

Unit 1. Radon Occurrence and Health Effects

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Objectives

- 01.01 Describe the types and characteristics of ionizing radiation.
- 01.02 ¹*/**Define the characteristics of radon and the radium decay chain.
- 01.03 Describe the measurement units for radon and radon decay products.
 - ***Describe the equation used to determine the cumulative exposure to radon decay products.
- 01.04 Define "Equilibrium Ratio" (ER).
 - a. */**Calculate and interpret an ER.
 - b. */**Identify factors that affect the ER.
- 01.05 Describe the health effects associated with radon.
 - a. Identify the factors that may increase the likelihood of radon-induced health effects.
 - b. */**Identify the types of evidence that indicate the harmful effects of radon.,
- 01.06. Compare the health risks associated with radon and radon decay product exposure to other health risks.

¹ *These objectives are only for radon measurement specialists.

**These objectives are only for radon mitigation specialists.

***These objectives are only for measurement applicants.

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

I. Introduction to Atoms and Ionization

The concept of the atom as a small unit of mass is not new. In the 5th Century, B.C., the Greek Democritus proposed that all matter is composed of very small particles, which he called atoms. This idea that all matter is composed of elemental substances has been developing ever since. The Russian, Mendeleev, finally arranged the known elements according to a periodic function which correlates their chemical properties to their atomic weights. Today, the table is essentially complete. It is now known that elements are indeed atomic and that the atoms themselves have a structure. Figure 1-1 shows the Periodic Chart of the Elements.

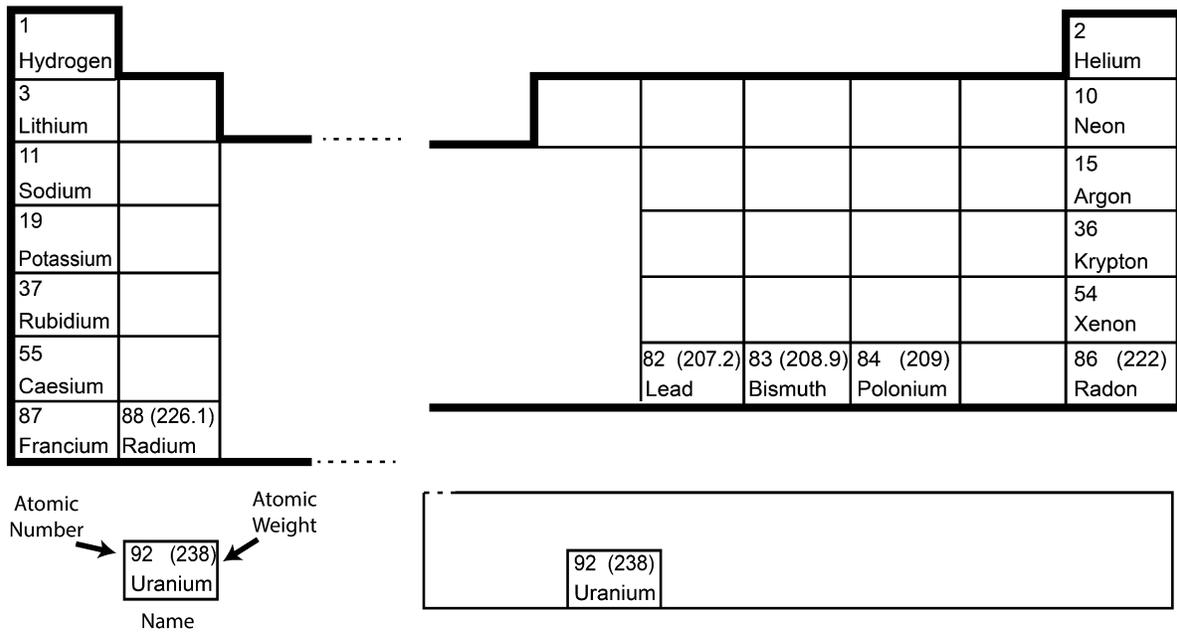
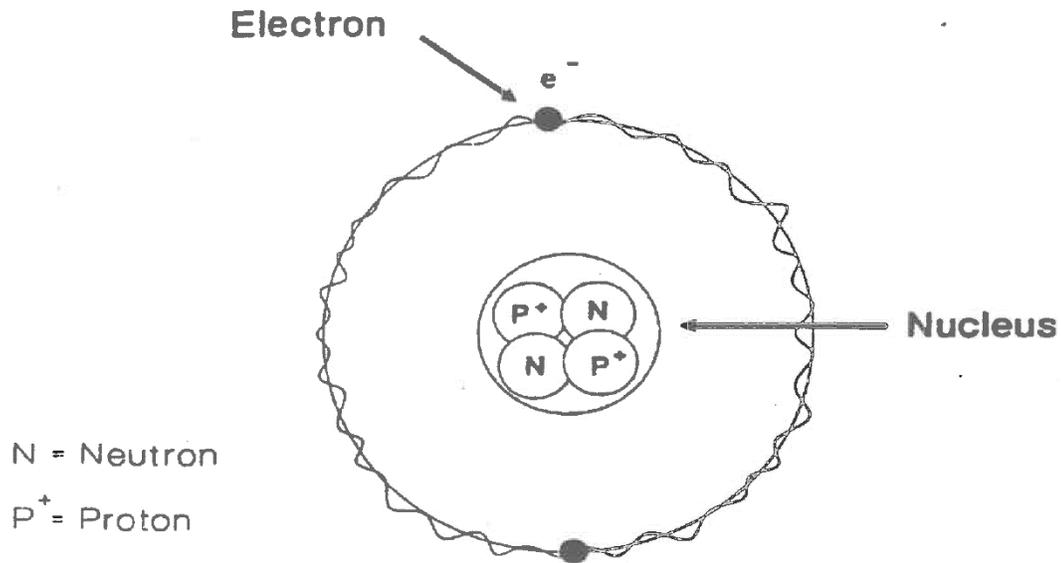


Figure 1-1. The Periodic Table Relative to Radon

The atom consists of a positively-charged nucleus and one or more negative electrons (e^-) arranged in circular or elliptical orbits around the nucleus. Although there are more than 30 known elementary particles and antiparticles, the nucleus can be considered as made up of singly-charged protons (p^+) and uncharged neutrons (n). The proton and neutron are approximately equal in size while the electron is approximately 1/2000 the size of these nuclear particles. A two-dimensional model of the atom is depicted in Figure 1-2.



In electrically neutral atoms, the number of electrons in orbit always equals the number of protons in the nucleus. The atomic number is equal to the number of protons in the atomic nucleus. The mass number is equal to the number of protons plus neutrons.

Figure 1-2. Structure of an Atom

By definition, an ion is an electrically charged atom or group of atoms. The process of ionization results in an ion pair. For example, a hydrogen atom (Figure 1-3) can become ionized by the removal of the single electron (e^-) in orbit about the hydrogen nucleus (proton, p^+). The resulting ion pair consists of a single electron and a single proton which are separated by a given distance. The greater the distance, the less likely that the two would recombine into the original configuration of the atom. The process of ionization is illustrated in Figure 1-3 where an x-ray is shown colliding with an orbital electron. The electron is knocked out of the atom and appears as an electron with one negative charge (negative ion). This leaves the hydrogen nucleus by itself. Since this nucleus has a single positive charge, it, too, is an ion. Thus illustrated is the formation of an "ion pair".

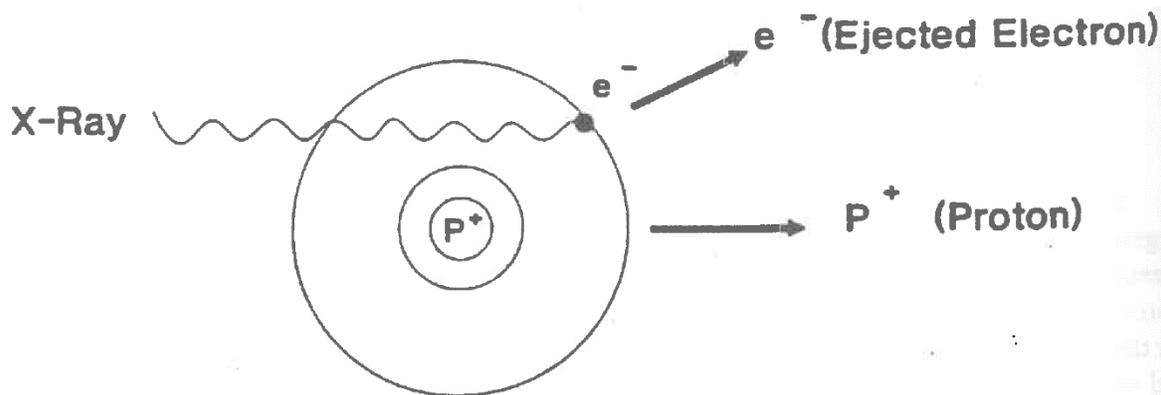


Figure 1-3. Ionization of a Hydrogen Atom by an X-Ray

The process of ionization is of considerable importance when radiation like x-rays, gamma rays, and alpha particles interact with air or tissue. Such interactions produce large numbers of ions. Any atom or molecule is likely to become ionized by these interactions. The ions formed can either react chemically with other matter, move in electric fields, recombine and emit light quanta, or serve as condensation nuclei. In Figure 1-4, two parallel metal plates are connected to a battery. Ions produced by radiation will be collected at these plates. Positive ions are always attracted to negative plates and negative ions are attracted to positive plates. The result of this ion collection can be measured in a variety of ways, for example, measuring current with a gauge or measuring a change of voltage on the battery (as in the electret ion chamber).

