement under the slab.

Grade-Beam Obstructions

A grade beam or intermediate footing is often installed beneath a slab to support a load-bearing wall, presenting a barrier to the lateral flow of air beneath the slab to the soil-gas collection point. There are a few options that can be used to avoid grade-beam obstructions to soil-gas air flow.

Option 1

Use post-and-beam construction by setting teleposts that support overhead beams on pads, rather than continuous footings.

Option 2

Provide a means for air to flow through the grade beam. This is can be done by inserting at least two 4-inch pipe sleeves between the form boards or trench, and pouring the grade beam over them. A minimum of two pipes should be installed at opposite ends of the grade beam. One pipe should be installed every 10 feet. Tape the ends so concrete does not enter the ends of the pipe while pouring the footing. Remove the tape when forms are removed and before connecting to the pipe loop, if a pipe loop is used.

Option 3

Add a second riser on the other side of the grade beam. Tie the riser into the vertical vent stack, or run a second vent stack.

Inserting Vent Pipe in Gravel

Place a 3- or 4-inch T-fitting at the location where you want the riser to extend through the slab. The size of the T or elbow will depend on the diameter of vent pipe you will be installing.

Connect a short stub (at least 8 inches) of 3- or 4-inch PVC pipe vertically into the T.

Recommended Improvement

Soil gas air flow can be somewhat restricted if the pipe is inserted into the gravel, and the gravel fills the pipe, especially if the system is later activated. To allow for airflow over a larger area, lay 3- or 4-inch perforated and corrugated pipe (recommended minimum length of 10 feet) in the gravel and connect it to the radon vent riser TEE fitting. Depending on the location of the riser, an elbow fitting may be used in place of a TEE fitting when using additional piping in the gravel. Make sure that the concrete does not plug up the pipe during pour.

Pipe Alternative

Perforated Pipe

Lay a 3- or 4-inch diameter perforated drain pipe in a trench around the foundation perimeter just inside the foundation footing. This could be the same pipe loop used for under-slab drainage. Be sure the pipe is covered by at least 1 inch of fill to keep concrete from filling perforations.

What kind of pipe works best?

Perforated and corrugated pipe is flexible, which makes it easy to lay down in a trench. The perforations also allow for good soil-gas collection. It is recommended that the pipe be covered with a geotextile cloth to prevent fines from clogging the holes.

How much pipe do I need?

Based on field work, it is recommended to lay a continuous loop of 3- or 4-inch diameter perforated pipe in the sub-grade, with the top of the pipe located a nominal 1 inch below the concrete slab, for slab areas less than 2,000 square feet. The pipe loop should be located approximately 12 inches from the inside of the exterior perimeter foundation walls. For slab areas greater than 2,000 square feet, but less than 4,000 square feet, the same configuration may be used, but the pipe size should be a minimum of 4 inches in diameter. Slab designs in excess of 4,000 square feet should have separate loops for each 2,000 to 4,000 square feet, depending on the size of pipe utilized (3-inch or 4-inch).

Install in loops rather than straight sections.

The reason for laying out the pipe in a loop is to allow for the soil gas to enter the collection pipe from two sides. Also, if the pipe is crushed at one point during the construction, the soil gas will still be drawn to the vent pipe.

Connecting Pipe Loop to Riser

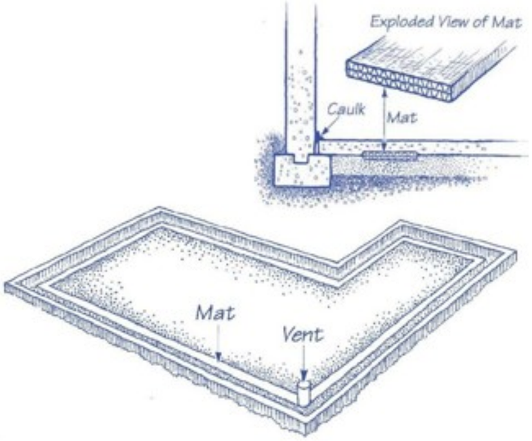
Close the loop by connecting the ends to short pipe stubs and to opposite legs of a 3- or 4-inch PVC T. Connect a short stub of 3- or 4-inch PVC pipe vertically into the T.

Installation Tip

For a more secure connection, when 3-inch corrugated pipe is used for the loop, the corrugated pipe can be inserted into a 4-inch PVC TEE by securing with sheet metal screws. When 4-inch corrugated pipe is used, 4-inch by 4-inch rubber couplings can be used to connect the perforated pipe to the solid PVC pipe stubs.

Crossing Grade Beams

In buildings where interior footings or other barriers separate the sub-grade area, the loop of pipe should penetrate or pass beneath these interior footings and barriers. Lay the loop before the grade beams are poured, or lay a length of non-perforated but corrugated pipe across the trench before pouring a grade beam. If the latter method is used, tape off the ends of the pipe before pouring the beam, remove the tape after pouring, and finish connecting the loop.



Mat Alternative

Soil-Gas Collection Mat

First, install a uniform layer of sand, a minimum of 4 inches thick. Next, place a layer of drainage matting over the sand, or lay a loop of matting inside the exterior perimeter foundation walls (no farther than a nominal 12 inches from the perimeter foundation walls).

In buildings where interior footings or other barriers separate the sub-grade area, the matting should penetrate these interior footings or barriers to form a continuous loop around the exterior perimeter.

Slabs larger than 2,000 square feet (but less than 4,000 square feet) should have an additional strip of matting that bisects the loop, forming two areas equally impacted by the two halves of the rectilinear loop. Slab designs in excess of 4,000 square feet should have successive loops of drain mat with one riser per 4,000 square feet of area.

Mat Material

Use a soil-gas collection mat or drainage mat having minimum dimensions of 1 inch in height by 12 inches wide, and a nominal cross-sectional air-flow area of 12 square inches. The mat matrix should allow for the movement of air through it, and yet be capable of supporting the weight of the concrete above it. The matrix should be covered by a geotextile filter cloth on all four sides to prevent dirt and wet concrete from entering the matrix. Repair all breaches and joints in the geotextile cloth prior to pouring the slab.

Some mats that are sold for radon reduction are only ½-inch high and have only one side covered with a geotextile cloth. If this material is used, use a minimum width of 24 inches. To keep concrete from entering the matrix, it will need to be covered with geotextile cloth. Do not cover with plastic strips because differential concrete drying can occur and cause a crack in the concrete along the edge of the plastic.

Connecting the Soil-Gas Collection Mat to the Vent Pipe

There is a special adaptor fitting that will accept the flat mat and adapt to a round vent pipe (see graphic). This type of adaptor is available from soil-gas collection mat and drainage mat suppliers, and from radon-mitigation equipment suppliers. The mat is inserted into the flat ends, and the geotextile fabric is taped to the edges to prevent wet concrete from entering the T-fitting. The top of the T is made of molded plastic to keep wet concrete out. After the concrete is poured, the top can be cut with a hacksaw, and a 4-inch riser inserted and glued or cemented into place.

Seal Cloth Tears with Duct Tape

To insure that wet concrete does not enter the mat interior, cuts and tears should be sealed with duct tape.

Making Splices

When making splices, slit the fabric of the two ends to be joined. Lay the core from one end on top of the core from the other end with a three inch overlap. Lay the fabric back over the top of the splice and thoroughly seal with duct tape to keep the wet concrete from seeping in. Drive at least two 8-inch long staples through the mat at this point, being sure to drive them through the point where the two ends overlap.

Making TEEs in Mat

If you need to connect a length of mat in the middle of another length of mat, make a TEE by: cutting back the geotextile cloth, overlapping the interior matrix, replacing the cloth, securing with nails or landscape staples, and using duct tape to seal openings in the geotextile cloth.

Securing the Mat

To keep the mat in place while the concrete is being poured, the mat should be nailed down with 8-inch landscape staples, or 60 penny nails, about every seven feet.

Installation: Step 1B

Plastic Sheeting

Laying plastic sheeting between the gas-permeable layer and the concrete slab or floor assembly serves several important purposes. The sheeting can prevent concrete from flowing down and clogging the gas-permeable layer. It can also bridge any cracks that may develop in the slab or floor assembly, thereby reducing soil-gas entry. Finally, the plastic sheeting can act as a vapor barrier to reduce moisture and other soil-gas entry (besides radon) into the home.

Prior to pouring the slab or placing the floor assembly, lay a minimum 6-mil (or 3-mil cross-laminated) polyethylene or equivalent flexible sheeting material on top of the gas-permeable layer. The sheeting should cover the entire floor area.

Separate sections of sheeting should be overlapped by at least 12 inches. Below a slab, it is not necessary to seal the joint between overlapping sheets of plastic.

Below: Thomas Dickey of the East Moline, Illinois Health Department inspects plastic sheeting installed for a group of townhomes.

The sheeting should fit closely around any pipes, wires and other penetrations.

Repair any punctures and tears in the material. Duct tape may work for small, uniform tears and holes. For larger tears, cover with an additional piece of overlapping sheeting.

Installation: Step 1C

Seal Off and Label Riser Stubs

Regardless of the sub-grade collection method used, you will have a short stub of pipe sticking up to which the vent piping system will later be attached. Care should be taken to cover the end of the pipe so that it does not become filled with concrete when the slab is poured.

Label this stub so that someone does not mistakenly think it is tied to the sewer and set a commode on it.

Support the stub, perhaps off a wall, so that it stays vertical as the wet concrete is poured.

Alternative for Combination Foundations

Some builders have found it to be more economical to tie the different foundations together into a single riser. Place a pipe to connect the sub-grade area to the crawlspace in the trench of the intervening footing prior to pouring the foundation walls. This pipe should be 4-inch perforated and corrugated pipe to prevent accumulation of water, which could block air flow. Cover with geotextile cloth. Tape the ends of the crossover to keep from getting debris in it until the pipe can be connected to the slab and crawlspace systems.

Installation: Step 1D

Lay Foundation

Foundation walls and slabs should be constructed to reduce potential radon entry routes. In general, openings in walls and slabs should be minimized, and necessary openings and joints should be sealed.

Foundation Walls

In poured concrete walls, all control joints, isolation joints, and any other joints should be caulked with an elastomeric sealant, such as polyurethane caulk.

Hollow-block masonry walls typically have cavities that can allow radon movement. To prevent this, hollow-block walls should be topped with a continuous course of solid block, or be grouted solid on the top. Alternatively, use a solid concrete beam at or above the finished ground level or a full sill plate.

Damp-proof foundation walls, and seal any penetrations through the walls.

Slab

Pour a strong slab, and take steps to control cracking. Although concrete slabs will almost inevitably crack, control joints can help the concrete to crack in planned locations. As with the foundation walls, all control joints or other joints should be sealed with polyurethane caulk to reduce radon entry.

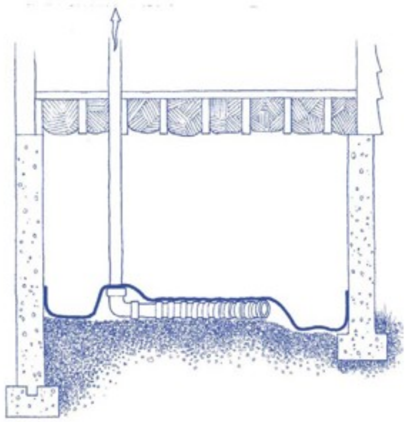
Do not deliberately puncture holes in the plastic sheeting prior to pouring the slab. Some contractors will do this to allow excess water to drain from the wet concrete. Putting holes in the plastic sheeting decreases (but does not eliminate) its effectiveness as a soil-gas retarder. It is preferable to use concrete with a lower water-to-cement ratio (low-slump concrete).

Similarly, some contractors will put a layer of sand on top of the polyethylene, both to protect it and to absorb water from the concrete mix. This practice is not recommended. The sand may become wet from the concrete or rising groundwater, and would have to dry to the interior through the concrete. The presence of the polyethylene sheeting during this drying process may cause moisture problems above the slab.

