A LIVING RADON REFERENCE MANUAL

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Abstract

This "living" manual is a compilation of facts, figures, tables and other information pertinent and useful to the radon practitioner, some of which can be otherwise difficult to find. It is envisioned as a useful addition to one's desk and radon library. This reference manual is also intended to be a "living" document, where its users may supply additional information to the editors for incorporation in revisions as well as updates to this document on-line. Topics contained within the current version include radon chemistry and physics, radon units, radon fans, epidemiology, ambient radon, diagnostics, dosimetry, history, lung cancer, radon in workplace and radon statistics. In some cases motivations and explanations to the information are given. References are included.

Introduction

This reference manual is a compilation of facts, figures, tables and information on various aspects of radon science. It is hoped that this manual may prove useful to federal and state employees, groups such as AARST and CRCPD, and industry.

There are numerous other reference manuals that have been produced on the various aspects of radon science; however, we hope that this manual will have a more "applied" use to all of the various radon practitioners who may use it.

Many of the snippets on the various pages are highlights from referenced sources. The snippet will obviously only provide one with the briefest of information. To learn more about that item go to the reference and read the whole paper.

It is our intent to continually update this manual with the help of all those mentioned above. Especially helpful would be remarks, comments and additions to the manual from anyone inclined to help. Please forward any contributions to rolewis@state.pa.us. The authors who will act as editors reserve all editorial rights.

September 14, 2009

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Chemistry of Radon

Atomic Number: 86

Symbol: Rn

Atomic Weight: 222.0176

Discovery: Fredrich Ernst Dorn 1898 or 1900 (Germany) discovered the element and called it radium emanation. Ramsay and Gray isolated the element in 1908 and named it niton.

Word Origin: from radium. Radon was once called niton, from the Latin word nitens, which means "shining."

Isotopes:
At least 20 isotopes of radon are known. Radon-220 is commonly called "thoron" and emanates naturally from radium-224, one of the decay products of thorium-232. Thoron is an alpha-emitter with a half-life of 55.6 sec. Radon-219 is commonly called "actinon" and emanates from radium-223, a decay product of actinium-227. It is an alpha-emitter with a half-life of 3.96 sec.

Properties:
Radon has a melting point of -71° C, boiling point of -61.8 °C, gas density of 9.73 g/l, specific gravity of the liquid state of 4.4 at -62°C, specific gravity of the solid state of 4 and usually a valence of 0 (it does form some compounds, however, such as radon fluoride). Radon is a colorless gas at normal temperatures. It is also the heaviest of the noble gases. When it is cooled below its freezing point it displays brilliant phosphorescence. The phosphorescence is yellow as the temperature is lowered, becoming orange-red at the temperature of liquid air. Inhalation of radon decay products presents a health risk. Radon build-up is a health consideration when working with radium, thorium or actinium. It is also an issue in uranium mines.

Sources:

It is estimated that each square mile of soil to a depth of 6 inches contains approximately 1 g of radium, which releases radon to the atmosphere. The average concentration of radon is about one in sextillion parts of air (1 radon atom in 10^{21} air atoms.). Radon naturally occurs in some spring waters.

Element Classification: Inert Gas

Density (g/cc): 4.4 (@ -62°C)

Melting Point (°K): 202

Boiling Point (°K): 211.4

Appearance: heavy radioactive gas

Specific Heat (@20°C J/g mol): 0.094

Evaporation Heat (kJ/mol): 18.1

First Ionizing Energy (kJ/mol): 1036.5

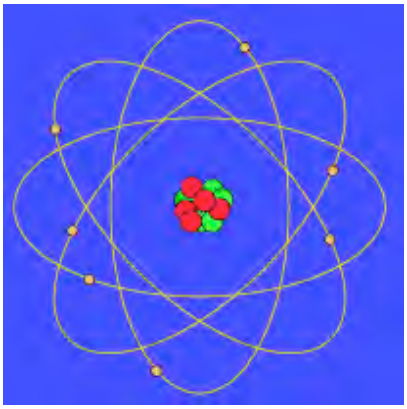
Lattice Structure: Face-Centered Cubic

References: Los Alamos National Laboratory (2001), Crescent Chemical Company (2001), Lange's Handbook of Chemistry (1952), CRC Handbook of Chemistry & Physics (18th Ed.) and http://chemistry.about.com/od/elementfacts/a/radon.htm

Physics of Radon

Atomic and Nuclear Structure

Let's first recognize that atoms consist primarily of electrons, protons and neutrons. Interestingly, the protons and neutrons exist in a very small central region called the nucleus, while the electrons orbit outside this region at quite a distance comparatively as seen in this drawing.