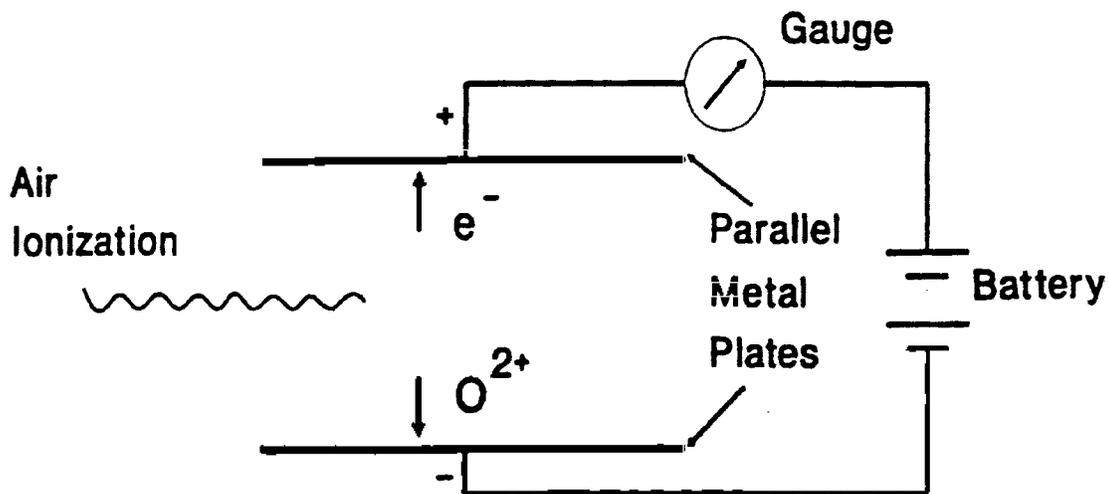


Figure 1-4. Ion Measurement

II. Introduction to Radon and Radioactivity

Radon is a colorless, odorless and tasteless gas produced by the decay of uranium and radium. Unlike some indoor pollutants, it cannot be detected by our senses. This naturally occurring, radioactive gas is produced in most soil or rock. As a result, all houses have some radon, as does the outdoor air. Radon is an inert gas, meaning that it is chemically inactive. Since it is not chemically bound or attached to other materials, radon can move easily through any material that has pores or void spaces through which gases can move. Void spaces and pores are found in the soil beneath any home.

A. Radioactivity

The protons and neutrons of an atom are held together by nuclear energy forces. Quite simply, radioactivity is the result of instability in some atomic nuclei where there are too many or too few neutrons to satisfy energy relationships within the nucleus. In the simplest case of hydrogen shown in Figure 1-5, the addition of one neutron to the hydrogen nucleus doubles its weight but does not make the resulting atom radioactive (deuterium). The addition of one more neutron to the deuterium nucleus causes instability and the resulting nucleus becomes unsettled or radioactive. In other words, adding two neutrons to the simple hydrogen nucleus causes it to become radioactive.

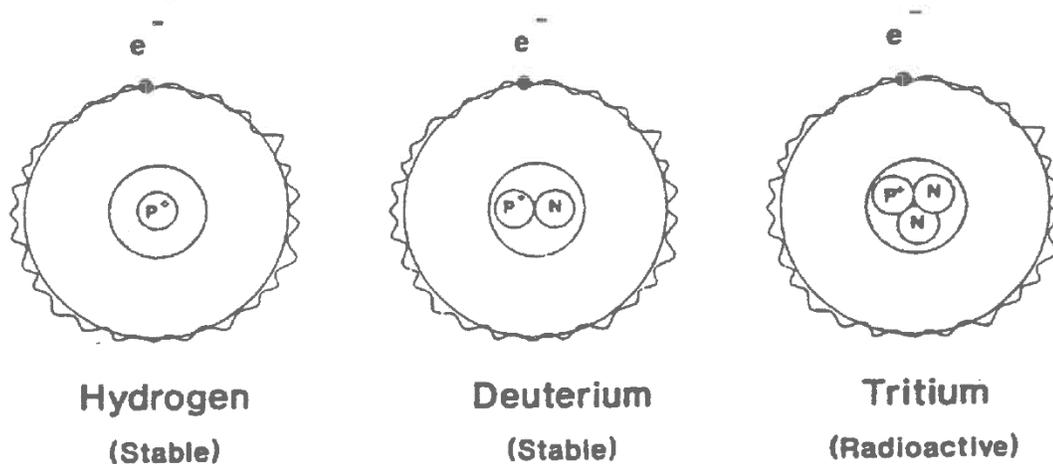


Figure 1-5. Stable and Unstable Atoms and Nuclei

B. Radioactive Decay

Radioactive decay is the disintegration of the nuclei of atoms in a radioactive element. These disintegrations are usually accompanied by release of pieces of the nucleus and sometimes by release of energy in the form of gamma rays. As the nucleus of an atom releases these particles and energy, it changes into the nucleus of a different atom.

The radioactive decay chain for radon begins with uranium. Uranium decays through several intermediate steps to produce radium, which in turn produces radon. Radon then decays into other substances (radon decay products) which are also radioactive. The process continues until non-radioactive lead is created (see Figure 1-6).

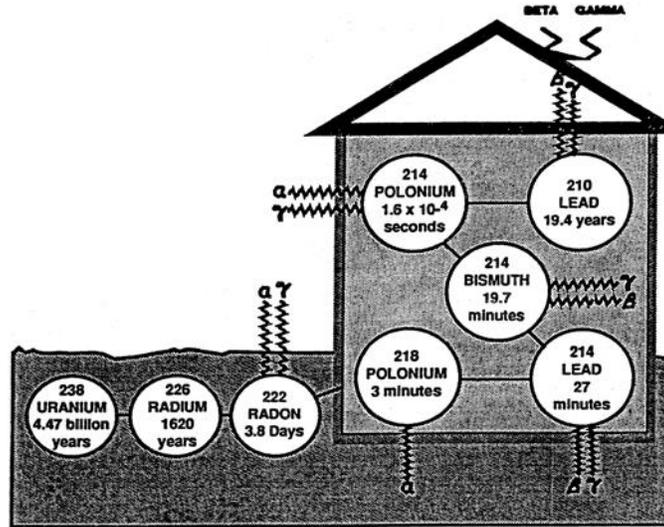


Figure 1-6. Uranium Decay Series

Each radioactive element in the radon decay chain has a different "half-life." Half-life is the time required for half the atoms of a radioactive element to decay. Thus, if you have an amount of material with a half-life of 3.8 days (radon for example), in 3.8 days you will have half as much. In another 3.8 days you will have half of that half, or one quarter of the material left. The process continues forever, since you can continue to divide the amount you have by two and never reach zero. Usually by the time ten half-lives have passed, there is so little left that one can call the remainder zero, for all practical purposes (see Figure 1-7).

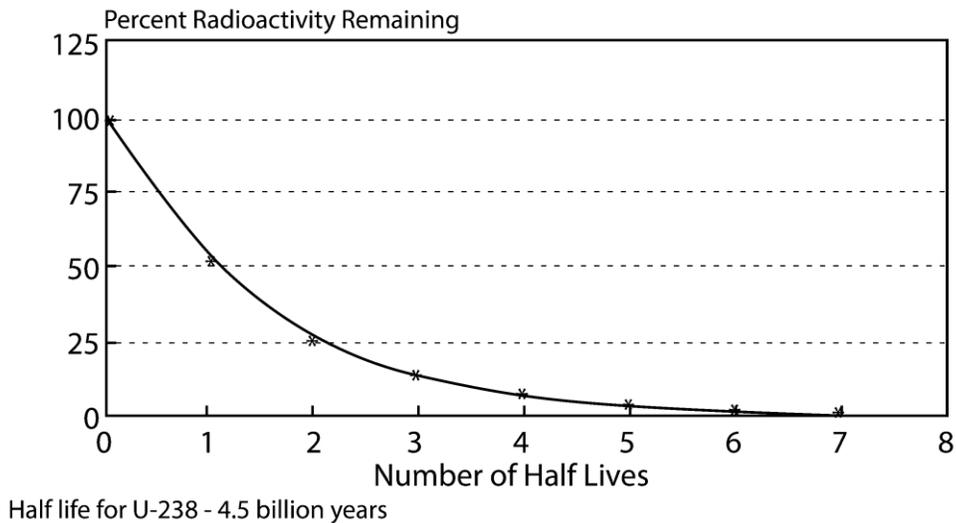


Figure 1-7. Radioactive Decay

The half-life is important, because that time interval determines the time available for radon and its decay products to be dispersed into the environment. The 3.8-day half-life is long enough to allow radon gas to move many feet in the soil. On the other hand, the half-lives of the first few radon decay products are sufficiently short; if inhaled, they can cause significant radiation to reach the inner surface of the lungs before the decay products are removed by the natural cleansing process of the lungs.

1. Uranium Decay Chain

The decay of uranium produces radium after several intermediate steps. Since uranium-238 has a half-life of about 5 billion years and the earth is assumed to be approximately 5 billion years old, there is about half the uranium-238 that was in the earth when it was formed. The numbers with the elements in Figure I-6 are the atomic masses, which are the sum of the number of protons and neutrons in the nucleus of the atom.

Most elements have many isotopes, each with their own half-life and decay products. Isotopes are different forms of an element that have the same number of protons but a different number of neutrons in their nucleus. For example, lead-214, lead-210 and lead-206 are all isotopes of lead. When you refer to radioactive materials, you must be isotope-specific, since each element can have several isotopes of concern. There are actually several different isotopes of radon. Currently, the primary isotope of radon which is of public health interest is radon-222, with 86 protons and 136 neutrons in its nucleus. Throughout this manual, references to "radon" mean radon-222 unless specified otherwise or obvious from the context.