Trap any condensate or floor drains which pass through the slab, or route them through non-perforated pipe to daylight. Mechanical traps should be used rather than “wet” traps, which can dry out.

Sump pits which are open to the soil or fed by drain tile loops should be covered with a gasketed lid.

Installation: Steps 2 & 3



Installation: Step 2

Crawlspace Construction

Crawlspaces are best treated by covering the entire crawlspace floor with plastic sheeting, laying a perforated collection pipe beneath the plastic sheeting, and connecting the pipe to the radon vent riser.

Crawlspaces should be constructed consistent with applicable building codes.

Access doors and other openings and penetrations between basements and adjoining crawlspaces should be closed, gasketed or otherwise sealed with materials that prevent air leakage.

Location of Riser

The riser can be located anywhere in the crawlspace. It does not need to be in the center, so plan on placing it anywhere in the crawlspace that will be convenient for crawlspace access and for routing the pipe up through the house.

Install Pipe

Lay a length of 3- or 4-inch diameter corrugated and perforated pipe, or a strip of geotextile drain matting on the soil at the location where you will run the radon vent pipe up.

Install Plastic Sheeting

Clear the crawlspace area of objects which may puncture the plastic sheeting.

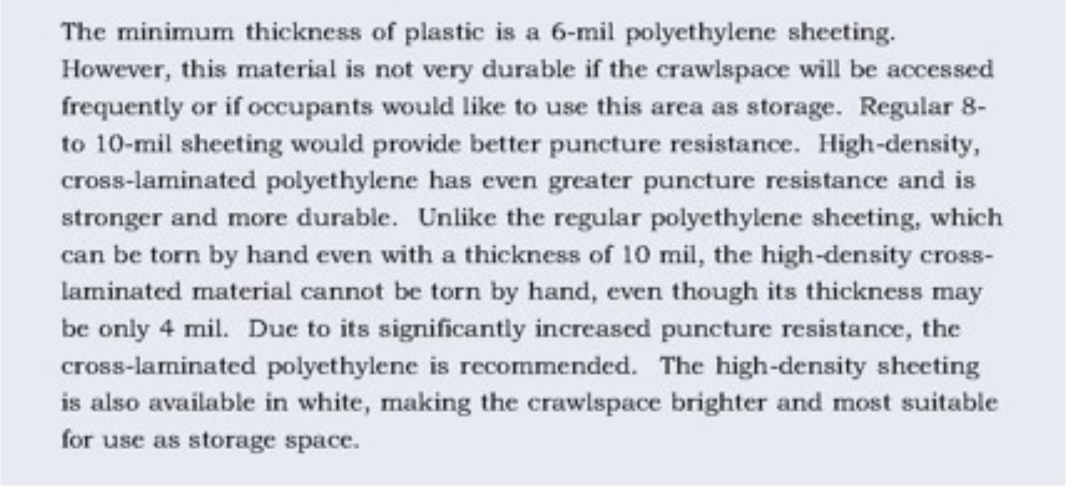
Lay a continuous layer of minimum 6-mil (or 3-mil cross-laminated) polyethylene sheeting (or equivalent membrane material) to cover the entire crawlspace area.

Amount of Plastic

Plan on using enough plastic to allow overlap of seams by 12 inches. The edges should also be brought up on the foundation walls about 12 inches to allow for proper adhesion. It is critical to allow for enough excess plastic so that if a vacuum is drawn underneath the plastic, the plastic can conform to the surface of the crawlspace floor (like vacuum packaging). If the amount of excess plastic is insufficient, the plastic may stretch over a depression in the dirt like a trampoline.

Special Precautions

It may be necessary to take special precautions to ensure that the plastic sheeting will not be damaged after occupancy. In high-traffic areas, the polyethylene should be overlain by heavier material along expected traffic routes. Various materials have been used for this purpose, including roofing felt, EPDM rubberized roofing membrane, and drainage mat. Also, if there may be foot traffic over the entire crawlspace floor, or if the crawlspace has very irregular floors, such as sharp, protruding rocks, it may be advisable to use thicker cross-laminated plastic sheeting, or to lay a heavier material underneath the polyethylene between the sheeting and the crawlspace floor.



The minimum thickness of plastic is a 6-mil polyethylene sheeting. However, this material is not very durable if the crawlspace will be accessed frequently or if occupants would like to use this area as storage. Regular 8- to 10-mil sheeting would provide better puncture resistance. High-density, cross-laminated polyethylene has even greater puncture resistance and is stronger and more durable. Unlike the regular polyethylene sheeting, which can be torn by hand even with a thickness of 10 mil, the high-density cross-laminated material cannot be torn by hand, even though its thickness may be only 4 mil. Due to its significantly increased puncture resistance, the cross-laminated polyethylene is recommended. The high-density sheeting is also available in white, making the crawlspace brighter and most suitable for use as storage space.

Optional Improvement: Sealing Seams and Edges of Plastic Sheeting

Sealing the Sheeting

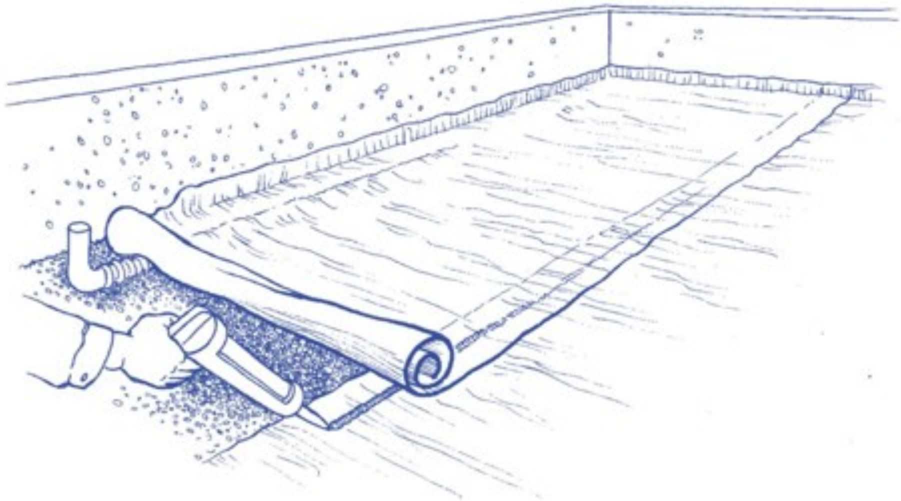
Although not required in current radon-resistant construction building codes, increasing the air-tightness of the seams in the plastic sheeting may enhance the system's effectiveness and integrity. Sealing should be sufficiently durable to withstand anticipated traffic through the crawlspace. To effectively seal the plastic sheeting, use a ½-inch-wide bead of caulk.

Type of Caulk

Polyurethane caulk will provide some adhesion to the polyethylene sheeting. However, acoustical sealant, butyl rubber, or butyl acrylic caulks form a more durable bond with the plastic. Field work suggests that other proprietary sealants are also effective, such as Proflex by GeoCel.

Sealing Seams

Seams between adjoining sheets of sheeting are usually sealed by applying a continuous bead of sealant between the sheets in the 12-inch strip where the sheets overlap. Press the overlapping sheets together firmly.



Sealing Edges and Seams

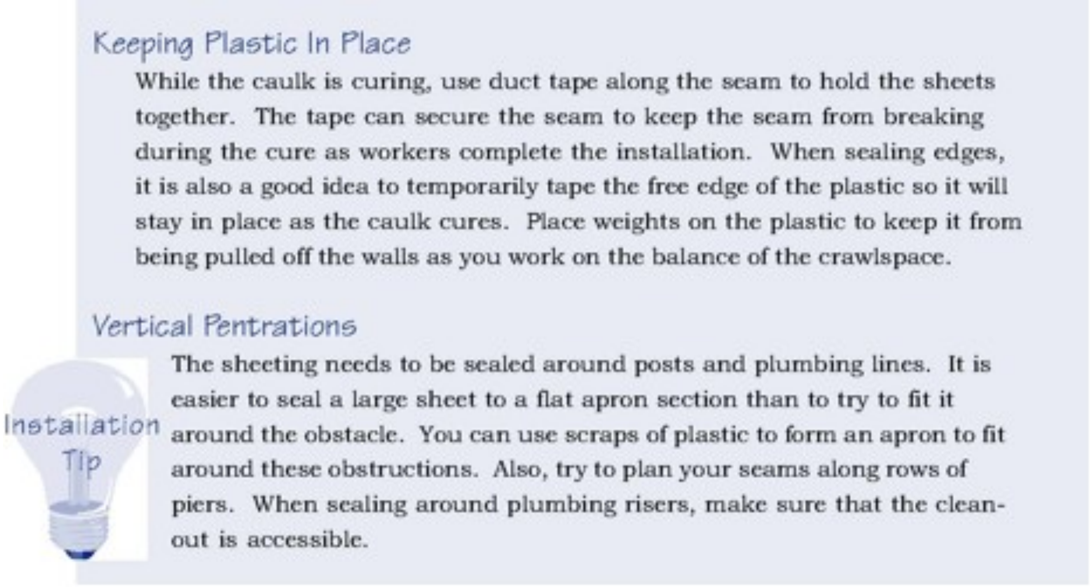
Brush the walls with a wire brush at 6 to 12 inches above the crawlspace floor to remove any dirt and loose deposits.

Make sure the sheeting lays flat on the crawlspace floor, right up to the wall. Leave several inches of slack on the vertical section of the plastic rising up the wall to help prevent the plastic from pulling on the seam due to foot traffic, or by the system itself when it is functioning.

Plan on using one 11-ounce tube of caulk to attach an 8-foot length of plastic to the wall.

Secure plastic to the wall at 6 to 12 inches above the crawlspace floor with a ½-inch-wide bead of acoustical sealant or butyl caulk along the wall.

For a more durable connection, consider using mechanical fasteners, such as strapping, to hold the plastic to the wall. If there is an obstruction to the wall within 6 to 12 inches of the floor, such as a crawlspace access door, trim the sheeting to pass beneath the obstruction, and caulk the sheeting to the wall around the obstruction. At corners, cut and tuck plastic sheeting neatly, and make sure that the sealing is also airtight.



Keeping Plastic In Place

While the caulk is curing, use duct tape along the seam to hold the sheets together. The tape can secure the seam to keep the seam from breaking during the cure as workers complete the installation. When sealing edges, it is also a good idea to temporarily tape the free edge of the plastic so it will stay in place as the caulk cures. Place weights on the plastic to keep it from being pulled off the walls as you work on the balance of the crawlspace.

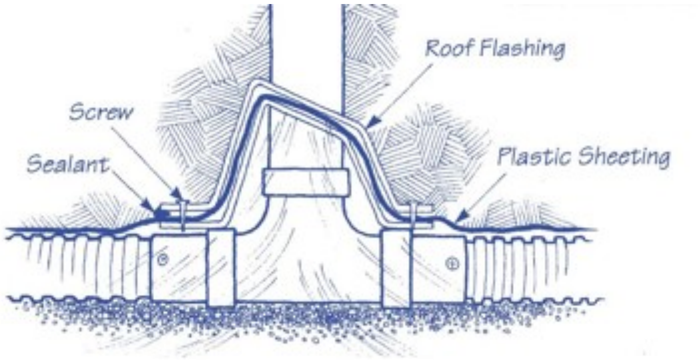
Vertical Pentrations

The sheeting needs to be sealed around posts and plumbing lines. It is easier to seal a large sheet to a flat apron section than to try to fit it around the obstacle. You can use scraps of plastic to form an apron to fit around these obstructions. Also, try to plan your seams along rows of piers. When sealing around plumbing risers, make sure that the clean-out is accessible.

Riser Installation

The vent pipe needs to be connected to the perforated pipe beneath the plastic in a manner that prevents air leakage. The plastic sheeting can be wrapped around the vent pipe and taped to the pipe securely.