The number of protons in the nucleus uniquely defines the element of which the atom is a part. For example, if there is only one proton in the nucleus of an atom, that atom is a hydrogen atom, no matter how many neutrons or electrons are also part of that atom. If there are 86 protons in the nucleus of an atom, that atom is a radon atom, again regardless of how many protons or neutrons are in that atom.

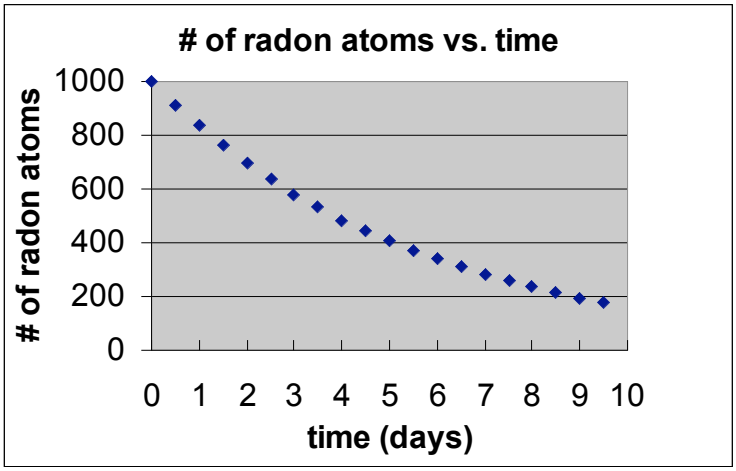
Radioactive decay is defined to be the spontaneous breakup of an atom. Not all atoms are radioactive and those that are not are called "stable." If we have a group of radioactive atoms, such as radon, or uranium or plutonium, if we just wait a while, some of them will break up or explode spontaneously. Moreover, it is interesting to note that this "break up" or decay is relatively easy to model.

An analysis of this decay points out that every radioactive element has a unique half-life. Half-life being defined as the time it takes for half of a sample's atoms to decay to the next nuclide in the decay chain.

For example, U-238 is radioactive with a half-life of 4.47 billion years. This means if you have 1000 U-238 atoms in your hand today and wait 4.47 billion years you will have only 500 U-238 atoms in your hand, and in another 4.47 billion years, you will then have only 250 U-238 atoms in your hand. All right, so there's a slight problem here in having you live that long, but you get the point.

If we take Radon as an example, its half-life is 3.82 days. Therefore, if you have 1000 radon atoms in your hand today, in 3.82 days you will have just 500 radon atoms and in

another 3.82 days, or a total of 7.64 days, you will have 250 atoms. The graph below depicts this decay rate.



This is also sometimes called exponential decay, simply because the number of radon atoms N(t) existing at the time t is given by the equation:

$$N(t) = N_i \times \exp^{-\lambda t}$$

Where N_i is the number of radon atoms existing initially at t = 0, λ is the decay constant, or the probability of decay per unit of time (e.g. 2 per second, or in this case 0.181 per day) and t is the time as measured from when the initial number N_i exist. Notice from the graph and the equation above that the number of radon atoms is predicted to go to zero only after a very long time. Actually, after the number of atoms decreases to a small number, the statistical assumptions leading to the concept of half-life fail. Fortunately, one very rarely comes upon situations where the number of atoms is that small.