When a radium atom decays, radon gas is released into the surrounding air or water. Since radon-222 has a half-life of 3.8 days, it has enough time to move from its radium source into buildings, where both the radon and its decay products can be inhaled, delivering a dose of radiation to the lung tissue. The decay products, polonium-218, lead-214, bismuth-214, and polonium 214, have very short half-lives. These decay products account for the major portion of the dose received in most situations and are the primary source of radon-induced lung cancer. Polonium-218 and Polonium-214 are the alpha emitters that do most of the damage. Bismuth-214 and lead-214 are beta emitters and also produce most of the gamma radiation in the decay series.

The RDPs are different from radon in several ways, including:

- They are short-lived (all less than 30 minutes).
- They are left with static electric charges as a result of the radioactive decay that produced them.
- They are chemically reactive.
- They are solid particles, rather than gases, that act like invisible aerosols in the air.

These properties mean that they easily attach themselves to solid objects such as dust, smoke, walls, floors, clothing, or any other object. If the RDPs attach to surfaces, such as walls or floors, they are said to be "plated out," that is, no longer floating about in the air. If they attach to dust or smoke particles they can be carried into the lungs, where they can lead to lung cancer (Figure 1-8).

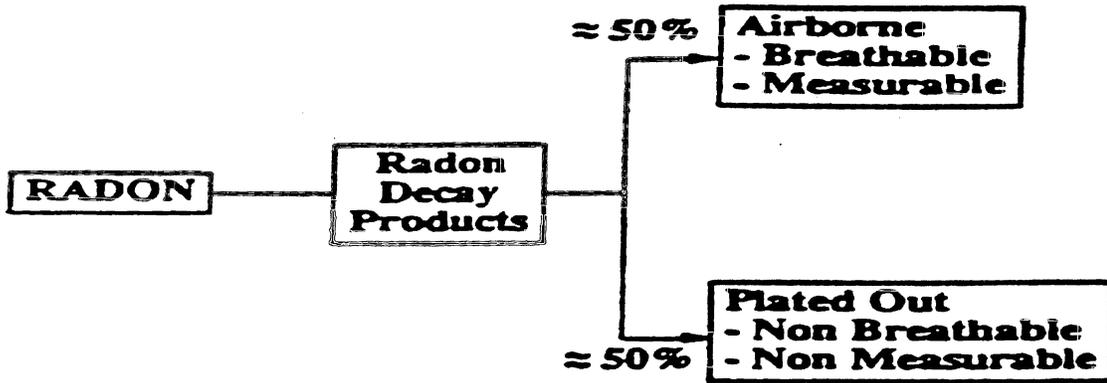


Figure 1-8. Fate of Indoor Radon

2. Types of Radiation

Alpha particles are released from the nuclei of atoms containing two neutrons and two protons, such as radium, radon and two of the short-lived RDPs during radioactive decay, (polonium-218 and polonium-214). Alpha particles are low in penetrating power, they are stopped by a few sheets of paper or the dead outermost layer of skin on the body. However, these particles can cause a great deal of damage to any living tissue within a very small distance of the atoms that produced them. Alpha radiation presents the greatest risk associated with radon and radon decay products. However, the major risk exists only when the alpha-emitting radioactive materials are inhaled into the lungs. Some alpha emitters are also dangerous if swallowed, but they are mostly a problem in the lungs.

Beta particles are electrons arising from conversion of a neutron to a proton and electron and are released by two other short-lived RDPs. Beta particles have medium penetrating power; they can penetrate the skin. They can travel several feet through air. Even though beta particles can travel farther into the body, alpha particles cause about 20 times as much damage inside the lungs as do beta particles.

Gamma rays are nothing more than bundles of energy (called photons) and are similar to the X-rays used in a dentist's office. They can travel much more deeply into objects than alpha or beta particles, and can pass through the body. While gamma radiation can penetrate all the way through your body, the amount emitted by radon and its RDPs is not nearly as detrimental to the lungs as alpha particles.

Figures 1-9 and 1-10 summarize the characteristics of these three types of radiation and describe their respective penetration properties. Note that the figures do not show the health risk of each type of radiation, only their penetrating power. Almost all the health risk of radon comes from inhaling in the alpha-emitting decay products.

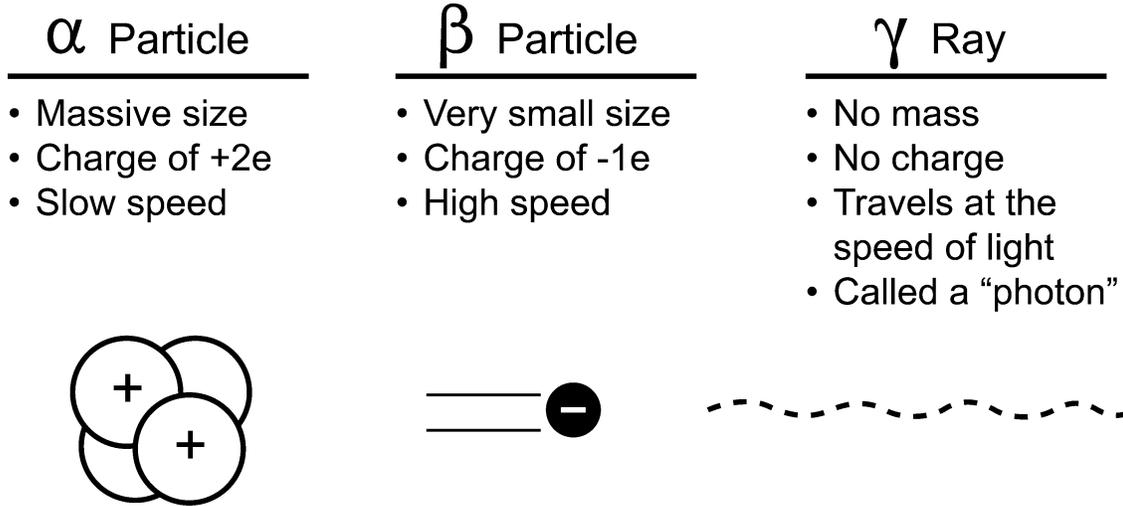


Figure 1-9. Radiation Types

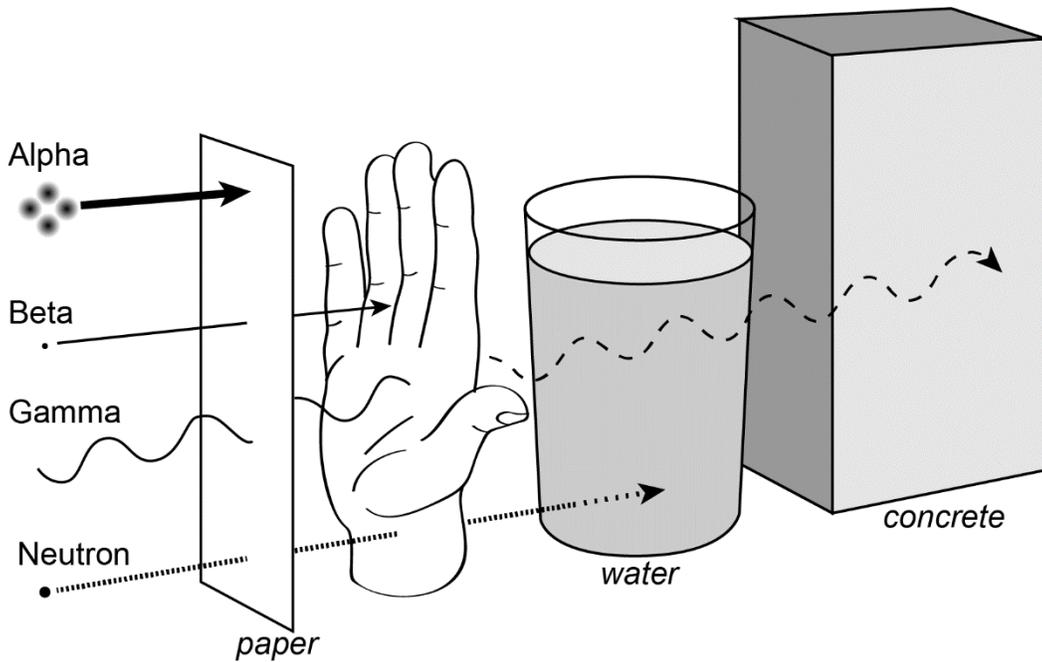


Figure 1-10. Penetrating Properties of Radiation (Source not cited.)

The radiation from RDPs can impact adjacent atoms. When this occurs, the impacted atom can be altered by changing its electrostatic charge. The atom is then referred to as an ion and can chemically react with other atoms. It is for this reason that alpha, beta, and gamma rays are called "Ionizing Radiations."

3. Natural Radiation and Other Sources

Figure 1-11 illustrates the contribution of radon-222 to our annual radiation exposure to naturally occurring and man-made radiations. Radon gas is very clearly the largest contributor to our annual radiation exposure.