Another way to prevent air leakage around the joint is to use two roof-flashing hoods. One roof flashing goes below the plastic and one is placed above the plastic to provide a flat area to which the plastic can be sealed. The riser is sealed by the rubber grommet on the roof flashing. The two roof flashings are then secured by sheet-metal screws. Depending on the location of the riser, there may be either a PVC T or an elbow beneath the plastic that has a short 4-inch stub of pipe to which the corrugated and perforated pipe will be connected.



Label Riser and Plastic

It is a very good idea to label the riser within the crawlspace so it is not confused with any other plumbing. It is also a good idea to label the plastic to state that the plastic should not be removed and, if cut, it should be patched or replaced.

After home construction is completed, inspect the sheeting for damage, and repair as necessary.

Installation: Step 3

Seal Openings

After pouring the slab or placing the floor assembly, seal major openings in the slab to retard soil-gas entry through openings in the slab or floor assembly.

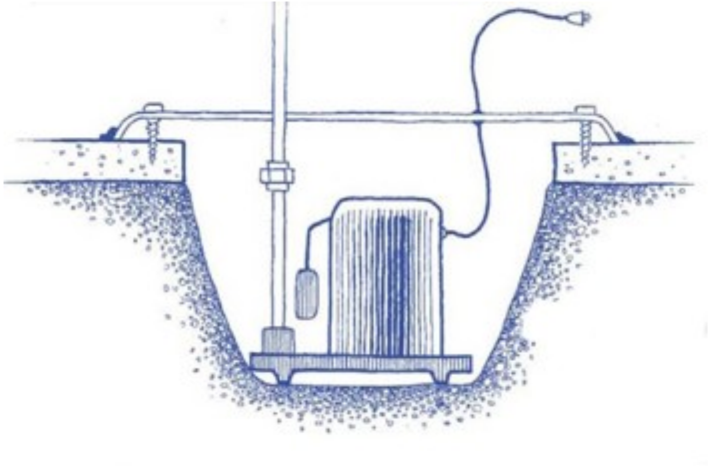
Use materials that provide a permanent, airtight seal, such as non-shrink mortar, grouts, expanding foam, or similar materials. When caulking slab openings, it is best to utilize a polyurethane caulk, which has excellent adhesion characteristics for concrete. The following are some examples of locations to be caulked after the concrete slab has cured and before framing is installed.

Seal floor-to-wall-joints.

Floor-to-wall joints are critical places to seal. Brush debris away from the joint before applying caulk. Apply enough caulk so that when smoothed with a piece of cardboard cut in a convex form, the caulk will come out onto the floor and up on the wall about 3/8-inch. For a cold joint type, an 11-ounce tube of caulk will cover approximately 12 feet. For an expansion-type, the same tube of caulk will cover 8 feet.

Seal control joints.

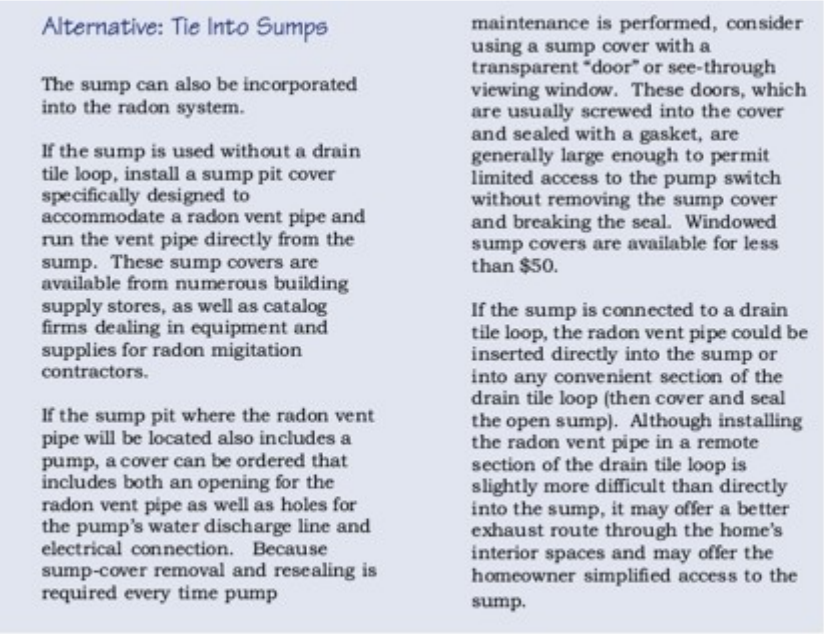
Control joints in the concrete slab, whether they are saw-cut or made with grooving tools, should be cleaned and filled with caulk. Even if they are not cracked initially, they will likely develop cracks in the future, and caulking them before the floor finishes are in place makes sense. A gun-grade polyurethane or flowable polyurethane can be used. This seal does not interfere with the expansion of the control joint, but does block radon entry.



Seal open sumps.

An open sump may allow radon into the house from beneath the entire house foundation. Make sure to cover and seal the sump. The sump cover, which must be removable to allow for regular maintenance and inspection of the sump pump, is usually sealed by bolting it directly to the slab or sump-liner lip, and made airtight through the use of a gasket or silicone-caulk seal.

If the sump is intended as a floor drain, make sure the lid is equipped with a trapped drain to handle surface water on the slab.



Alternative: Tie Into Sumps

The sump can also be incorporated into the radon system.

If the sump is used without a drain tile loop, install a sump pit cover specifically designed to accommodate a radon vent pipe and run the vent pipe directly from the sump. These sump covers are available from numerous building supply stores, as well as catalog firms dealing in equipment and supplies for radon migitation contractors.

If the sump pit where the radon vent pipe will be located also includes a pump, a cover can be ordered that includes both an opening for the radon vent pipe as well as holes for the pump's water discharge line and electrical connection. Because sump-cover removal and resealing is required every time pump maintenance is performed, consider using a sump cover with a transparent "door" or see-through viewing window. These doors, which are usually screwed into the cover and sealed with a gasket, are generally large enough to permit limited access to the pump switch without removing the sump cover and breaking the seal. Windowed sump covers are available for less than $50.

If the sump is connected to a drain tile loop, the radon vent pipe could be inserted directly into the sump or into any convenient section of the drain tile loop (then cover and seal the open sump). Although installing the radon vent pipe in a remote section of the drain tile loop is slightly more difficult than directly into the sump, it may offer a better exhaust route through the home's interior spaces and may offer the homeowner simplified access to the sump.

Other Places to Seal the Slab and Foundation:

Use a polyurethane caulk around locations where plumbing and other utility service lines pass through slab and below-grade walls.

Use a full sill plate over the upper row of block walls in basements, or make the upper row solid block.

Seal hollow-block foundation walls at the top. Use at least one continuous course of solid masonry, one course of masonry-grouted solid, or a poured concrete beam at or above the finished ground surface. Where a brick veneer or other masonry ledge is installed, the course immediately below that ledge should be sealed.

Caulk joints, cracks and other openings around all penetrations of both exterior and interior surfaces of masonry block or wood foundation walls below the ground surface. Penetrations of poured concrete walls should also be sealed on the exterior surface. This includes sealing wall-tie penetrations.

Other Considerations

Placing air-handling ducts in or beneath a concrete slab floor, or in other areas below grade, is not recommended unless the air-handling system is designed to maintain continuous positive pressure within the ductwork. This is to prevent radon from being drawn into the ductwork and then distributed throughout the house.

If ductwork does pass through a crawlspace or beneath a slab, it should be of seamless material or sealed tightly. Where joints in the ductwork are unavoidable, seal to prevent air leakage.

Placing air-handling units in crawlspaces, or in other areas below grade and exposed to soil gas, is not recommended. However, if they are installed in these areas, make sure that they are designed or sealed in a durable manner to prevent air surrounding the unit from being drawn into the unit.

Avoid using floor drains and air-conditioning condensate drains which discharge directly into the soil below the slab or into the crawlspace. If installed, these drains should be routed through solid pipe to daylight, or through a trap approved for use in floor drains. Mechanical traps should be used rather than “wet” traps, which can dry out.

The bottom of channel-type (French) drains should be sealed with a backer rod and caulking. Water drainage should be directed to a suitable drain.

Installation: Step 4

Install Vent Pipe

Be sure to run the pipe up through the roof before the roofer installs the roof system. This will allow the roofer to properly flash around the pipe. Avoid angles in the pipe, if possible, to increase air flow through the vent pipe and maximize radon reduction.

Type of Pipe

Use Schedule 40 PVC or ABS pipe. The pipe does not need to be pressure-rated, so a pipe rated for drain, waste and vent (DWV) applications will be the most cost-effective. Do not use a pipe thinner than Schedule 40. Do not use sheet-metal ductwork due to the likelihood of breakage or leaks at joints.

All joints should be primed and glued in a manner similar to indoor plumbing.

Do Not Trap Pipe

Plan your pipe routing to minimize the length of pipe and fittings and to contain no traps.

Do not install traps, intentional or accidental, in the pipe that will collect water and restrict or stop air movement. Air from the soil will have some moisture in it. As this air moves through sections of the vent pipe located in cold spaces, such as an attic, some moisture can condense. It is important that this water can drain back down to the soil. Insulating the pipe in the attic will reduce moisture condensation and maintain upward thermal draft in the pipe as it passes through unconditioned space.

Piping should also slope back to the suction pipe at a minimum angle of 1/8-inch per foot.

Use either PVC or ABS pipe, not both. The two types of pipe require different cleaners and cements.

Allow for Future Installation of Fan

Although passive radon systems are effective for reducing radon levels by an average of about 50%, it is always a good idea to plan ahead in case adding an in-line fan is needed for further radon reduction to bring indoor levels below 4 pCi/L, or in case the future occupant wants to lower the radon levels as much as possible.

During installation of the vent pipe, consider these criteria for locating a fan in the future:

- it cannot be inside the living space of the house;
- it cannot be in the crawlspace beneath the home;
- it is most often located in attics or garages (unless there is living space above the

garage);
- it requires a 30-inch vertical run of pipe for installation; and
- it requires an unswitched electrical junction box.

Maintain Fire-Resistance Rating of Walls and Ceilings

If you route your vent pipe through the wall between the house and the garage, you will need to put a fire-barrier around the pipe (on the inside of the garage) to maintain the integrity of the wall. Install a fire barrier with a rating equal to the wall.

Note that some ceilings are also fire-rated ceilings and will require fire barriers, as well.

Label the Radon Vent Pipe

(Photo courtesy of Dennis R. Goudreau of DRG Inspections)

Label the exposed portions of the pipe so that, during construction, other people will be aware that the pipe is not part of the sewer system. It is recommended that the radon vent system be labeled in a conspicuous location on each floor level. Also, occupants and future occupants will know that it is part of a "radon vent system."

Places to label include:

- where the riser exits the slab;
- where the pipe is seen in closets; and
- at pipe run through the attic.

Recommended Improvement:

Screen on Discharge

It is a good idea to put a ¼-inch mesh screen on the discharge to keep birds from nesting in the pipe.

Rain caps can reduce radon flow and can force radon (if the system is activated) back down toward the openings into the living spaces. In most areas, they are not needed. For very high rainfall areas, use alternative special devices which prevent large amounts of rain from entering the system while still allowing the air to vent up and away from the building. These devices are available through radon mitigation supply distributors. Another design option, which is more commonly used with commercial applications than with residential installations, is an annular rain cap, pictured here.

Installation Tip

Support the pipe

Support the pipe using plumbers strapping at least once every 6 feet in horizontal runs and once every 8 feet in vertical runs.

Insulate the pipe

In cold climates, insulate the pipe where the pipe is routed through unheated spaces, such as the attic.

Installation: Step 5

Seal Ducts and Air-Handling Units

HVAC systems should be carefully designed, installed and operated to avoid depressurization of basements and other areas in contact with the soil. Ideally, ductwork should remain in the conditioned space of the home. It is very important to seal joints in air ducts and plenums passing through unconditioned spaces, such as attics, crawlspaces and garages.