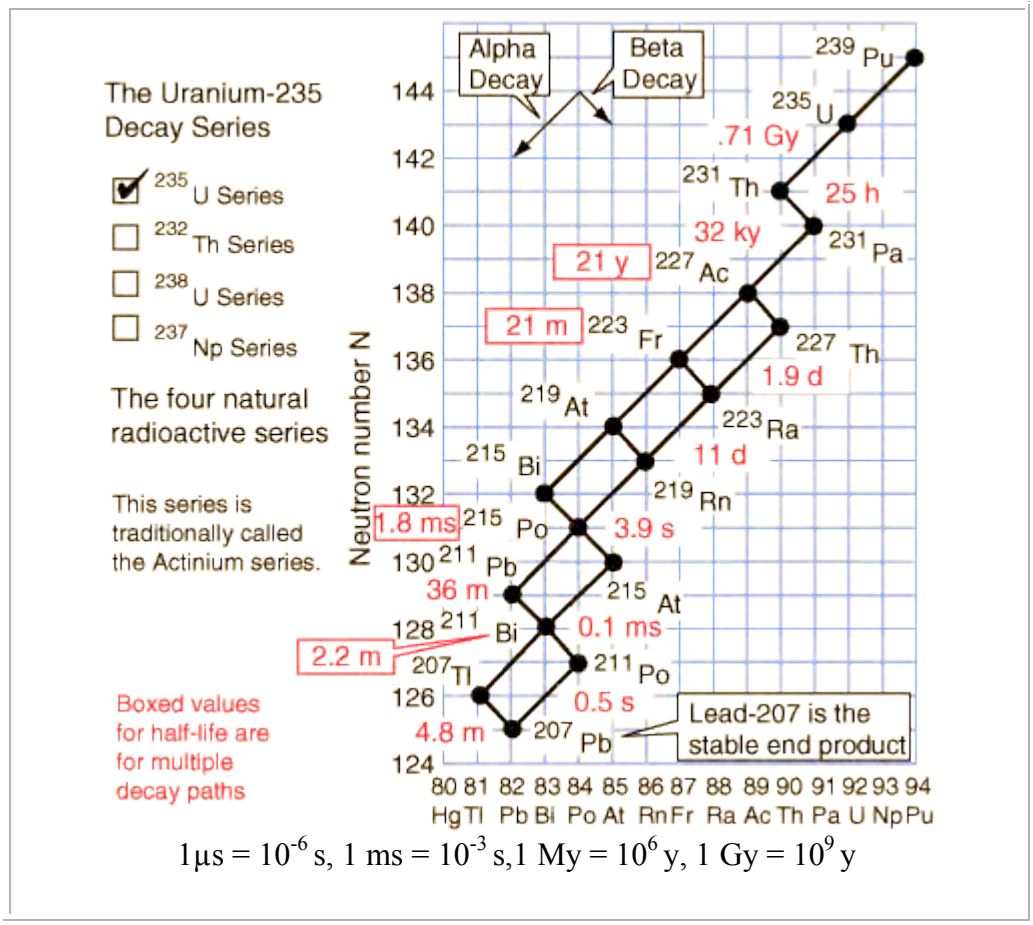
Distribution of the Heavy Elements

Uranium is a common element found almost everywhere within both the earth's crust and seawater in varying concentrations.

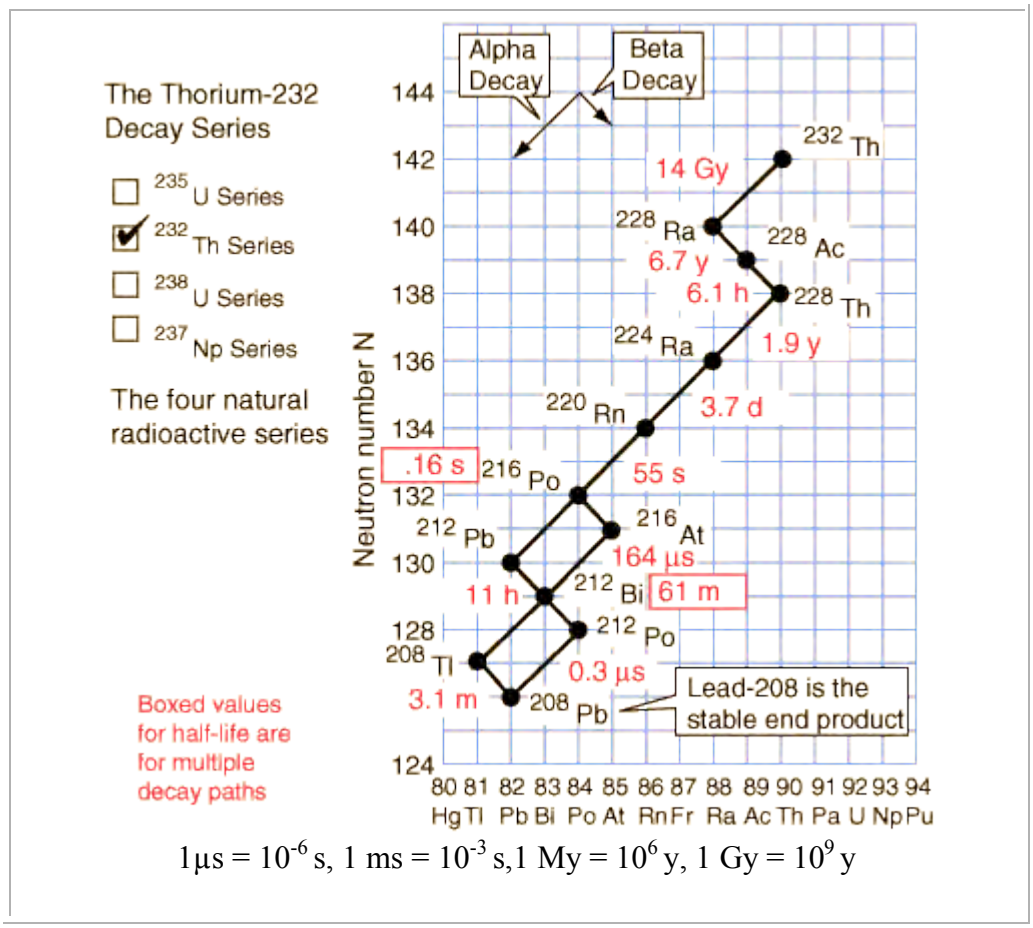
In nature, uranium atoms exist as uranium-238 (99.284%), uranium-235 (0.711%) and a very small amount of uranium-234 (0.0058%). Uranium decays slowly by emitting an alpha particle. The half-life of uranium-238 is about 4.47 billion years and that of uranium-235 is 704 million years, making them useful in dating the age of the Earth.