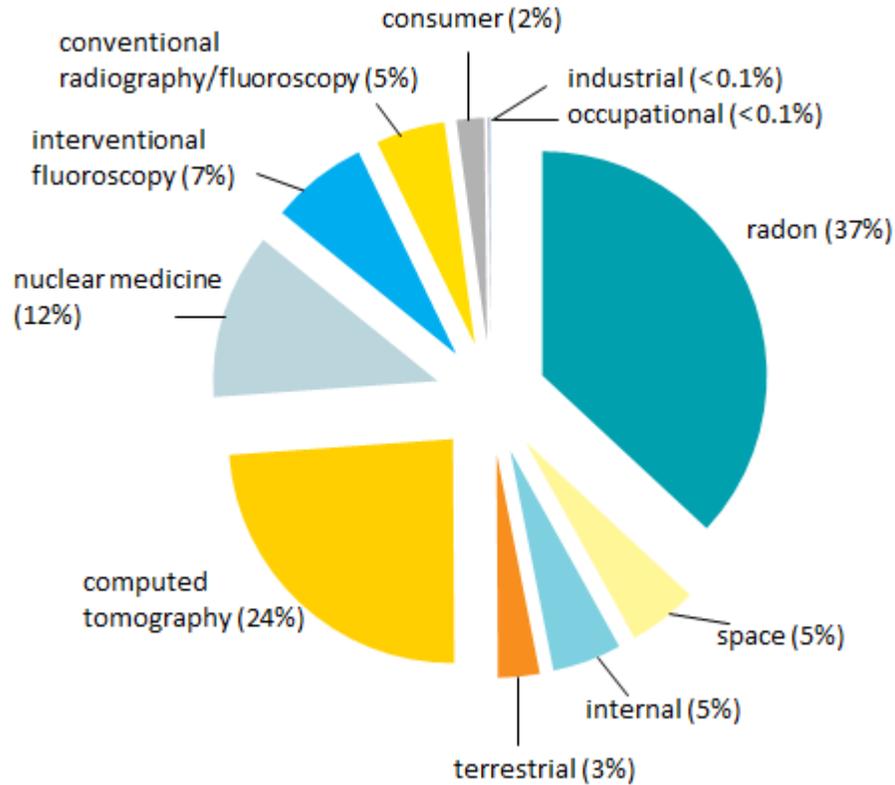


Figure 1-11. Radiation Sources: Annual U.S. Exposure

4. Sources of Radon

Figure 1-12 tabulates the contribution of various sources to atmospheric radon from a global point-of-view. Soil is well known as a major contributor of radon. Ground water piped directly into structure is the second most important source. Building materials may contribute to indoor radon problems if they contain source materials (uranium or radium).

Sources of Radon	Curies Per Year
Emanation from soil	2,000,000,000
Ground Water	500,000,000
Emanation from oceans	30,000,000
Phosphate residues	3,000,000
Uranium tailings piles	2,000,000
Coal residues	20,000
Natural gas	10,000
Coal combustion	900
Human exhalation	10

Figure 1-12. Sources of Radon

C. Measurement Units

In the United States, radioactive materials are measured in curies. A curie (named after Marie Curie) is the radioactivity associated with one gram of radium. A picocurie is a millionth of a millionth or a trillionth of a curie (curies divided by 1,000,000,000,000; see Figure 1-13). A picocurie refers to an amount of radioactivity that emits 2.22 atomic disintegrations per minute. Reference is sometimes made to becquerels per cubic meter as another unit of measure for radon. One (1) picoCurie per liter of radon is the same as 37 becquerels (Bq) per cubic meter.

Multiple	Decimal Equivalent	Prefix	Symbol
10^6	1,000,000	mega	M
10^3	1,000	kilo	k
10^2	100	hecto	h
10	10	deka	da
10^{-1}	0.1	deci	d
10^{-2}	0.01	centi	c
10^{-3}	0.001	milli	m
10^{-6}	0.000,001	micro	μ
10^{-9}	0.000,000,001	nano	n
10^{-12}	0.000,000,000,001	pico	p
10^{-15}	0.000,000,000,000,001	femto	f

Figure 1-13. Fractions and Multiples Used with Scientific Units

Radon gas is measured in picocuries per liter (pCi/L), which is a measure of the number of radioactive disintegrations per minute in a liter. A pCi/L is 2.22 disintegrations per minute for each liter (a liter is a little larger than a quart). Thus if a gallon container held air with 4 pCi/L, there would be about 4 (quarts

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per gallon) times 4 (pCi/L) times 2.22 disintegrations per minute, or about 35.2 disintegrations per minute of radon atoms in the container.

Radon decay products are measured in working levels (WL). A WL unit is any combination of short-lived daughters in one liter of air that will result in the emission of 1.3×10^5 MeV (million electron volts) of potential alpha energy. One working level is the concentration of RDPs produced from one liter of air containing 100 pCi of radon. (Note that some of the RDPs produced may be attached to the walls of the container and, therefore, not measurable.)

It may be helpful to visualize the WL as a unit of measurement of radioactive dust in the atmosphere. Radon decay products are measured by pulling a sample of air across a piece of filter paper to catch this dust. The radioactivity of the dust captured on the filter paper is then counted by special equipment. The results are reported as working levels or WL.

D. Equilibrium Ratio

Since every radon atom decays into an atom of polonium-218, the gallon container in the previous example will soon have a large number of atoms of polonium-218. However, the polonium-218 will also decay because it is radioactive. Since polonium-218 has a relatively short half-life of 3 minutes, it will decay quickly after it is formed. After a while, there will be as many atoms of polonium-218 decaying as there are atoms formed. Since 2.22 disintegrations per minute of any radioactive substance is a picocurie, the gallon container will soon contain 35.2 picocuries of polonium-218 (assuming the radon concentration is maintained at 35.2 pCi/L). Once there are as many atoms of polonium decaying as are formed, the concentration of polonium-218 will not increase any further. This condition is called secular equilibrium.

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. In an ideal container, where the decay products are not lost to plate out, this takes approximately 4 hours. Thus, for a constant level of 100 pCi/L of radon, RDPs will achieve in 1 to 4 hours a maximum concentration of 1 working level. This concentration can be reached if, and only if, there is nothing removing the RDPs. If something is removing the RDPs, there will be less than 1 working level for each 100 pCi/L of radon in the air.

Once radon enters a home, it begins to form decay products. In a home, however, there are other things happening that did not happen in the ideal container above. For example, air might be filtered by the furnace, which would remove some of the decay products (but not the radon because it is an inert gas). Air leakage might allow some of the decay products to escape. The decay products might cling to or plate out on walls, floors or other solid objects. All of these mechanisms can prevent the decay products from reaching the maximum concentration as in the example above. They will, however, reach a final concentration which is a balance of the amount of RDPs that are produced and are lost through plate out and ventilation. This balance is referred to as the dynamic equilibrium ratio (sometimes called transient equilibrium and is to be distinguished from the secular equilibrium). In a home, it typically takes about 12 hours for this dynamic equilibrium to be achieved after doors and windows have been closed (see Figure 1-14).

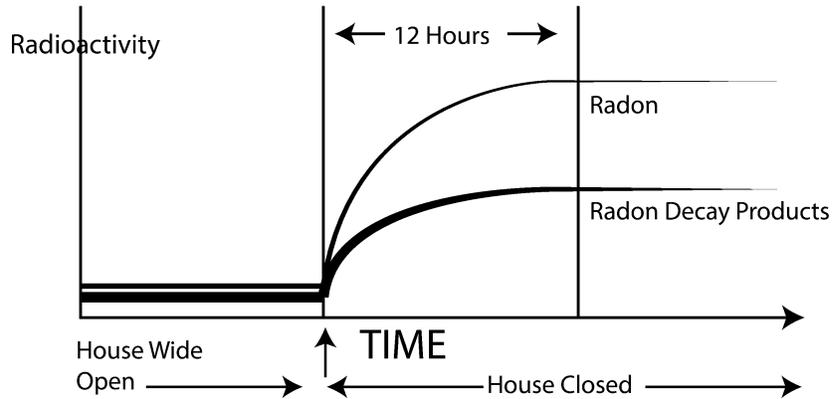


Figure 1-14. Dynamic Equilibrium in a Home

Dynamic equilibrium, hereafter referred to as equilibrium ratio, can be calculated as follows:

$$ER = \frac{(WL \text{ value}) \times 100}{\text{Radon Concentration}}$$

For example, if the radon concentration is 50 pCi/L and the decay product concentration is 0.3 WL, the equilibrium ratio would be calculated as follows:

$$ER = \frac{(0.3) \times (100)}{50} = 0.6$$

In any real situation, an equilibrium ratio of 1 does not occur in houses, because ventilation removes both radon and its decay products. In addition, it takes time for entering radon to produce decay products. As a result, the ER always will be less than 1. Further, because RDPs have a static charge, they plate out or cling to walls, furniture and other solid objects, which reduces the ER without affecting the radon concentration.

This equation can be rearranged to allow one to convert between radon and working levels if an equilibrium ratio is known (some people find Figure 15 an easy way to remember these formulas):

$$Rn = \frac{WL \times 100}{ER}$$

Or

$$WL = \frac{Rn \times ER}{100}$$

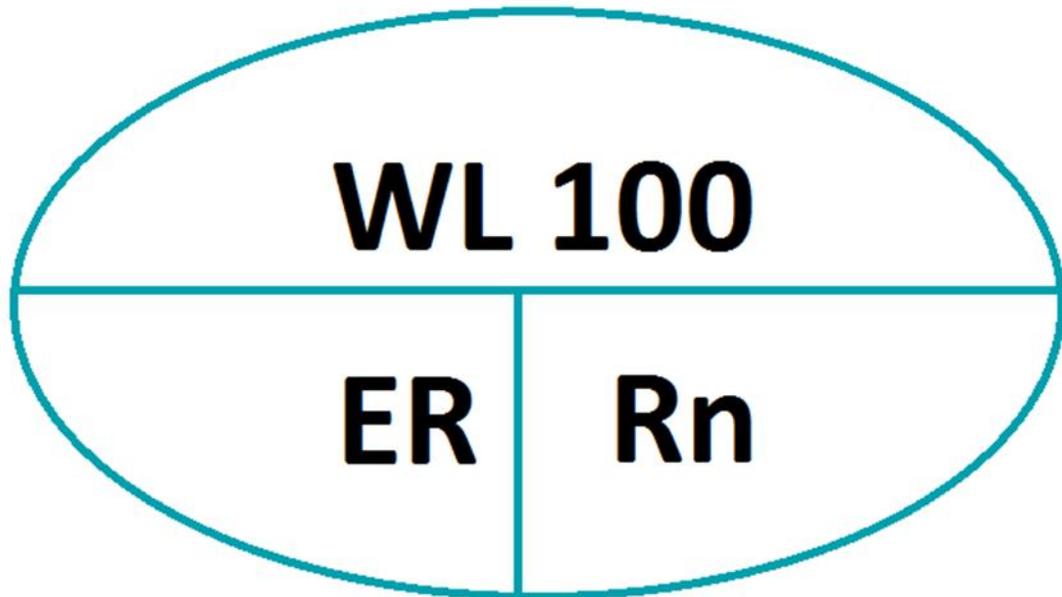


Figure 1-15. Alternate Solutions of Equilibrium Ratio Equation

In most houses, 100 pCi/L produce from 0.3 to 0.7 WL of RDPs. Conversely, a radon concentration of 4 pCi/L would produce between 0.012 and 0.028 WLs. The equilibrium ratio consequently ranges between 0.3 to 0.7; an ER of 0.5 is commonly assumed as an average. Based on this assumption, a house with 50 pCi/L can be expected to have about 0.25 WL, whereas a house with 4 pCi/L is likely to have about 0.02 WL.