In addition to avoiding problems with unwanted air distribution, sealing ducts can save energy, make homes more comfortable, and lower heating and cooling costs.

Installation: Step 6

Install an Electrical Junction Box for Future Installation of a Fan

Although, in most cases, the passive system alone is enough to keep radon levels below 4 pCi/L, occasionally, the homeowner will want or need to activate the system by adding a fan to further lower radon levels in the home. To prepare for this possibility, pre-wire the attic when installing a passive system. An unswitched electrical junction box should be installed in the attic or garage within 6 feet of the vent pipe.

For attics with interior access, many building codes require a light in the attic. In this case, if the junction box for the light is located at an appropriate location for the fan, another junction box will not be necessary, and wiring the additional outlet will be simple. The fan outlet does not require a dedicated circuit; it may branch off the existing circuit for the light.

Installation: Step 7

Post-Occupancy Testing

The figure above illustrates one example of a radon-testing device. There are many other types of radon testing devices available.

Testing is simple and easy.

After the home is complete and occupied, it should be tested to determine whether the passive system needs to be activated. You should recommend to the homebuyer that they test the home after they move in, and activate the system if the radon level is at or above 4 pCi/L.

Some builders installing passive systems are testing the homes they build and activating the passive radon systems if radon levels are at or above 4 pCi/L. In all cases, you should advise the homeowners to re-test sometime in the future to confirm that radon levels remain low.

Obtaining a Test Kit

Radon test kits can often be obtained at a local hardware store. There are many kinds of low-cost, do-it-yourself radon test kits you can get through the mail off the Internet, as well as at hardware stores and other retail outlets. Coupons for short-term and long-term radon test kits are also available from the National Safety Council.

Types of Radon Tests

Short-Term Tests

The quickest way to test is with short-term tests. Short-term tests remain in the home for two days to 90 days, depending on the device. Because radon levels tend to vary from day to day and season to season, a short-term test is less likely than a long-term test to give the home’s year-round average radon level. If you or the homeowner need results quickly, a short-term test followed by a second short-term test may be used, or two short-term tests may be performed simultaneously.

Long-Term Tests

Long-term tests remain in a home for more than 90 days. A long-term test will give a reading that is more likely to give a home’s year-round average radon level than a short-term test.

How to Use a Test Kit

Follow the test kit's instructions. For short-term tests, close all windows and outside doors, and keep them closed throughout the test, except for normal entry and exit. If you are doing a short-term test lasting just two or three days, be sure to also close windows and outside doors at least 12 hours before beginning the test. Do not conduct short-term tests lasting just two or three days during unusually severe storms or periods of unusually high winds, because these conditions can affect the test results.

The test kit should be placed in the lowest lived-in level of the home (for example, the basement) if it is to be frequently used; otherwise, place the kit on the first floor. It should be put in a room that is used regularly, such as a living room, play room, den or bedroom, but not the kitchen or bathroom. Place the kit at least 20 inches above the floor in a location where it won't be disturbed, and away from drafts, high heat, high humidity and exterior walls. Leave the kit in place for as long as specified in the device's instructions. Once the test is completed, re-seal the package and send it to the lab specified on the package right away for analysis. You should receive test results within a few weeks.

Steps for Testing

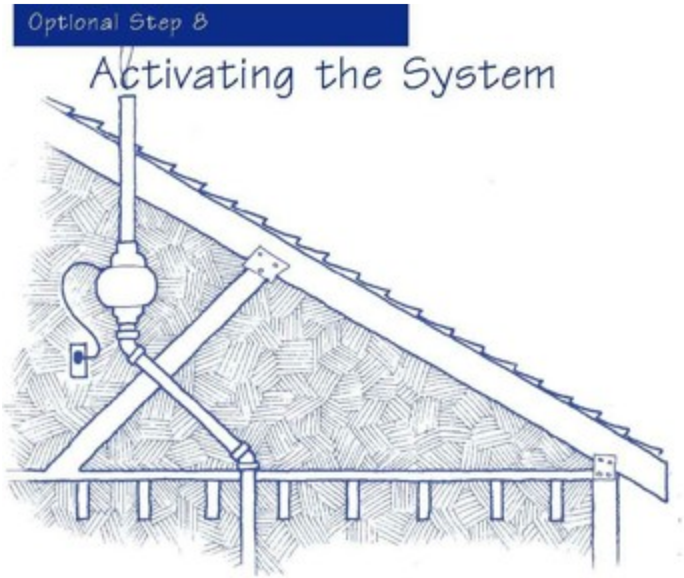
If you are conducting the radon test prior to the sale of the home, you will likely want to get results as quickly as possible by following these testing steps:

Step 1
Conduct a short-term test for at least 48 hours. After the first test has been completed, conduct a follow-up short-term test for at least 48 hours.

Alternatively, take two short-term tests at the same time in the same location for at least 48 hours.

Step 2
If the average of the two tests is 4 pCi/L or more, activate the passive radon reduction system.

Optional Step 8: Activating the System



This section provides basic guidelines if you decide to install an in-line fan to activate the system. Some states require that in-line fans for radon reduction be installed by a certified radon mitigation contractor. Call your state radon contact for a list of certified contractors (see Appendix D for a list of phone numbers).

Location

The fan and all positively-pressurized portions of the vent pipe should be located outside habitable space in the building.

The ideal location is in the attic or, perhaps, in an attached garage, where the fan housing and vent pipe can be sheltered from the elements, yet be outside the building's conditioned spaces. Sheltering the fan maximizes its efficiency and life-expectancy by minimizing exposure to extreme temperatures and moisture. Placement in a non-conditioned space prevents the accidental pumping of radon directly into a home, should a leak occur in the fan housing or at the vent-pipe joints.

Building designs that call for a flat roof or cathedral ceiling, or some other design feature that makes the attic installation unworkable, may necessitate placing the fan on the roof or in an exterior venting pipe.

Appropriate Fan Locations:
- unoccupied attic;
- outside the house; or
- in the garage.

Inappropriate Fan Locations:
- in the crawlspace;
- in the basement; and
- in an occupied attic.

Type of Fan

Although various types of fans are suitable for this purpose, the most commonly-used fans are centrifugal fans, often referred to as “in-line,” “tubular” or “tube” fans.

The size and air-movement capacity of the vent pipe fan should be sufficient to maintain a pressure field beneath the slab or crawlspace membrane that is lower than the ambient pressure above the slab or membrane. Most contractors have found 90-watt in-line fans to be adequate for most home styles, locations and sizes. You can also look for a fan capable of moving 100 cubic feet of air per minute at 1 inch of water column, which should be sufficient for most applications.

How to Install

Install the fan in a vertical run of the vent pipe. This will prevent outdoor precipitation from accumulating in the fan and fan's housing. Do not use an angled portion of the pipe.

To reduce vibrations and noise transmission, use flexible, airtight couplings instead of rigid couplings. Secure couplings tightly to the fan using circular hose clamps.

In regions with prolonged or extreme cold, both fans and attic vent pipes should be insulated to reduce condensation and the possibility of vent exhaust freeze-up. Freeze-up is most often found in regions with extremely cold winters, and in systems having high air-flow rates, as well as high moisture levels in the sub-slab soil.

Install a System-Failure Warning Device

A system-failure warning device should be used to alert occupants to any malfunction of the system or drop in its suction flows. Types of warning devices include pressure gauges, manometers, and visual or audible alarms. Unless the indicator is integral to the fan's power supply, the audible or visual alarm should be connected to a separate circuit so that it will activate if power to the fan is interrupted.

Sold: Working with Home Buyers
Get an Edge on the Market

All home buyers want to know that they are buying a quality home. There are a few simple things you can do to educate your home buyers that radon-resistant features make sense both from a health standpoint and an investment standpoint.

The activities suggested here are inexpensive and easy to implement. They will make your company stand apart from the other builders in your area by demonstrating your commitment to customer satisfaction and healthy homes.

Make the Radon System a Custom Feature

Prominently list the availability of a radon system as a custom feature in all your sales, promotional and advertising materials. Emphasize the desirability of a radon system in the same way you would hardwood floors, 9-foot ceilings, upgraded appliances, master bedroom suites, etc. These are all features that enhance the value of the house and make it more enjoyable to live in. Stress the economic advantage of adding a radon system while the home is being built, thereby avoiding a more expensive, retrofit installation.

Include a Brochure on Radon Systems in All Sales Information

Provide a pamphlet on the basics of a radon system in all sales handout materials. You might include radon maps for your specific geographical area, as well as easy-to-understand information on why a radon system is important, how it operates, the costs involved, and other questions that home buyers might ask when considering a radon system. A number of useful consumer-oriented publications are available and can be ordered in bulk, such as the brochure *Buying a New Home? How to Protect Your Family from Radon,* as well as radon maps. See Appendix C for more information.

Educate Your Sales Team

All sales associates should be as knowledgeable and positive about the value of a radon system as they are about every other feature you offer. Have them stress not only the amenities you provide, but also the solid construction techniques you offer, including a radon system. Help your sales staff understand the radon system and how it works so that they can explain its benefits to sales prospects. An on-site review of the system by a construction supervisor is an excellent way to start. In addition, have your sales personnel become familiar with your radon information materials, and ask them to go over these materials with prospective home buyers.

Use Your Model Home as a Promotional Tool

Install a radon system in your model home. Advertise it as another "must-have" feature that is desired by many new home buyers. Consumers expect a builder to include the “latest and greatest” product offerings in the model home; make a radon system one of those special elements, and promote it accordingly.

Post Signs

Highlight the value of a radon system by placing an explanatory sign in the basement or near the crawlspace area of your model home. This will make prospective home buyers aware of the system’s availability, function and benefits. As you prepare to install radon systems in your new homes, increase the interest of drive-by prospects by placing a “Radon System Being Installed” placard on the site.

Generate Buyer Awareness

To increase home buyers’ awareness of radon, consider the following **promotional activities**:

Print Media

Prepare a news release on the availability of your new homes. This can include a complete discussion of features, size, location, floor plans, etc. Prominently mention that you are the “only builder in your area” to offer radon systems (if this is appropriate and accurate). Explain why you have chosen to provide this important feature to members of your community.

Web Site Promotion

More consumers are relying on the Internet for information about buying a new home. Develop a special Web page on radon systems to integrate with your existing Web site.

Make a Name for Yourself

One of the most effective ways of marketing radon systems is to establish yourself as a knowledgeable builder concerned about radon, and equipped to do something about it. By providing consumers with general information about radon and radon systems, you will establish yourself as a socially responsible builder who is attentive to the health and well-being of the community's families. This reputation is likely to give you an edge over your competitors by making your homes more desirable to today’s health-conscious consumers.

The following **marketing activities** are simple ways to build your reputation in the community as a knowledgeable builder of quality, radon-resistant homes:

Alert Local Realtors

Many realtors are familiar with the radon issue as it relates to existing homes. Consider holding a seminar or informal gathering of local realtors to discuss the importance of including radon systems in new construction. Let them know that you are a builder who offers such systems in your houses, and that you are willing to work with any client they may have who is concerned about the possibility of radon in their home.

Consider a Public Service Announcement

A radio public service announcement about radon's health effects and the value of a radon system in protecting people is a relatively inexpensive, but highly effective, means of increasing community awareness about radon and expanding the demand for radon systems. Your 30-second announcement can conclude by identifying your company as the sponsor of the information and a builder who is interested in protecting people from radon.

Offer Community Education Materials

Brief informational brochures and fact sheets on radon and radon systems can be developed for free distribution in grocery stores, schools, libraries, banks, community centers, etc. These materials can help increase awareness of radon's impact on the community and the value of radon systems in reducing radon exposure. Display your company's name and logo on all educational materials you distribute.

Become a Television Star

Community television programs on "moving up" or "buying your dream home" are always of interest to consumers. Use these programs to promote radon systems. Arrange to appear on a community-based television program and use the opportunity to talk about why you offer radon systems in your homes. Local cable stations are especially good outlets for this type of activity.