There are four decay chains of importance when considering naturally occurring radioactive materials, each defined by its heaviest natural (not man-made) element. These are the U-235 series (also called the Actinium Series), the thorium-232 series (the Thorium Series), the U-238 series (the Uranium Series) and the Np-237 series (the

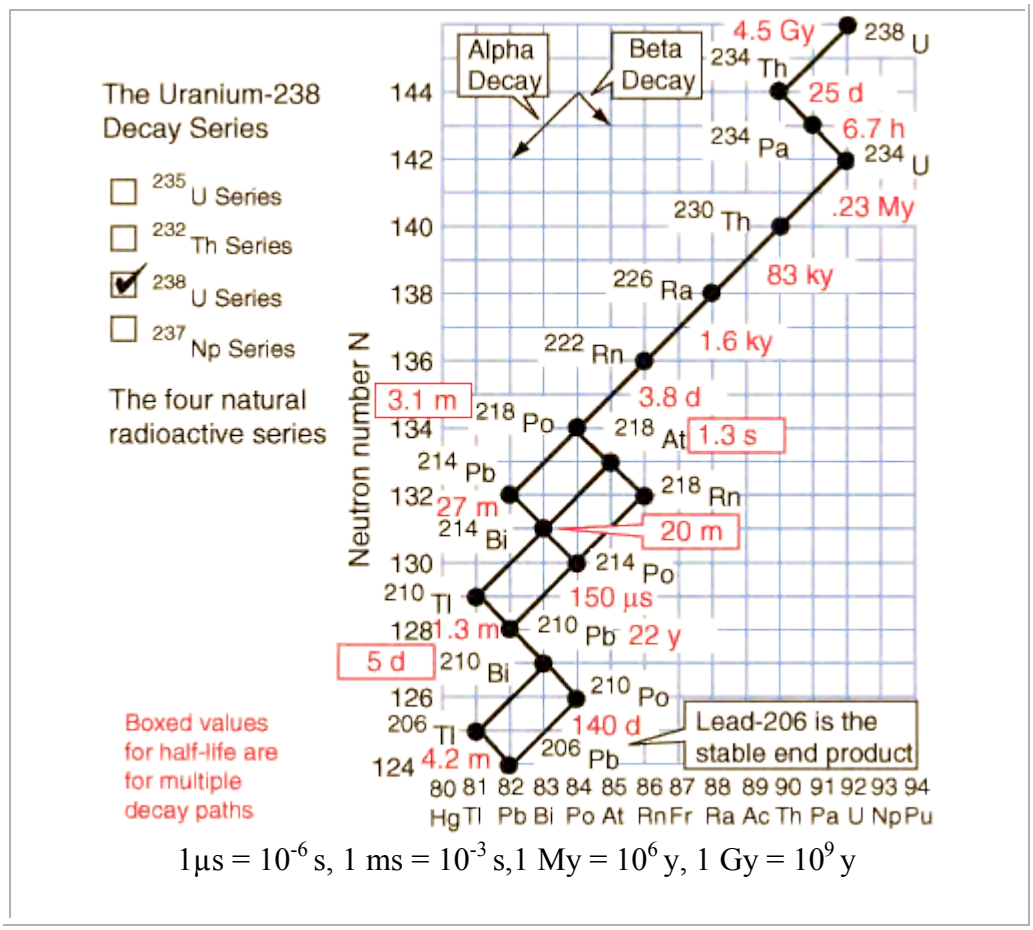
Neptunium Series); graphical depictions of each are shown below. The one of most interest to us is the decay chain that includes radon-222, namely the U-238 series.