If the ratio is unexpectedly high, indicating more decay products than anticipated, there is probably a relatively stable indoor environment with little air movement removing decay products. On the other hand, an unexpectedly low ratio suggests a high degree of air movement or possibly a whole house filter system removing decay products. If only radon-222 is present, an equilibrium ratio above 1 is impossible and indicates a problem with the measurement or interference of the measurement from other isotopes, such as thoron.

The Fate of Indoor Radon

Once radon enters a house, it can decay in the house air and continue decaying through its short-lived decay products, or it can be blown outside by ventilation air before it has a chance to decay. Figure 1-16 is a flowchart illustrating the fate of indoor radon.

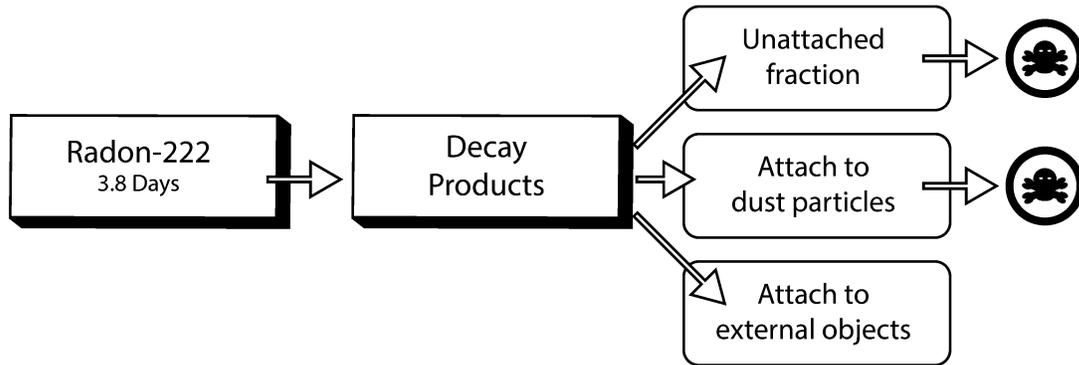


Figure 1-16. Fate of Radon in Indoor Air

Until decay products stick to some object, they are referred to as the unattached fraction. These unattached decay products are part of the hazard. As solid, electrically charged particles, they can be inhaled and become lodged in the lung. When they stick to an object, RDPs can still present a health hazard if the object is small enough to float in the air (dust, smoke and pollen). If they plate out on to a wall or some other non-breathable object, however, they are no longer a hazard.

If air is being circulated by fans or blowers, a large portion of the decay products can come in contact with walls, floors, furniture, etc., where they can plate out. Working levels can be lowered by running fans; the radon concentration will be the same, but the equilibrium ratio will be lower. The equilibrium ratio is also low immediately after a house has been extensively ventilated and then closed up. The soil gas entering the house has radon in it, but it is extremely low in decay products because they have plated out in the soil.

Therefore, if a house is aired out and then closed up, it takes several hours for the decay products to return to a dynamic equilibrium with the radon (see earlier Figure 1- 14).

If radon is removed from a house by ventilation before decay occurs, it no longer presents a health risk in the house. Outside, it mixes with fresh air, and quickly drops to very low concentrations.

III. Health Risk

A. Introduction

Radon is a known human carcinogen. Based on the strongest data available for predicting risks to human populations (data from human epidemiologic studies), the carcinogenicity of radon has been established by the scientific community, including the World Health Organization, the National Academy of Sciences' Biological Effects of Ionizing Radiation Committee, the International Commission on Radiological Protection and the National Council on Radiation Protection and Measurement.

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In addition, radon has been identified as a serious public health problem by a number of U.S. health organizations such as the Centers for Disease Control, The American Lung Association, the American Medical Association and the American Public Health Association. In 1988, the U.S. Surgeon General issued the following national radon health advisory to the public:

Indoor radon gas is a national health problem. Radon causes thousands of deaths each year. Millions of homes have elevated levels. Most homes should be tested for radon. When elevated levels are confirmed, the problem should be corrected.

U.S. Surgeon General

B. History

As early as the 1400s, lung disease was associated with the mining of metal ores in the Erz Mountains of Eastern Europe. A study conducted in the same area in the late 1800s reported that miners were developing lung cancer. In the 1950s and 1960s, through additional studies of miners, the inhalation of RDPs was accepted as the cause of lung cancer in these and other groups of exposed miners.

Beginning in the late 1960s, homes with elevated indoor radon concentrations were discovered in the United States. These elevated radon levels were due to the use of building materials contaminated with radioactivity, such as vanadium and uranium mill tailings, high uranium content concrete, or wallboard constructed with phosphor-gypsum.

In the 1980s, the potential threat to the public health posed by naturally occurring radon became a major concern with the discovery of homes with extremely high radon levels (more than 3,000 pCi/L) on the Reading Prong, a uranium-bearing formation that extends through eastern Pennsylvania, northern New Jersey and southern New York.

C. Mechanism of Lung Cancer Induction

The primary risk of lung cancer from exposure to radon does not come from exposure to the gas itself, but from exposure to its decay products. When radon decays, a number of short half-life decay products are formed, principally polonium-218, lead-214, bismuth-214 and polonium-214.

Polonium-218 and polonium-214 both decay by alpha decay, emitting alpha particles which deposit their energy over a very short distance. Beta or gamma radiation, on the other hand, deposit their energy over greater distances. For radiation protection purposes, alpha particles are considered to be 20 times as harmful inside the lungs as the same energy of either gamma or beta radiation. Thus, polonium-218 and polonium-214 contribute most of the dose responsible for lung cancer. For a given amount of energy, gamma or beta radiation deposit their energy in a manner comparable to patting twenty people on the back. Alpha radiation deposits its energy in a manner comparable to summing all those pats into one solid punch to one individual.

When a radon atom is inhaled, it is likely that it will be exhaled again before it decays. This is because it is inert and does not easily adhere to surfaces. Further, since it has a 3.8-day half-life, radon is unlikely to decay while in the lung. However, as radon concentrations increase, the quantity that decays in the lung increases, resulting in a greater health risk. Experts do not believe that radon gas, exclusive of its decay

products, is a major contributor to the risk of cancer. This is why a filter respirator, which does not remove radon gas, can still provide substantial protection for mitigation workers.

Short-lived RDPs can be breathed in directly (unattached) or attached to particles of smoke, dust, lint or biological aerosols that are floating in the air (see Figure 1-17).

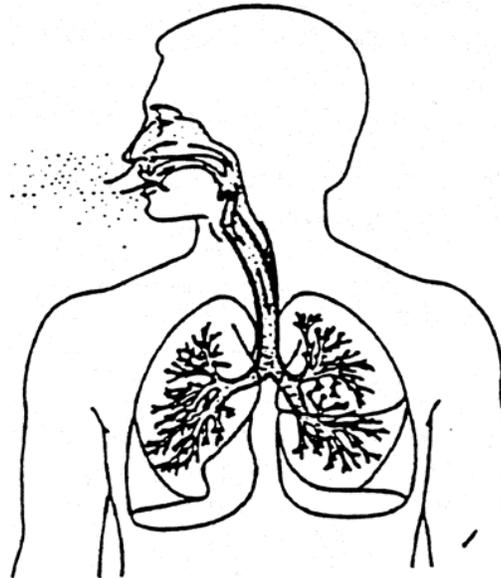


Figure 1-17. Inhalation of Radon Decay Product

Many of these attached and unattached decay products will not be exhaled, but will instead adhere to tissue in the lung. Given the short half-lives of the decay products, the remaining alpha particle decays will occur while in contact with the lung. A portion of the alpha particles emitted will penetrate lung tissue where damage can occur. The energy released by alpha particles can cause permanent damage to DNA molecules, either physically or by chemical means. Most of this damage can prevent further cell division, and eventually the cell will die. Cells also have the capability to repair some damage. In a very small portion of the irradiated cells, the damaged DNA will be replicated in actively dividing cells which may induce lung cancer (see Figure 1-18). This is why exposure to radon and RDPs does not mean that you necessarily will contract lung cancer, but exposure increases that risk.