What to Tell Home Buyers

Once you have sold the house, there are a few key items to tell your home buyer about the radon features that you have installed in their new home.

What Features Have Been Installed?

Let your home buyer know whether you have installed a passive radon system, an active radon system, or a rough-in for a sub-slab depressurization system. Explain what the features are designed to do.

Passive System

If you have installed a passive system, let the home buyer know that they should test their home for radon. Tell the homeowner that if the tests indicate a radon level at or above the action level of 4 pCi/L, it is recommended that they hire a radon mitigation contractor to activate the system, or you could offer to activate the system.

Active System

If you have installed an active system, recommend to the home buyer that they conduct a radon test after they have occupied the home. Let him/her know where the system-failure warning device is located, and inform them that if the device indicates a system failure, the fan is no longer working to vent radon out of the home. The homeowner should then contact a radon mitigation contractor to check the system.

Rough-In for Sub-Slab Depressurization

If you have installed a rough-in for sub-slab depressurization, it is very important for the home buyer to be aware that the house has not been equipped with a functioning radon system. Explain that the home would need to be tested for radon. If the tests indicate a radon level at or above the action level of 4 pCi/L, it is highly recommended that the s/he hire a radon mitigation contractor to install the rest of the radon system.

Does This Mean This House Has High Radon?

Some home buyers may be concerned that you have installed the radon system because the house has high radon levels. Simply explain that there is no way of knowing whether a home has high radon until the home is completed and a radon test is performed. Tell them that a passive system will reduce radon levels on average by about 50%. Also tell them that the home should be tested, and that the system should be activated if further reductions are desired, or if radon levels are at or above 4 pCi/L. If the radon features had not been installed, it could cost $800 to $2,500 to fix a radon problem after construction has been completed.

How Does the Home Buyer Test for Radon?

The following are recommended steps for the home buyer to test for radon once they have moved into the home. These steps are slightly different from the steps outlined for builders because the homeowner has more time to perform long-term tests.

Step 1

Conduct a short-term test for at least 48 hours. If the result is 4 pCi/L or higher, take a follow-up test (Step 2) to be sure.

Step 2

Follow up with either a long-term test or a second short-term test. For a better understanding of the year-round average radon level, take a long-term test. For faster results, take a second short-term test.

Step 3

If you followed up with a long-term test, activate the passive system if the long-term test result is 4 pCi/L or higher. If you followed up with a second short-term test, consider activating the system if the average of the two short-term tests is 4 pCi/L or higher. The higher the short-term results, the more certain you can be that you should activate a passive radon system. Once a system has been activated, the radon testing should be repeated with a short-term test (preferably between 24 hours and 30 days after activation).

Hopefully, you now see the benefit of building homes with radon-resistant features, and you are familiar with the techniques for installing the features.

To follow is additional information which you may find useful, including architectural drawings, and information about how to order a video by the National Home Builders Association to view the features being installed.

Become one of the many builders nationwide who are helping to reduce the risks of radon!

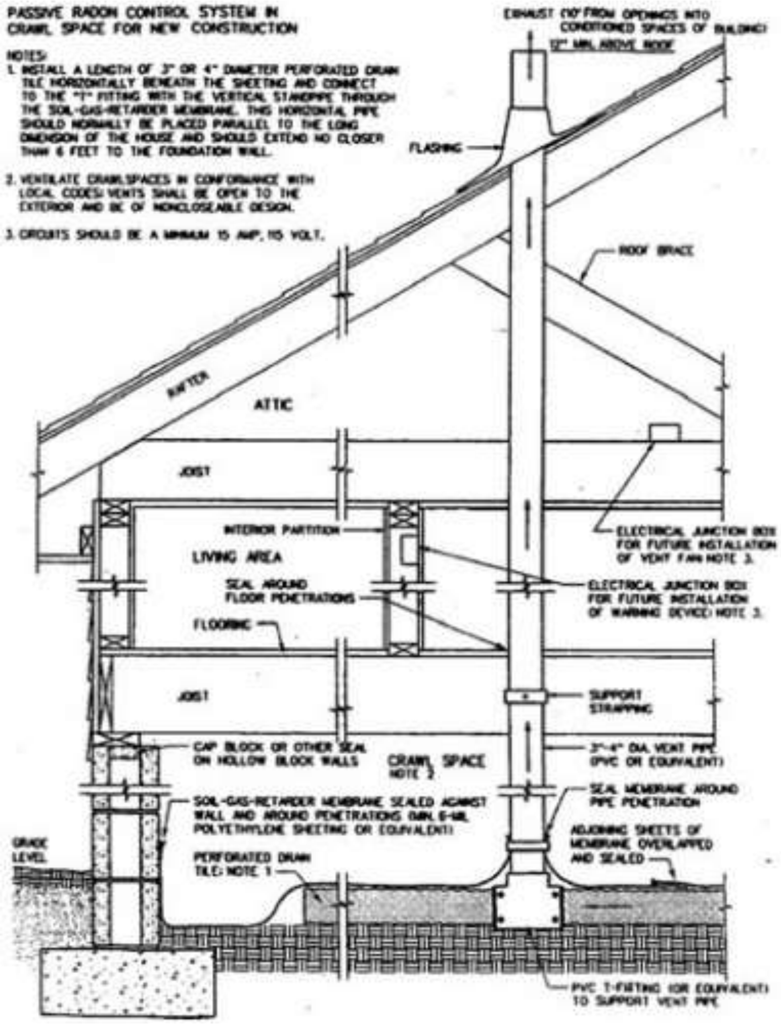
Appendix A: Architectural Drawings

The following are three architectural drawings of the passive, active and crawlspace radon-reduction systems to help you visualize the complete radon features as they should be installed.

These drawing are available free in a larger format through the National Service Center for Environmental Publications as EPA Document 402-F-95-012. They are also available electronically on the EPA's Web site as PDF files and as CAD drawings. For more information, see Appendix C.

Passive Sub-Slab Depressurization System

Used for basement and slab-on-grade construction:



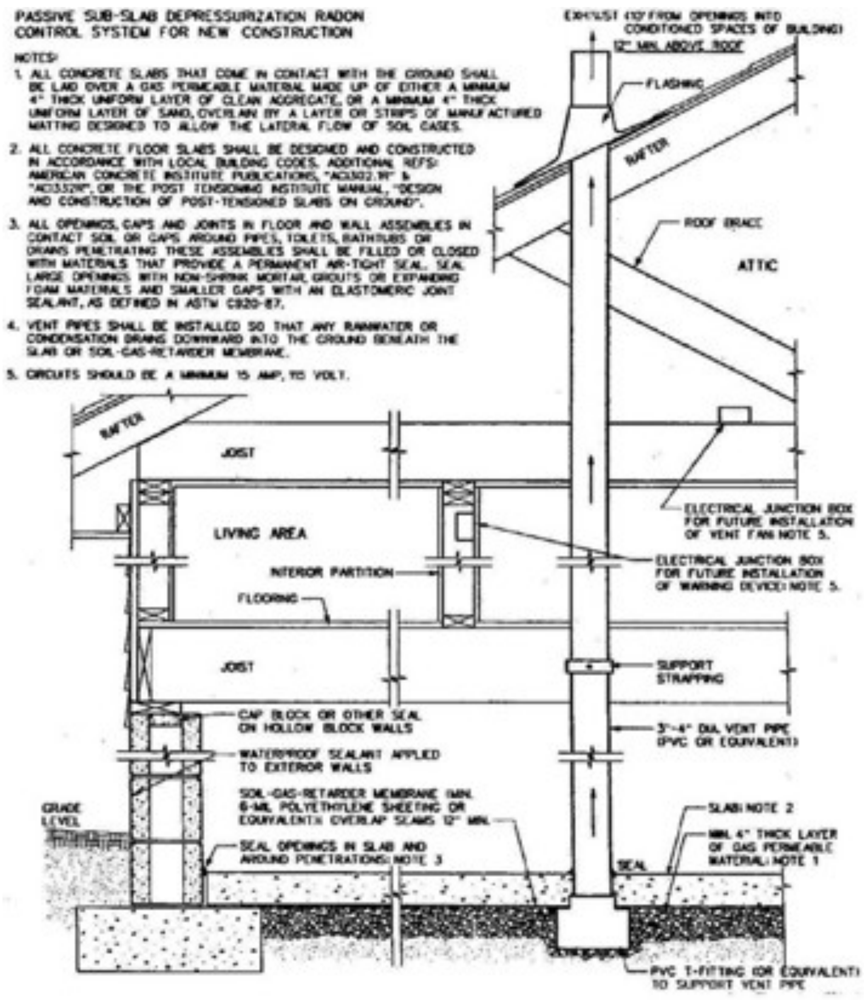
PASSIVE RADON CONTROL SYSTEM IN
CRAWL SPACE FOR NEW CONSTRUCTION

NOTES:

1. INSTALL A LENGTH OF 3" OR 4" DIAMETER PERFORATED DRAIN TILE HORIZONTALLY BENEATH THE SHEETING AND CONNECT TO THE "T" FITTING WITH THE VERTICAL STANDPIPE THROUGH THE SOIL-GAS-RETARDER MEMBRANE. THIS HORIZONTAL PIPE SHOULD NORMALLY BE PLACED PARALLEL TO THE LONG DIMENSION OF THE HOUSE AND SHOULD EXTEND NO CLOSER THAN 6 FEET TO THE FOUNDATION WALL.
2. VENTILATE CRAWLSPACES IN CONFORMANCE WITH LOCAL CODES; VENTS SHALL BE OPEN TO THE EXTERIOR AND BE OF NONCLOSEABLE DESIGN.
3. CIRCUITS SHOULD BE A MINIMUM 15 AMP, 115 VOLT.

Passive Sub-Membrane Depressurization System

Used for crawlspace construction:



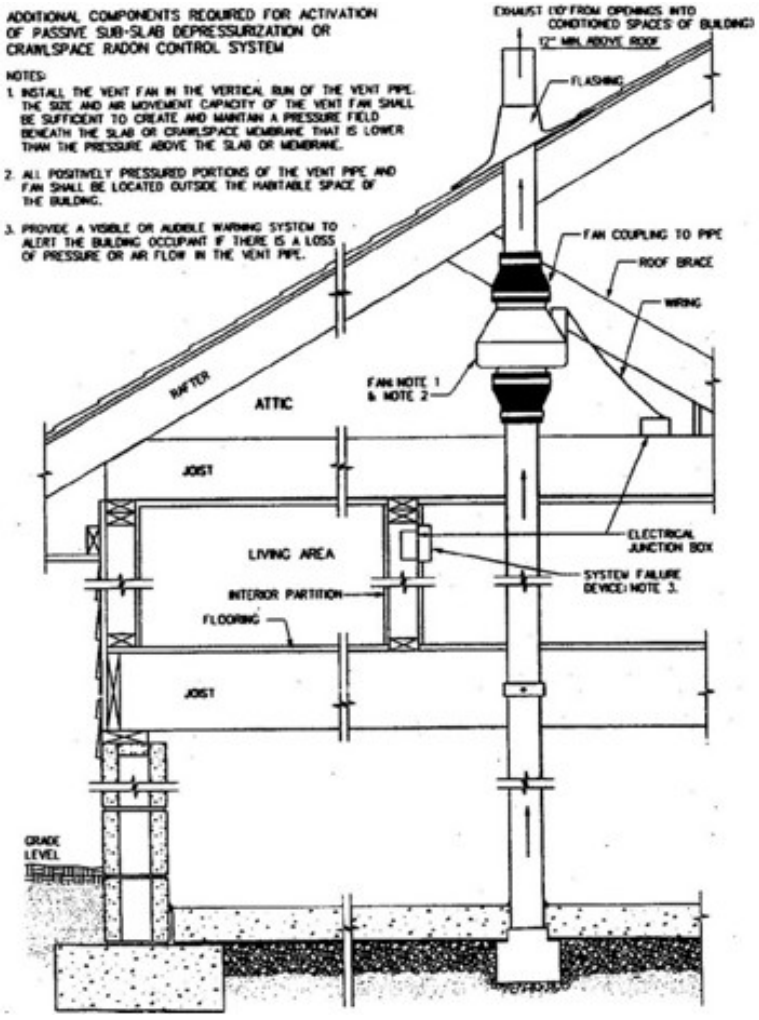
PASSIVE SUB-SLAB DEPRESSURIZATION RADON CONTROL SYSTEM FOR NEW CONSTRUCTION

NOTES:

1. ALL CONCRETE SLABS THAT COME IN CONTACT WITH THE GROUND SHALL BE LAID OVER A GAS PERMEABLE MATERIAL MADE UP OF EITHER A MINIMUM 4" THICK UNIFORM LAYER OF CLEAN AGGREGATE, OR A MINIMUM 4" THICK UNIFORM LAYER OF SAND, OVERLAIN BY A LAYER OR STRIPS OF MANUFACTURED MATTING DESIGNED TO ALLOW THE LATERAL FLOW OF SOIL GASES.
2. ALL CONCRETE FLOOR SLABS SHALL BE DESIGNED AND CONSTRUCTED IN ACCORDANCE WITH LOCAL BUILDING CODES. ADDITIONAL REFS: AMERICAN CONCRETE INSTITUTE PUBLICATIONS, "ACI302.1R" & "ACI332R", OR THE POST TENSIONING INSTITUTE MANUAL, "DESIGN AND CONSTRUCTION OF POST-TENSIONED SLABS ON GROUND".
3. ALL OPENINGS, GAPS AND JOINTS IN FLOOR AND WALL ASSEMBLIES IN CONTACT SOIL OR GAPS AROUND PIPES, TOILETS, BATHTUBS OR DRAINS PENETRATING THESE ASSEMBLIES SHALL BE FILLED OR CLOSED WITH MATERIALS THAT PROVIDE A PERMANENT AIR-TIGHT SEAL. SEAL LARGE OPENINGS WITH NON-SHRINK MORTAR, GROUTS OR EXPANDING FOAM MATERIALS AND SMALLER GAPS WITH AN ELASTOMERIC JOINT SEALANT, AS DEFINED IN ASTM C920-87.
4. VENT PIPES SHALL BE INSTALLED SO THAT ANY RAINWATER OR CONDENSATION DRAINS DOWNWARD INTO THE GROUND BENEATH THE SLAB OR SOIL-GAS-RETARDER MEMBRANE.
5. CIRCUITS SHOULD BE A MINIMUM 15 AMP, 115 VOLT.

Active Sub-Slab Depressurization System

Uses a fan to mechanically draw air from beneath the slab (or membrane) through the vent pipe:



Appendix B: Glossary

· **active system:** passive system with the addition of a fan to more actively draw radon from the soil into the stack where it dissipates into the atmosphere. A system-failure warning device (alarm) is also installed to alert the occupant if the system is not working.

· **action level:** homeowners should take action to lower radon levels indoors when levels are at or above 4 pCi/L.

· **aggregate:** a coarse material, such as gravel, placed below the slab.

· **ASTM Standard Guide 1465-92:** a guidance booklet published in 1992 by the American Society for Testing and Materials according to their consensus process for deciding on the content.

· **building code:** criteria or requirements (i.e., minimum standards) set forth and enforced by a state or local agency for the protection of public health and safety; is usually based on a model code (see below) and/or Model Standards published by acknowledged organizations or associations.

· **condensation:** Vapor in the air turns into water on cold surfaces. Beads or drops of water (and frost in extremely cold weather) accumulate on the inside of the exterior covering of a building when warm, moisture-laden air from the interior reaches a point where the temperature no longer permits the air to sustain the moisture it holds.

· **condensate drains:** drains which remove condensation from air-conditioning or other equipment, frequently emptying into the sump or below the slab.

· **damp-proofing:** sealing the foundation walls to prevent outside moisture from entering the basement, although not as tightly as in water-proofing.

· **drain tile loop:** typically refers to a length of perforated pipe extending around all or part of the footing perimeter for draining water away from the foundation of a home.

· **flashing:** material for reinforcing and weather-proofing the joints and angles of the roof and penetrations through the roof.

· **footing:** the supporting base for the foundation walls of a house.

· **gas-permeable:** a material through which gas passes easily.

· **International Codes:** model codes published by the International Code Council (ICC) to combine all four model building codes into one. The International Residential Code was published in early 2000.

· **junction box:** an enclosed box used to connect or branch electrical wiring.

· **Map of Radon Zones:** the EPA's Map of Radon Zones assigns each of the 3,141 counties in the United States to one of three zones based on radon potential:

- Zone 1 counties have a predicted average indoor screening level greater than 4 pCi/L;
- Zone 2 counties have a predicted average indoor screening level between 2 and 4 pCi/L; and
- Zone 3 counties have a predicted average indoor screening level less than 2 pCi/L.

Note that elevated radon have been found in all counties.

· **Model Codes:** documents specifying requirements for building, mechanical, plumbing and fire-prevention installations, often the basis for state and local building codes.

· **Model Standard:** a document that has been developed and established to connote specified consensus and approval of certain techniques and standards; a prescribed level of acceptability or an approved model used as a basis for comparison; voluntary technical guidance until adopted into a building code. The EPA has published one for radon-resistant new construction, called *Model Standards and Techniques for Control of Radon in New Residential Buildings.*

· **passive system:** short for "passive sub-slab depressurization system," and includes features to reduce radon levels by utilizing barriers to radon entry and stack effect-reduction techniques, and 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, and the rest of the home and the outside air.

· **picocuries per liter (pCi/L):** a unit of measuring radon levels.

· **polyethylene sheeting** (used as soil-gas-retarder): plastic sheeting, about drop-cloth weight, used over gravel and under the concrete slab to prevent soil gases from entering a home. The sheeting also prevents the concrete from flowing into the gravel and blocking air flow beneath the slab; also used as a moisture barrier.

· **PVC pipe:** a hollow, plastic pipe generally used for plumbing in home construction.

· **slab:** the concrete “floor” poured over the ground between the foundation walls, either at ground floor or basement level.

· **soil gas:** any gas emanating from the soil, including radon, methane and water vapor.

· **stack effect-reduction techniques:** features that prevent or reduce the flow of warm conditioned air upward and out of the building's super-structure. If not reduced, stack effect can actually draw soil gas containing radon into the lower levels of the house. Most of these techniques are part of the International Code Council’s Model Energy Code.

· **sub-membrane depressurization:** a system designed to achieve lower sub-membrane air pressure relative to crawlspace air pressure by use of a vent that draws air from beneath the soil-gas retarder membrane; may be a passive system (without fan) or active system (with fan).

· **sub-slab depressurization:** a system designed to achieve lower sub-slab air pressure relative to indoor air pressure; may be a passive system (no fan) or active system (with fan).

· **sump/sump pit:** a hole going below the slab into which water is drained in order to be pumped out; should be sealed to prevent radon from entering the home.

Appendix C: For More Information

Hotlines

National Safety Council:
1-800-55-RADON
Hotline answers consumers' specific questions dealing with radon.

Consumer Federation of America Foundation's Radon Fix-It Program:
1-800-644-6999
Hotline answers questions for consumers with high radon levels about how to fix the problem.

IAQ Info:
1-800-438-4318
Hotline answers specific indoor air-quality questions.

Literature Referrals

National Hispanic Indoor Air Quality Hotline:
1-800-SALUD-12
Bilingual health information specialists provide answers about radon and provide test kits to consumers with bilingual instructions.

EPA Web site:
Check out the Indoor Environments Division Home Page for information and online publications about radon and indoor air quality at http://www.epa.gov/iaq.

Publications

Protecting Your Home from Radon
Second edition, 1997 (Kladder, D.L., Burkhart, J.F., Jelinek, S.R.). This document details many radon-resistant construction techniques, and includes many useful photos and illustrations. It is available in many public libraries or from the National Environmental Health Association at 1-800-513-8332 orhttp://www.neha.org.

Radon-Resistant Construction and Building Codes
This document provides general information on radon, and an explanation on each section in Appendix D of the *1998 International One- and Two-Family Dwelling Code.*

ASTM E1465-92 Standard Guide for Radon Control Option for the Design and Construction of New Low-Rise Residential Buildings

This guide covers design and construction methods for reducing radon entry into new low-rise residential buildings and is intended to assist designers, builders, building officials and others involved in the construction of low-rise residential buildings. Available from the American Society for Testing and Materials: 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, or by calling (610) 832-9585, or by visiting their Web site at http://www.astm.org

EPA Publications

Order copies in singles or in bulk from the National Service Center for Environmental Publications (NSCEP) 1-800-490-9198

Sample of available publications:

Building A New Home: Have You Considered Radon?
EPA/402-F-98-001
Colorful brochure on the basics of radon-resistant features

Buying A New Home? How To Protect Your Family From Radon
EPA/402-F-98-008
This brochure provides a quick summary and diagram of the major components of the radon-reduction system -- great for educating home buyers about radon.

Model Standards and Techniques for Control of Radon in New Residential Buildings
EPA/402-R-94-009

EPA Map of Radon Zones (color)
EPA/402-F-93-013

Radon Doesn't Have to be a Problem
EPA/402-V-95-015
This 12-minute video by the National Association of Home Builders (NAHB) explains radon-resistant features.

Radon Resistant New Homes: A Public Official's Guide to Reducing Radon Risk
EPA/402-V-95-014
Short video by the National Conference of States on Building Codes and Standards (NCSBCS) on radon-resistant features

Other Sources of Information

International Code Council (ICC)
5203 Leesburg Pike, Suite 708
Falls Church, VA 22041

phone: (703) 931-4533; fax: (703) 379-1546
http://www.intlcode.org

The ICC publishes model codes, including the International Residential Code (IRC). The IRC contains an appendix on radon-resistant construction. They also publish a separate guide to radon-resistant construction.

Appendix D: State Radon Contacts

For a complete, up-to-date listing, visit the EPA's website at: http://www.epa.gov.

Alabama: 800-582-1866
Alaska: 800-478-8324
Arizona: (602) 255-4845 x244
Arkansas: 800-482-5400
California: 800-745-7236
Colorado: 800-846-3986
Connecticut: (860) 509-7367
Delaware: 800-464-4357
District of Columbia: (202) 535-2999
Florida: 800-543-8279
Georgia: 800-745-0037
Hawaii: (808) 586-4700
Idaho: 800-445-8647
Illinois: 800-325-1245
Indiana: 800-272-9723
Iowa: 800-383-5992
Kansas: 800-693-5343
Kentucky: (502) 564-4856
Louisiana: 800-256-2494
Maine: 800-232-0842
Maryland: 800-438-2472 x2086
Massachusetts: 800-RADON-95
Missouri: 800-669-7236
Montana: 800-546-0483
Nebraska: 800-334-9491
Nevada: (775) 687-5394 x275
New Hampshire: 800-852-3345 x4674
New Jersey: 800-648-0394
New Mexico: (505) 476-8531
New York: 800-458-1158
North Carolina: (919) 571-4141
North Dakota: 800-252-6325
Ohio: 800-523-4439
Oklahoma: (405) 702-5100
Oregon: (503) 731-4014 x664
Pennsylvania: 800-237-2366
Rhode Island: (401) 222-2438
South Carolina: 800-768-0362
South Dakota: 800-438-3367
Tennessee: 800-232-1139
Texas: 800-572-5548
Utah: 800-458-0145
Vermont: 800-439-8550
Virginia: 800-468-0138

Michigan: 800-723-6642	Washington: (360) 236-3253
Minnesota: 800-798-9050	West Virginia: 800-922-1255
Mississippi: 800-626-7739	Wisconsin: 888-569-7236
<><><><><><><><><><><><><><>	Wyoming: 800-458-5847

U.S. Territories:

Guam: (671) 475-1611
Puerto Rico: (787) 274-7815
Virgin Islands: (212) 637-4013

Tribal Radon Program Offices:

Hopi Tribe in Arizona: (520) 734-2442 x635
Navajo Nation: (520) 871-7863
Inter-Tribal Council of Arizona: (602) 307-1527
Duckwater Shoshone-Paiute Tribe in Nevada: (702) 863-0222

Note:

As of September 30, 1998, the EPA no longer runs a National Radon Proficiency Program. Some states regulate providers of radon measurement, mitigation service providers and measurement devices by requiring registration, certification or licensing. Some of these states issue identification cards. Call your state to learn more. You can also contact the National Environmental Health Association's (NEHA) National Radon Proficiency Program at 1-800-269-4174, or contact them at: radonprog@aol.com. Contact the National Radon Safety Board (NRSB) at (303) 423-2674 or by emailing them at info@nrsb.org for more information on radon proficiency.

Quiz on Sections 14 through 18

T/F: For a builder, it is cheaper to install a radon-reduction system during construction than to go back and fix a radon problem identified later.

- True
- False

T/F: Plastic sheeting and foundation sealing and caulking can serve as barriers to radon entry, entry of other soil gases, and moisture.

- True
- False

T/F: For a builder, it is much more cost-effective to run the vent pipe through the house during construction rather than after the walls have been closed up.

- True
- False

T/F: Sealing large cracks and openings is important to do when you build a home, both in the lower portion of the home to reduce radon entry points, and in the upper portion of the home to reduce stack effect.

- True
- False

Section 19: InterNACHI SOP for Inspecting Radon Systems

Section 19: InterNACHI SOP for Inspecting Rn

19. International Standards of Practice for Inspecting Radon Mitigation Systems

19.1 About radon and these standards for inspecting mitigation systems:

Radon is a radioactive gas that has been found in homes, schools and buildings around the world. Radon comes from the natural breakdown of uranium in soil and rock and moves up into the indoor air that people breathe. Radon is the leading cause of lung cancer in non-smokers. Radon mitigation systems reduce radon levels in homes and buildings. Inspection of these systems helps assure that they were installed properly and are performing as designed.

Although this standard applies to both commercial and residential radon mitigation systems, this standard exceeds the requirements of both InterNACHI's commercial and residential standards of practices.

19.2 Purpose

The purpose of this document is to establish international standards for the inspection of radon mitigation systems. This document also provides universal radon mitigation inspection reporting language.

19.3 Definitions

19.3.1 Radon mitigation system-specific definitions:

- **active soil depressurization system:** one or more of the following types of radon mitigation system types involving mechanically-driven soil depressurization: sub-slab depressurization; sump (pit) depressurization; drain tile depressurization; sub-membrane depressurization; hollow-block wall depressurization; and crawlspace depressurization.
- **crawlspace depressurization:** an active radon mitigation system that lowers the air pressure inside a crawlspace in relation to the rooms adjacent or above the crawlspace. A fan draws air directly from the air space of the crawlspace and discharges to the air outside. This type of system is typically not the best choice because of the great potential for appliance back-drafting and energy loss.
- **defect:** a condition of a radon mitigation system that may have an adverse impact on its performance.
- **depressurization:** a negative pressure created in one area compared to an adjacent area.
- **discharge:** the end of a vent stack pipe open to outside air.
- **drain tile depressurization:** an active soil depressurization system whereby a suction point is located at a drain tile.
- **heat-recovery ventilation system:** a system that lowers radon levels by using outside air to dilute and pressurize indoor air. HRV systems
are considered active radon systems.

- **hollow-block wall depressurization:** an active radon system that depressurizes the open spaces within concrete-block foundation walls.

- **inspection:** a non-invasive, visual examination of a radon mitigation system.

- **manifold pipe:** pipe between a vent stack pipe and suction point pipe with two or more suction points.

- **radon mitigation system:** any system designed to reduce the radon concentrations of indoor air.

- **radon system piping:** the piping of a passive or active radon system that is composed of suction point pipe, manifold pipe and vent stack pipe.

- **readily accessible:** an item or component that is, in the judgment of the inspector, capable of being safely observed without the removal of obstacles, detachment or disengagement of connecting or securing devices, or other unsafe or difficult procedures to gain access.

- **sub-membrane depressurization:** an active radon mitigation system creating a low air pressure under a vapor retarder. A common example is when a vapor retarder (polyethylene plastic sheet) is installed over the exposed dirt floor of a crawlspace. The radon fan draws air from below the vapor retarder and sends it outside.

- **sub-slab depressurization (active):** a radon system that creates a low air pressure under a concrete floor using a fan.

- **sub-slab depressurization (passive):** a radon system that creates a low air pressure under a concrete floor without the use of a fan.

- **suction point:** the end of a radon system that penetrates the slab, wall, vapor barrier, sump cover or drain tile.

- **sump (pit) depressurization system (active):** a radon system that has a suction point installed in the sump (pit).

- **vent stack pipe:** pipe leading from the suction point (in a system with a single suction point) or the manifold pipe (in a system with more than one suction point) to outside air. In active radon mitigation systems, the radon fan is installed vertically in the vent stack pipe.

19.3.2 Terminology commonly found in commercial property inspection reports
Visit http://www.nachi.org/comsop.htm#101

19.4 Goal of Inspection

The goal of the inspection is to provide observations which may indicate that a radon mitigation system was installed improperly, is not performing as designed, or is in need of repair.

19.5 Limitations

The inspection is limited to readily accessible and visible portions of the radon mitigation system. The inspection should not be considered all-inclusive or technically exhaustive. It is not a substitute for a radon level measurement.

This standard does NOT require the inspector to:

- inspect any portion of the system that is not readily accessible and visible;
- activate a system that has been turned off, unplugged or de-activated; or
- measure the radon level.

19.6 Optional Add-On Inspection Service

Although InterNACHI's Standards of Practice for Inspecting Commercial Properties and InterNACHI's Residential Standards of Practice do not require the inspector to perform radon mitigation system inspections, radon mitigation system inspections may be offered in conjunction with a complete commercial or residential property inspection, or as separate, stand-alone inspection services.

19.7 Visual Inspection

19.7.1 Radon System Type

19.7.1.1 The inspector shall describe the radon system as one of the following types:

- active sub-slab depressurization;
- passive sub-slab depressurization;
- sump (pit) depressurization;
- drain tile depressurization;
- sub-membrane depressurization;
- hollow-block wall depressurization;
- crawlspace depressurization; or
- heat-recovery ventilation.

19.7.2 Drain Tile Depressurization Systems

The inspector should inspect drain pipes that extend to daylight for missing devices, such as one-way flow valves or water traps that prevent outdoor air from entering the sub-slab area.

19.7.3 Sub-Membrane Depressurization Systems

The inspector should inspect the vapor retarder used for sub-membrane depressurization systems (passive or active) for seams that are overlapped less than 12 inches, and edges that are not sealed to the walls, posts and other penetrations.

19.7.4 Hollow-Block Wall Depressurization Systems

The inspector should inspect hollow-block walls for cracks, openings and open top-courses.

19.7.5 Crawlspace Depressurization Systems

The inspector should inspect the crawlspace for the presence of asbestos-like material, and combustible, fuel-served appliances located within the crawlspace or in spaces adjacent to the crawlspace.

19.7.6 Heat-Recovery Ventilation (HRV) Systems

The inspector should inspect the area around the HRV system for the presence of asbestos-like material.

19.7.7 Piping and Fittings

The inspector should inspect for:

- piping that is not PVC or ABS or downspout (outside);
- piping subjected to weather or physical damage that is not Schedule 40;
- pipe and fitting connections of different materials;
- piping that isn't solid and rigid;
- reducers that are installed in the direction of air flow; and
- piping that is not continually sloped toward the suction point.

19.7.8 Piping Supports

The inspector shall inspect for:

- supports installed more than 6 feet apart on horizontal runs; and

- supports installed more than 8 feet apart on vertical runs.

19.7.9 Discharges

The inspector should inspect for:

- discharges less than 10 feet above ground-level;
- discharges less than 6 inches above a roof edge, rake or gable that its stack passes by;
- discharges that exhaust less than 12 inches above a roof surface through which its stack pipe passes;
- discharges that exhaust below the roof surface of the highest roof of the building; and
- discharges within 2 feet directly above or less than 10 feet from any window, door or opening, including those in adjacent buildings.

19.7.10 Radon Fan

The inspector should inspect for:

- interior radon fans installed in occupied or conditioned spaces;
- exterior radon fans installed underground;
- radon fans that are not connected to the piping with removable couplings or flexible connections; and
- radon fans that are not mounted vertically.

19.7.11 Condensate Bypass

The inspector should inspect for missing condensate bypass mechanisms on systems in cold climates.

19.7.12 Electrical

The inspector should inspect for:

- cord and plug assemblies supplying power to radon fans that are more than 6 feet in length;

- cord and plug assemblies supplying power to radon fans that pass through walls, floors or ceilings, or are concealed within building components;
- missing means of disconnect, such as a dedicated, labeled electrical breaker, switch or an electrical plug cord;
- means of disconnects not in sight of their radon fans;
- missing grounded receptacles (required within 6 feet of radon fans installed under roofs);
- missing GFCI receptacles (required within 6 feet of radon fans installed above roofs); and
- missing electrical junction boxes (required within 6 feet of radon fan locations of both active and passive systems).

19.7.13 Condensate Drain Pipes

The inspector should inspect for condensate drain pipes that are not directed into condensate pumps, not directed into trapped floor drains, or do not have 6-inch or greater standing water trap seals.

19.7.14 Monitoring Device

The inspector should inspect for missing air-flow or pressure-monitoring devices (required to provide easily visible or audible indication of system failure or performance in active systems).

19.7.15 Labeling

The inspector should inspect for:

- missing piping labels (required on each floor to identify piping as part of a radon system);
- missing labels on the plastic vapor barrier (if installed);
- labels that are illegible from a distance of 3 feet;
- piping or vapor barrier labels that fail to display one the following: "Radon Mitigation System," "Radon Reduction System," "Radon System" or "Radon Removal System";
- a missing main label that contains the mitigator's name and contact information, date of installation, and a recommendation to test the building for radon every two years; and
- a missing "Radon," "Radon Fan" or "Radon System" label at the disconnect breaker controlling the electrical circuit to the radon fan.

19.8 Sample Reporting Language

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Radon Mitigation System Inspection Report

Client: ____

Location of radon mitigation
system: ____

This inspection was performed in substantial compliance with InterNACHI's International Standards of Practice for Inspecting Radon Mitigation Systems. It is designed to provide an indication as to whether or not the radon mitigation system was installed improperly, is not performing as designed, or is in need of repair. It is not a substitute for a radon level measurement.

Radon is a radioactive gas that has been found in homes, schools and buildings around the world. Radon comes from the natural breakdown of uranium in soil and rock, and moves up into the indoor air that people breathe. Radon is the leading cause of lung cancer in non-smokers. Radon mitigation systems reduce radon levels in homes and buildings.