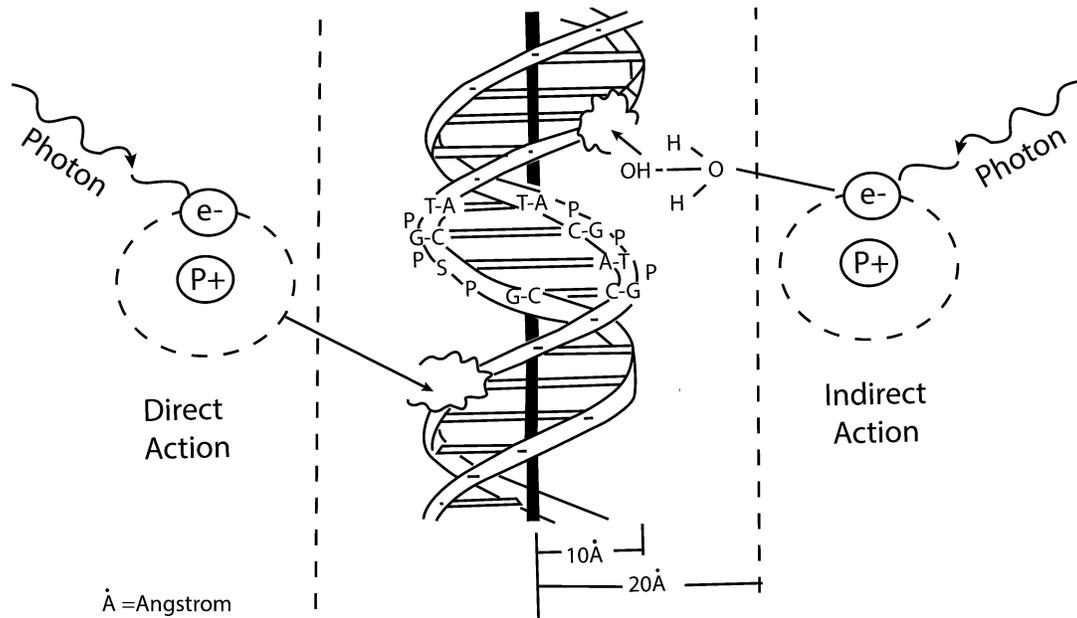


Figure 1-18. Impact of Ionizing Radiation on DNA

D. Scientific Basis for Radon Risk Estimates

The classification of radon as a known human carcinogen and the estimation of health risks from indoor exposure to radon are based on an extensive and consistent body of epidemiologic research on lung cancer mortality in underground miners exposed to radon progeny. Approximately 20 epidemiologic studies of occupational exposure to radon and lung cancer risk have been conducted, and all have indicated an increase in lung cancer incidence with exposure to radon.

1. Miner Studies

Miner studies have been conducted in the United States, Canada, Australia, China and Europe on miners who work in metal, flourspar, shale and uranium mines. In addition to consistently showing an increase in lung cancer risk with exposure to radon, a number of studies have had other important findings (see Figure 1-19 which shows the results of 6 separate studies).

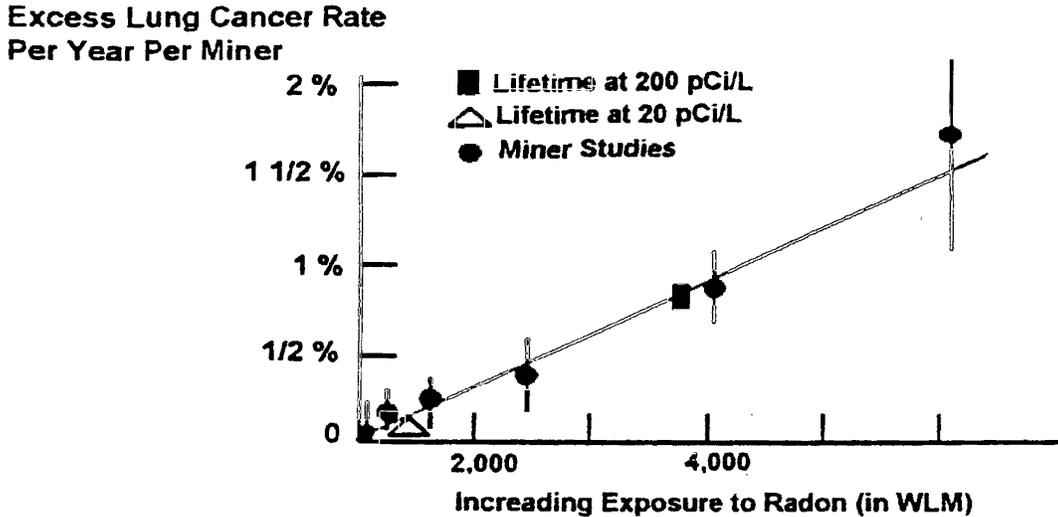


Figure 1-19. Lung Cancer Risk: U.S. Uranium Miners

The miner studies are based upon working level measurements that were made in these occupational settings. Exposure times were also recorded to determine a time and dose record for each of the miners. The term that was used to express the time dose relationship is working level months (WLM). It is an expression of the amount of RDPs to which a person is exposed multiplied by the duration of exposure expressed in fractions of a month. This term comes from occupational exposure records that pertain to the underground mining industry. It can be expressed mathematically:

$$\text{Working level month (WLM)} = \frac{\text{RDP (WL)} \times \text{hours of exposure}}{170 \text{ hours/working month}}$$

Note that the working month is defined as 170 hours and never changes (see Unit 6 for additional explanation).

The assumption is that the degree of risk is a linear relationship between the concentration of exposure and the duration of exposure. For example, a person exposed at 4 pCi/L for 1 year is at the same risk as someone who is exposed at 2 pCi/L for 2 years or 16 pCi/L for three months.

Increased lung cancer risk has been observed at low cumulative exposures (WLM) comparable to cumulative lifetime residential exposures. For example, in a study on uranium miners in Ontario, Canada, the death rate from lung cancer was found to be significantly increased for cumulative exposures as low as 40-70 WLM (exposure to a radon concentration of 4 pCi/L in a home over a lifetime of 70 years, assuming 75% occupancy and an equilibrium fraction of 50% is equivalent to a cumulative RDP exposure of 54 WLM).

In some studies, low exposures over longer periods of time were associated with greater risk than high exposures of shorter duration. This may be particularly important to the estimation of risk from residential radon exposure, as residential exposures tend to be lower exposures received over longer periods of time, while occupational exposures tend to be higher levels received over shorter time

periods. If the lower exposure rates do in fact pose more risk, the current EPA radon risk assessment may be underestimating the risk from residential exposures.

Although the data are presently limited, a National Academy of Science Committee has concluded in its report, entitled Biological Effects of Ionizing Radiation (BEIR IV) that lung cancer risk increases multiplicatively with joint exposure to radon and smoking. In other words, the risks from combined exposure to radon and smoking is greater than the sum of the risks from exposure to either acting alone. As a result of these studies, the EPA has developed a risk chart for residential settings for smokers and non-smokers (see Tables 1-2 and 1-3).

2. Residential Studies

Due to the uncertainty associated with the projection of lung cancer risk from occupational radon exposures to the general population for residential exposures, residential studies have been conducted to examine directly the association between lung cancer risk and exposure to radon progeny in the home. Some of these studies, called ecologic studies, tried to relate the number of lung cancer deaths for a region with substitute measures of exposure for that region. Many of these studies showed a relationship between exposure to radon and an increased risk of lung cancer.

In other studies, called case-control studies, individuals with lung cancer (cases) and individuals without Lung cancer (controls) were compared for differences in home exposures, again using substitute measures of radon exposure. A number of these studies also found an association between indoor exposure to radon and increased lung cancer risk. The 1989 International Workshop on Residential Radon Epidemiology endorsed the use of case-control studies for residential radon research and recommended against the further use of ecologic studies. The reason for this recommendation is that an ecologic study cannot relate the level of radon exposure for an individual to that individual's health status. This type of study does not consider information on individual smoking history or mobility, both of which are very important variables in radon risk assessment. Therefore, ecologic studies are not recommended for the further study of residential radon risk.

Since they collect information on individual subjects, case-control studies have a greater ability to control for factors which may hide the true relationship between radon and lung cancer (e.g., smoking, diet, mobility). They are more appropriate, therefore, for examining the relationship between radon and lung cancer. Recently, four case-control studies were completed, which, unlike most of the earlier studies, used measurements to determine residential radon exposure. The results of these studies were mixed, with two studies finding an association between residential exposure to radon and increased lung cancer risk and two studies finding no association between the two.

In reviewing these and other current residential radon studies, scientists at the 1989 International Workshop on Residential Radon Epidemiology determined that the majority of these studies, when taken individually, do not have the statistical power necessary to give a conclusive picture of the radon-lung cancer association. For this reason, workshop participants decided to pool the results of international case-control residential studies as they are completed. By pooling the data, and thus increasing sample size, scientists hope to determine conclusively the association between indoor radon and lung cancer risk in the residential setting.

3. *Animal Studies*

Experimental animal studies have clearly demonstrated that radon is a lung carcinogen. They have provided important information on the exposure-response relationship, the effect of exposure rate on cancer risk, and the potential effect of simultaneous exposure to radon and other contaminants on the radon-lung cancer relationship. The following is a summary of relevant findings to date from animal studies:

- Health effects observed in animals exposed to radon include lung carcinomas, pulmonary fibrosis, emphysema, and a shortening of life-span.
- Rats exposed to low levels of radon (as low as 20 WLM) were found to have an increased number of respiratory tract tumors.
- The number of respiratory tract tumors were found to increase as cumulative radon exposure increased. Decreased exposure rate was also found to increase the incidence of respiratory tract tumors.
- Rats exposed to radon progeny and uranium dust simultaneously were found to have elevated lung cancer risk at exposure levels similar to those found in homes. The risk decreased as radon exposure decreased.
- Exposure to ore dust or diesel fumes simultaneously with radon did not increase the incidence of lung tumors above that produced by radon exposures alone.

E. Risk Estimates

EPA calculates the lung cancer risk to the U.S. population from residential exposure to radon using the risk projection model developed by the National Academy of Sciences' (NAS) BEIR IV Committee. This model is based on a detailed analysis of four major groups of underground miners.

In estimating radon risks, the EPA has made two adjustments to the model described in the NAS report. First, the model was adjusted to account for background radon exposure, reducing the lifetime risk estimates by about 15% from those projected by the unadjusted model. The second adjustment was based on findings from the NAS report on *Comparative Dosimetry of Radon in Mines and Homes*, which estimated that the dose per unit exposure in homes is approximately 70% of that in mines.

Applying the adjusted BEIR IV mode to a life table based on U.S. 1980 vital statistics gives a risk factor of 224 lung cancer deaths/106 person-WLM, for constant lifetime exposure. The estimated uncertainty range is 140 to 570 lung cancer deaths/106 person-WLM.

As estimated in the EPA's National Residential Radon Survey, the average annual radon exposure is 0.242 WLM (based on the assumption of an equilibrium ratio of 0.5, 75% occupancy, and an average radon concentration of 1.25 pCi/L). Using the above risk factor and the estimate of average annual radon exposure, the number of radon-induced lung cancer deaths per year is estimated to be approximately 14,000.

The uncertainty range for this estimate is approximately 7,000 to 30,000 lung cancer deaths per year in the United States alone. This estimate of uncertainty is detailed in the current EPA radon risk

assessment. An in-depth analysis of the uncertainties associated with the estimation of radon risks was done using an approach developed by the National Institutes of Health. A number of uncertainties associated with both the risk factor and the estimate of average residential radon exposure were quantified. Examples of factors considered in the uncertainty analysis are:

- The effect of age on radon risk.
- Possible differences between homes and mines in terms of dose per unit exposure.
- The effect of exposure-rate on radon risk.
- The effect of mine exposures other than radon (silica dust, diesel fumes, etc.).
- The relationship between radon risk and smoking.

Of these sources of uncertainty, the relationship between radon risk and smoking is often of the greatest concern, because smoking is the leading cause of lung cancer. Although the data are presently limited, scientists at the National Academy of Sciences assume that smoking multiplies the risk from radon exposure. Based on EPA's risks calculations, the risk of lung cancer from radon exposure is almost twenty times greater for a current smoker than for someone who has never smoked.

1. Comparison of Risk Estimates

It may be of interest to compare the EPA estimate of lifetime risk of lung cancer from lifetime exposure to radon with those estimates made by other scientific groups. Table 1-1 lists the risks estimates of the EPA, the BEIR IV Committee, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the National Council on Radiation Protection and Measurements (NCRP).

Report	Cancer Deaths/10⁶ Person WLM
EPA(1992)	224
BEIR VI (1999)	350
UNSCEAR (1977)	200-450
NCRP (1984)	130

Table 1-1 Lifetime Risk of Lung Cancer Mortality from Lifetime Exposure to Radon

2. EPA Citizens Guide

Tables 1-2 and 1-3 are risk tables for smokers and non-smokers which are part of the EPA's 1992 edition of the Citizens Guide to Radon (see appendix I-1). These tables are extremely helpful and should be used in interpreting risks to clients of a radon professional.

Unit 1. Radon Occurrence and Health Effects

Radon Level (pCi/L)	If 1,000 people who smoked were exposed to this level over a lifetime*	The risk of cancer from radon exposure compares to**	Solution: <i>Stop smoking and...</i>
20	About 260 people could get lung cancer	250 times the risk of drowning	Fix your home
10	About 150 people could get lung cancer	200 times the risk of dying in a home fire	Fix your home
8	About 120 people could get lung cancer	30 times the risk of dying in a fall	Fix your home
4	About 62 people could get lung cancer	5 times the risk of dying in a car crash	Fix your home
2	About 32 people could get lung cancer	6 times the risk of dying from poison	Consider fixing between 2 and 4 pCi/L
1.3	About 20 people could get lung cancer	(average indoor radon level)	Reducing radon levels below 2 pCi/L is difficult
0.4	About 3 people could get lung cancer	(average outdoor radon level)	

Note: If you are a former smoker, your risk may be lower.
 *Lifetime risk of lung cancer deaths from EPA Assessment of Risks from Radon in Homes (EPA 402-R-03-003)
 **Comparison data calculated using the Centers for Disease Control and Prevention's 1999-2001 National Center for Injury Prevention and Control Reports.

Table 1-2. Radon Risk if You Smoke

Unit 1. Radon Occurrence and Health Effects

Radon Level (pCi/L)	If 1,000 people who never smoked were exposed to this level over a lifetime*	The risk of cancer from radon exposure compares to**	Solution:
20	About 36 people could get lung cancer	35 times the risk of drowning	Fix your home
10	About 18 people could get lung cancer	20 times the risk of dying in a home fire	Fix your home
8	About 15 people could get lung cancer	4 times the risk of dying in a fall	Fix your home
4	About 7 people could get lung cancer	The risk of dying in a car crash	Fix your home
2	About 4 people could get lung cancer	The risk of dying from poison	Consider fixing between 2 and 4 pCi/L
1.3	About 2 people could get lung cancer	(average indoor radon level)	Reducing radon levels below 2 pCi/L is difficult
0.4	No information	(average outdoor radon level)	

Note: If you are a former smoker, your risk may be higher.
 *Lifetime risk of lung cancer deaths from EPA Assessment of Risks from Radon in Homes (EPA 402-R-03-003)
 **Comparison data calculated using the Centers for Disease Control and Prevention's 1999-2001 National Center for Injury Prevention and Control Reports.

Table 1-3 Radon Risk if You Have Never Smoked

F. National Radon Programs

The discovery of elevated indoor radon concentrations from naturally occurring radon sources prompted action at the federal level in the United States to reduce both occupational and residential exposure to radon.

1986: The United States Environmental Protection Agency recommended that all homes be tested for radon and that elevated levels be reduced.

1987: The National Institute for Occupational Safety and Health recommended a reduction in the limit for exposure to radon progeny in underground mines from 4 WLM per year to 1 WLM per year.

1988: The United States Congress enacted the Indoor Radon Abatement Act (IRAA), which set as a national goal the reduction of radon levels in buildings to the level in ambient air outside buildings.

1989: The United States Environmental Protection Agency recommended that school nationwide be tested for radon.

Under the IRAA, the EPA is directed, among other things, to establish action levels and to describe the health risks associated with different levels of indoor radon exposure.

The EPA has set a radon action level of 4 pCi/L. This means that the Agency recommends that action be taken to reduce radon levels in homes or buildings that are found to be at or above 4 pCi/L.

Unit 1. Radon Occurrence and Health Effects

The governments of Canada and many western European nations have also instituted radon programs and have established recommended action levels. Some governments also have programs that offer financial aid for mitigation of homes with high radon levels. Table 1-4 lists recommended action levels both for existing and new buildings across countries that currently have an action level.

Recommended Action Level Bq/m³ and pCi/L

Country	Existing Dwellings		New Buildings	
	Bq/m ³	pCi/L	Bq/m ³	pCi/L
Canada	200	5.4	-	-
Finland	800	22	200	5
Germany	250	7	250	7
Ireland	200	5	200	5
Luxembourg	250	7	-	-
Norway	800	22	200	5
Spain	400	11	200	5
Sweden	400	11	140	4
Switzerland	200	5	-	-
United Kingdom	200	5	200	5
United States	150	4	150	4

Table 1-4. Comparison of International Radon Action Levels

G. Comparative Radiation Standards

Table 1-5 compares the EPA action guideline of 4 pCi/L for indoor radon to several regulatory radiation standards.

Unit 1. Radon Occurrence and Health Effects

Standard	Value	pCi/L Equivalent
EPA		
Radon Action Level	4 pCi/L	4 pCi/L (0.02 WL)
Nuclear Regulatory Commission*		
Current Public Exposure Limit	0.5 rem/yr*	2 pCi/L **
Proposed Public Exposure Limit	0.1 rem/yr *	0.4 pCi/L **
Occupational Exposure Limit	5 rem/yr *	20 pCi/L **
Occupational Safety & Health Administration		
Miner Exposure Limit	4WLM/yr	16 pCi/L **
National Institute for Occupational Safety & Health		
Proposed Miner Exposure Limit	1WLM/yr	4 pCi/L **

* Whole Body Radiation Exposure

**Assumes 100% occupancy and 50% equilibrium fraction

Table 1-5. Comparison of Regulatory Radiation Standards and EPA's Action Level

References

Note: the following incomplete citations (sic) were provided in current EPA draft "Reducing Radon in Structures" Manual.

1. Axelson, O., "Mining, Lung Cancer and Smoking," *Scandinavian Journal of Work and Environmental Health* 4, 46, 1978.
2. Chameaud, J., "The Influence of Radon Daughter Exposure and Low Doses on Occurrence of Lung Cancer in Rats," *Radiation Protection Dosimetry* 7, 385, 1984.
3. Eheman, C., "Lung Cancer Risks from Exposure to Radon," Centers for Disease Control.
4. Hoffinan, W., "Lung Cancer Risk at Low Dose of Alpha Particles," *Health Physics* 5 1,457, 1986.
5. Klotz, J., "Estimating Lung Cancer Risks of Indoor Radon: Applications and Prevention," proceedings of APCA Specialty Conference - Indoor Radon, 1985.
6. Klotz, J., personal communication to Terry Brennan, December 1987.
7. Martell, E., "Alpha Radiation Dose at Brochial Bifurcations of Smokers from Indoor Expo- sure to Radon Progeny," proceedings of the National Academy of Sciences USA, 80, 1285, 1983.
8. National Council on Radiation Protection and Measurements, "Exposures from the Uranium Series with Emphasis on Radon and its Daughters," NCRP Report No. 78, 1984.
9. Nazaroff, W.W. and Nero, A.V., *Radon and its Decay Products in Indoor Air*, John Wiley & Sons, 1988.
10. Park, J., "Estimation of Lung Cancer Risk from Inhaled PuO₂ in Beagle Dogs," *Health Physics*, 1985.
11. US EPA, Office of Air and Radiation, *Citizens Guide to Radon*, Document 402- K92- 001, May 1992.