The inspector noted that the radon system type is:
~~~~~~~~~~~~~~~~~~~~~~~~~~~~

___ active sub-slab depressurization
___ passive sub-slab depressurization
___ sump (pit) depressurization (active)
___ drain tile depressurization
___ sub-membrane depressurization
___ hollow-block wall depressurization
___ crawlspace depressurization
___ heat-recovery ventilation

Drain Tile Depressurization Systems:
___ The inspector noted that the drain pipes that extend to daylight were missing devices, such as one-way flow valves or water traps that prevent outdoor air from entering the sub-slab area.

Sub-Membrane Depressurization Systems:
___ The inspector noted that the vapor retarder used for the sub-membrane depressurization system (passive or active) had seams that were overlapped less than 12 inches, or edges that were not sealed to the walls, posts or other penetrations.

Hollow-Block Wall Depressurization Systems:
___ The inspector noted that the hollow-block walls had cracks, openings or open top-courses.

Crawlspace Depressurization Systems:
___ The inspector noted that the crawlspace had the presence of asbestos-like material, or combustible, fuel-served appliances located within the crawlspace, or in spaces adjacent to the crawlspace.

Heat-Recovery Ventilation (HRV) Systems:
___ The inspector noted the area around the HRV system had the presence of asbestos-like material.

Piping and Fittings:
___ The inspector noted piping that is not PVC or ABS or downspout (outside).
___ The inspector noted piping subjected to weather or physical damage that is not Schedule 40.
___ The inspector noted pipe and fitting connections of different materials.
___ The inspector noted piping that wasn't solid or rigid.
___ The inspector noted reducers that were installed in the direction of air flow.

___ The inspector noted piping that was not continually sloped toward the suction point(s).

Piping Supports:
___ The inspector noted supports installed more than 6 feet apart on horizontal runs.
___ The inspector noted supports installed more than 8 feet apart on vertical runs.

Discharges:
___ The inspector noted discharges less than 10 feet above ground level.
___ The inspector noted discharges less than 6 inches above a roof edge, rake or gable that its stack passed by.
___ The inspector noted discharges that exhausted less than 12 inches above a roof surface through which its stack pipe passed.
___ The inspector noted discharges that exhausted below the roof surface of the highest roof of the building.
___ The inspector noted discharges within 2 feet directly above or less than 10 feet from any window, door or opening.

Radon Fan:
___ The inspector noted interior radon fans installed in occupied or conditioned spaces.
___ The inspector noted exterior radon fans installed underground.
___ The inspector noted radon fans that were not connected to the piping with removable couplings or flexible connections.
___ The inspector noted radon fans that were not mounted vertically.

Condensate Bypass:
___ The inspector noted missing condensate bypass mechanisms on a system in a cold climate.

Electrical:
___ The inspector noted cord and plug assemblies supplying power to radon fans that were more than 6 feet in length.
___ The inspector noted cord and plug assemblies supplying power to radon fans that passed through walls, floors or ceilings, or were concealed within building components.
___ The inspector noted missing means of disconnect, such as a dedicated, labeled electrical breaker, switch or an electrical plug cord.

___ The inspector noted means of disconnects not in sight of their radon fans.
___ The inspector noted missing grounded receptacles (required within 6 feet of radon fans installed under roofs).
___ The inspector noted missing GFCI receptacles (required within 6 feet of radon fans installed above roofs).
___ The inspector noted missing electrical junction boxes (required within 6 feet of radon fan locations of both active and passive systems).

Condensate Drain Pipes:
___ The inspector noted condensate drain pipes that were not directed into condensate pumps, not directed into trapped floor drains, or did not have 6-inch or greater standing water trap seals.

Monitoring Device:
___ The inspector noted missing air-flow or pressure-monitoring devices (required to provide easily visible or audible indication of system failure or performance in active systems).

Labeling:
___ The inspector noted missing piping labels (required on each floor to identify piping as part of a radon system).
___ The inspector noted missing labels on the plastic vapor barrier (if installed).
___ The inspector noted labels that are illegible from a distance of 3 feet.
___ The inspector noted piping or vapor barrier labels that fail to display one the following: “Radon Mitigation System,” “Radon Reduction System,” “Radon System” or “Radon Removal System.”
___ The inspector noted a missing main label that contains the mitigator’s name and contact information, date of installation, and a recommendation to test the building for radon every two years.
___ The inspector noted a missing “Radon,” “Radon Fan” or “Radon System” label at the disconnect breaker controlling the electrical circuit to the radon fan.

This inspection was performed by:

____
Signature

~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

Quiz on Section 19

A sub-slab depressurization system is a type of radon _____ system.

- mitigation
- introduction
- addition
- filtering

An active radon mitigation system is one with a ____ installed.

- fan
- vapor diffuser
- vent stack hood
- radon test

T/F: A heat-recovery ventilation system is a type of radon reduction system.

- True
- False

T/F: At a sub-membrane depressurization system, the seams in the vapor retarder plastic sheet are overlapped, but not sealed.

- False
- True

T/F: For a crawlspace depressurization system, a combustion appliance is allowed to be installed inside the crawlspace.

- False
- True

For an active radon mitigation system, the location of the discharge should be at least ___ feet above ground-level.

- 10
- 20
- 2
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

- 8

T/F: For all active radon systems, there should be a label that displays the date of the installation of the system.

- True
- False

Section 20: Radon in Water and Removal Methods

Section 20: Radon in Water & Removal Methods

Radon in drinking water is a significant health hazard, though a lesser hazard than radon in indoor air. Homes supplied with drinking water from a private well and community water systems that use wells as water sources have a greater risk of exposure to radon in water.

Radon in water is found in nearly all sources of surface water and ground water. It is created by the radioactive decay of radium, a naturally occurring radioactive element found in underground rock formations, particularly granite and quartz. Water that flows through or over radium-rich rock formations accumulates radium and, thus, radon resulting from the decay process.

Typically, groundwater has much higher levels of radon than surface water. This is because radon in groundwater is "trapped" by being submerged underground and cannot easily escape. Because of this, water supplies from underground wells have a much higher probability of having significant levels of radon. Drinking water originating from a surface-water source is probably not a significant health hazard for radon in water. Large, pre-treated municipal water supplies typically have negligible levels of radon in water because, usually, this type of water supply is drawn from surface-water sources, and because water treatment tends to reduce radon levels even further.

While most radon-related deaths are due to radon gas accumulated in houses from seepage through cracks in the foundation, up to 1,800 deaths per year are attributed to radon from household water. Showering, washing dishes and laundering can disturb the water and release radon gas into the breathable air.

Drinking water that has high levels of radon may be a health risk, but breathing air high in radon concentration is more harmful to one's health. Breathing in radon gas over a long period of time can increase the risk of getting lung cancer. Drinking water contaminated by radon may increase the chances of developing stomach cancer.

Before testing water for radon, the air should be tested. If the indoor radon level is high and the homeowners use groundwater, test the water. If the radon level is low in the air, there is no need to test the water. Test results are expressed in picocuries of radon per liter of water (pCi/L). In general, 10,000 pCi/L of radon in water contributes roughly 1 pCi/L of airborne radon throughout the house. The U.S. Environmental Protection Agency currently advises consumers to take action if the total household air level is above 4 pCi/L.

For waterborne radon, a simple step is to make sure the bathroom, laundry room and kitchen are well-ventilated. If the well water has only moderate levels of radon, this may adequately reduce the exposure to waterborne radon. However, if the well has high levels of radon, it may be necessary to use water-treatment devices, such as granular activated-carbon (GAC) units and home aerators.

Radon can be removed from the drinking water by using one of two methods:

- aeration treatment: spraying water or mixing it with air and then venting the air from the water before use; or

- GAC treatment: filtering water through carbon. Radon attaches to the carbon and leaves the water free of radon. Disposing the carbon may require special handling if it is used at a high radon level, or if it has been used for a long time.

In either treatment, it is important to treat the water where it enters the home (a point-of-entry device) so that all the water will be treated. Point-of-use devices, such as those installed on a tap or under the sink, will treat only a small amount of the water and are not effective in reducing radon in the water. It is important to maintain home water-treatment units properly because failure to do so can lead to other water contamination problems. Some homeowners use a service contract from the installer to provide carbon replacement and general system maintenance.

Aeration

Removing radon from water by aeration takes advantage of the fact that radon is readily given off (or volatile) from water to air. Radon in water is removed by passing as much air through water as efficiently as possible. By venting the now radon-rich air to the outdoors, aeration can remove up to 99.9% of radon from water. Aeration is practical for central treatment of radon in water (i.e., at a water treatment plant, etc.), but is expensive for individual households and small public water systems. A household aeration system suitable for high-efficiency radon removal typically costs between $3,000 and $5,000. Special maintenance is required to ensure that waterborne minerals, such as iron and manganese, do not accumulate and foul the aeration system, which may reduce radon removal-efficiency.

Granular Activated-Carbon (GAC) Absorption

A second method for treating radon in water is granular activated-carbon, or GAC, absorption. Water is filtered through granulated carbon (usually in the form of activated charcoal), and radon is attracted onto the surface of the carbon. Maximizing the carbon's surface area and the length of filtration time are crucial to peak radon-removal efficiency. GAC absorption can remove up to 99.9% of radon from water if large amounts of carbon and long contact times are used. Typical removal efficiencies for GAC vary from 50 to 99%. GAC can be used for central treatment schemes for small systems (several hundred users or fewer), but becomes more expensive for larger systems. GAC is also fairly cost-effective for individual residential wells. If high levels of radon are present, disposing of spent carbon filters may be difficult due to the significant amount of radioactive material present in the filter. Small carbon filters attached to kitchen faucets or under sinks are inadequate for removing radon from drinking water.

Alternatives

An alternative to these active mitigation systems is simple storage. Because radon is a radioactive element which decays over time (Radon-222 has a half-life of 3.8 days), radon levels in water storage tanks will decrease over time. This strategy would probably be most effective for small systems with average radon levels just a bit above the EPA's maximum concentration level.

Another alternative for some private well owners is to connect to an existing community water system with low radon levels. Drinking bottled water alone will not completely eliminate exposure to radon in water, since this strategy does not prevent radon gas from escaping from well water into indoor air.

More information

For a more in-depth discussion of these technologies and their associated costs, read the EPA's *Health Risk Reduction and Cost Analysis for Radon in Drinking Water*. Section 5 of the Federal Register Notice, *Costs of Radon Treatment Measures*, is particularly helpful in understanding the different technologies.

Quiz on Section 20

T/F: While most radon-related deaths are due to radon gas accumulated in houses from seepage through cracks in the foundation, up to 1,800 deaths per year are attributed to radon from household water.

- True
- False

T/F: If the radon level is low in the air, there is no need to test the water.

- True
- False

T/F: The NAS concluded that the findings of BEIR VI showed that if homeowners haven?t yet tested their homes for radon and mitigated them if the levels are elevated, they don?t need to.

- False
- True

T/F: Once radon enters a house, it can decay inside the house and float in the air unattached, it may attach to dust particles, or it may attach to solid objects and plate out.

- True
- False

T/F: The EPA Measurement Protocols are designed primarily for use in residential buildings.

- True
- False

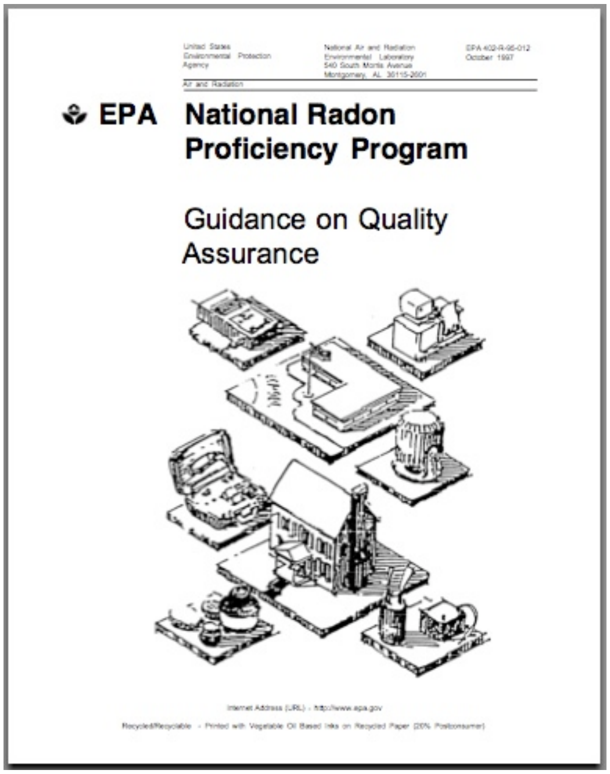
T/F: There is a strong correlation between areas identified on aero-radioactivity maps as having high levels of surface uranium, and areas for which high levels of indoor radon have been reported.

- True
- False

Section 21 QA Booklet

EPA-402-R-95-012 QA Guidance Booklet

[EPA-402-R-95-012 QA Guidance Booklet (PDF)]



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