Unit 1. Summary and Highlights

- **Fundamental**—atoms consist of a positively-charged nuclei and one or more negative electrons. The nucleus of an atom contains one or more positively-charged protons and uncharged neutrons. Protons and neutrons are about the same size while electrons are much smaller. The atomic number of an element reflects the number of protons while the mass number reflects the number of protons and neutrons. Radon 222 (mass number) has 86 protons (atomic number) and 136 neutrons. An ion is one or more electrically-charged atoms where protons and electrons are not equal. Energetic radiations can impact and alter atoms, such as those in human tissue, produce ions, and are known as ionizing radiation.
- **Radon** is responsible for the majority of the U.S. population's exposure to radiation. The major source of radon is emanation from soil.
- **Basic/Foundation**—radon is a radioactive element that is an inert or chemically inactive gas produced by decay of natural radium. Since it is a gas, radon moves easily through small spaces. Radon is odorless, invisible, and tasteless as well as moderately soluble in water. Radium, which produces radon, is the decay product of thorium and uranium found in rock and soil. Uranium-238 decays to radium-226 which decays into radon-222. Thorium-232 decays to radon-220 (a radon isotope called thoron) which has a half-life of only 55 seconds and thus represents a less important source of radon exposure than radon-222 (estimated to be about 25%). Thus, only radon-222 is specifically addressed in most EPA documents.
- **Radioactive decay** involves the release of radiation (charged alpha and beta particles and gamma rays from the decay of the nucleus of an atom). The level of radioactivity is measured in curies and 1 curie = 37 billion disintegrations per minute (the radioactivity of 1 gram of radium).
- Radon is measured in picocuries per liter (pCi/L) where 1pCi/L is =2.2 disintegrations per minute/per liter of air. One picocurie is one trillionth of a curie.
- Alpha particles have high ionizing capacity (greatest health risk - damaging DNA molecules of living cells) but are low in penetrating power.
- Beta particles have moderate penetrating power.
- Gamma rays have high penetrating power.
- **Radon has a half-life** of 3.8 days which means that half of the radon in a sealed volume will have decayed in 3.8 days, half of the remainder in the next 3.8 days, and so on. Thus, if we seal 200 pCi/L in a cell, 3.8 days later we would have 100 pCi/L, 7.6 days later we would have 50 pCi/L, and 11.4 days later we would have 25 pCi/L and so on.
- Radon decays into a series of elements commonly referred to as **radon decay products** (RDPs). RDPs have short half-life (minutes or less), are electrically charged, chemically reactive particles that represent a greater health risk than radon itself. Specifically, polonium 218 and polonium 214 are alpha emitters in the RDP chain.
- RDPs are measured in working levels (WL) where 1 WL = ultimate emission of 1.3×10^5 of MeV of potential alpha energy.

Unit 1. Radon Occurrence and Health Effects

- **FORMULA** - if we seal radon in a cell it will decay into RDPs. In about 4 hours, 100 pCi/L will produce a maximum concentration of 1 WL of RDPs. Thus, using the formula ER =

$$\frac{WL \times 100}{pCi/L}$$

or

$$\frac{1 \times 100}{100} = 1$$

- The maximum theoretical equilibrium ratio (ER) = 1 (although some measurements may capture the decay of thoron, another radon isotope, that could result in an erroneous ER above 1).
- Key - indoors, ER is commonly assumed to be equal to 0.5 (0.3 to 0.7) since some radon infiltrates and exfiltrates before decaying. Furthermore, some RDPs "plate out" to surfaces due to electrical charges. A high ER = little air movement or low outdoor air exchange; a low ER = lot of air movement and perhaps filtering.
- The best documented health risk of exposure to radon and RDPs is Lung cancer; other cancer risks are possible but are not as well documented. Chapter 2 of the Technical Support Document for the 1992 Citizen's Guide to Radon as well as Unit 1 in "Reducing Radon in Structures"; present a summary of radon health risk estimates.
- Health risk has been established by: 1) accepted scientific models of physical damage from alpha radiation; 2) studies of animal exposure; 3) comparative studies of underground miners over time (epidemiologic studies; ecologic studies, using group exposure and disease data, cannot establish a cause-effect relationship; case-control studies of residential radon exposure and lung cancer risk are underway); and 4) documentation of human exposure. Radon is a Class A (known human) carcinogen.
- Risk is related to: 1) cumulative length of exposure; and 2) concentration of radon and RDPs; as well as 3) compounding factors, especially smoking (about 85% of lung cancers attributed to smoking also involve radon). There is no known safe level or threshold of radon exposure.
- **FORMULA** - the RDP-time-dose-exposure relationship is expressed in working level months (WLM) where

$$1 \text{ WLM} = \frac{WL \times \text{hours}}{170 \text{ hours}}$$

- **New** - radon outdoors in the U.S. averages, on an annual basis, about 0.4 pCi/L and indoors, in living areas of residences, is 1.25 pCi/L. The indoor average is based upon year-long radon measurements of all lived in levels in 6,000 randomly selected U.S. homes. Thus, the average U.S. cumulative residential radon exposure is 0.242 WLM (assumes ER=0.5 and 75% average day in home).
- **New** - EPA estimates 20,000 (10,000 to 30,000) annual lung cancer deaths in the U.S. due to residential radon exposure.
- **New** - EPA estimates that 6% of U.S. homes have average annual indoor radon concentrations in "frequently occupied" areas above 4 pCi/L.

Unit 1. Radon Occurrence and Health Effects

- **New** - at 4 pCi/L in the home, EPA estimates the radon risk over a life-time at about:
 - 1% or 1 in 100 for the total U.S. population.
 - 3% or 1 in 33 for smokers (about 100 times the risk of dying in an airplane crash).
 - 0.2% or 1 in 500 for non-smokers (about the risk of drowning or 2 times the risk of dying in a home fire).
- **New** - although EPA continues to use 4 pCi/L as an "action level," the Agency has clarified that radon levels lower than 4 pCi/L pose a risk and thus, EPA advises that the public may wish to consider reducing levels to between 2 and 4 pCi/L.
- **UBI (Useful or Useless Bit of Information)** - EPA's threshold for action (4 pCi/L) is not a health-based standard; rather, it's based upon technology available in the 1970's to reduce radon in homes contaminated with uranium mine tailings. Always test and mitigate if levels are between 3 and 4 pCi/L.

Unit 1. Review Questions, Form A

1. Which of the following has a charge of +2e?
 - A. alpha radiation
 - B. beta radiation
 - C. gamma radiation
 - D. X radiation

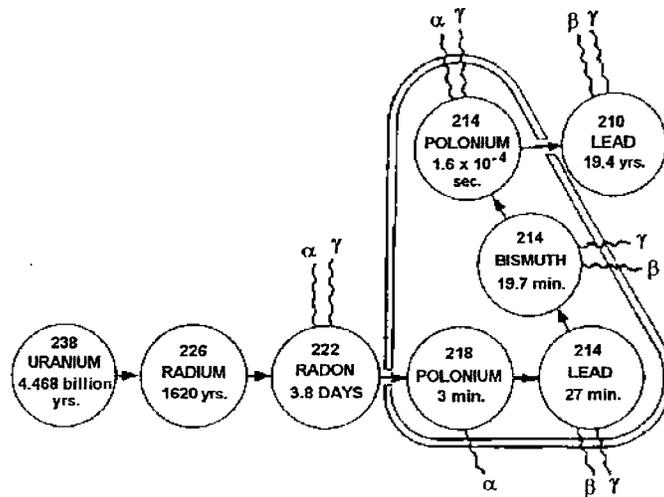


Figure 102

2. Given a 20 gram source of pure polonium-218, use the information in figure 102 to approximate how many grams of polonium-218 should remain after 9 minutes.
 - A. 10.00
 - B. 5.00
 - C. 2.50
 - D. 1.25
3. What is radon equilibrium ratio?
 - A. the relationship between unattached radon decay product concentration and attached radon decay product concentration

Unit 1. Radon Occurrence and Health Effects

- B. the relationship between radon decay product concentration and radon gas concentration
 - C. the fraction of waterborne radon that escapes when the water is no longer under pressure
 - D. the proportion of indoor radon concentration to outdoor concentration
4. Which approach will definitely reduce a person's risk of developing a radon or radon decay product related cancer?
- A. cleaning air by filtering it
 - B. exhausting air from the building with a whole-house fan
 - C. improving air circulation in a room with a ceiling paddle-fan
 - D. limiting the duration of the exposure
5. Why is the USEPA action level for radon in homes set at 4 pCi/l instead of 0 pCi/l?
- A. USEPA believes its choice of an action level is a safe level
 - B. It can be very difficult to lower radon levels below 2 pCi/l
 - C. The biological effects information does not warrant a lower action level
 - D. The radon lobby was successful in adjusting the action level upward

Unit 1. Answers to Review Questions, Form A

Review Question	Answer	Student Manual; Unit 1, Page Number
01.1	A	7
01.2	C	4-5
01.3	B	10-12
01.4	D	16-19
01.5	B	20-23