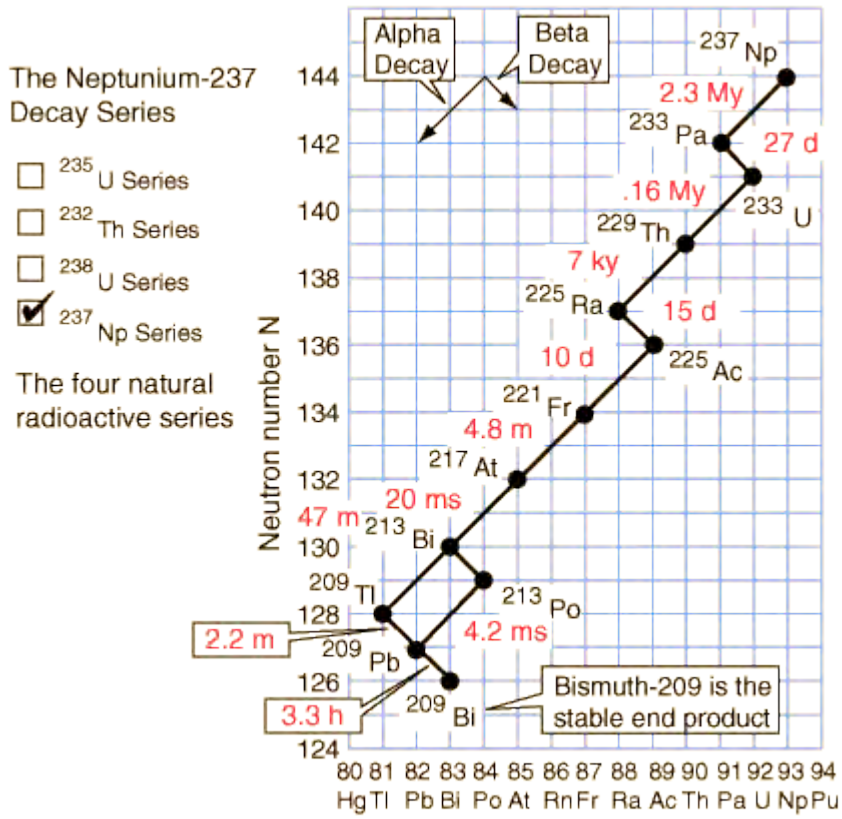
$1\mu s = 10^{-6}$ s, 1 ms = 10^{-3} s,1 My = 10^{6} y, 1 Gy = 10^{9} y



$1\mu s = 10^{-6}$ s, 1 ms = 10^{-3} s,1 My = 10^{6} y, 1 Gy = 10^{9} y



$1\mu s = 10^{-6}$ s, 1 ms = 10^{-3} s,1 My = 10^{6} y, 1 Gy = 10^{9} y



$1\mu s = 10^{-6}$ s, 1 ms = 10^{-3} s,1 My = 10^{6} y, 1 Gy = 10^{9} y

The members of this series are not presently found in nature because the half-life of the longest-lived radionuclide in the series is short compared to the age of the earth. Further, this chain does not include an isotope of radon.

Reference: http://hyperphysics.phy-astr.gsu.edu/HBASE/hframe.html

The U-238 series is the one that produces radon 222 and if you'll note from that series, radon is the only element which is gaseous at STP. This is the crux of the problem for as the uranium-238 decays into its decay products, all the solids remain within the earth (or seawater), and the radon, being gaseous, has the mobility to percolate up through the earth and into the atmosphere, or into a house which may be above the percolating radon.

If you will consider for a moment the radioactive decay series above, which begins with U-238, we see that one of the radionuclides in that decay chain is radon 222. And when radon 222 decays it does so by giving off an alpha particle, leaving behind a polonium-218 atom, which then decays further to At-218 or Pb-214. In this case, it has two routes by which it can decay; the one is by alpha decay, the other by beta decay.

The route which is called "alpha decay" is called that simply because the Po-218, or for that matter the Rn-222, emits an alpha particle, which consists of two protons and two neutrons held tightly together. (This alpha particle is also the nucleus of the helium atom.) The route called beta decay is called that simply because the Po-218 can decay when one of its neutrons, within the nucleus, breaks up into a proton and an electron, emitting the electron immediately. So the net result in this case is an electron is shot out from the nucleus. Now this is not one of the electrons that have been orbiting the nucleus, but a new one made up from the neutron that decayed. So to prevent us from confusing that electron from the orbiting ones, that electron is called a "beta" particle. It is identical to all electrons in all regards, but is called a beta particle to remind us of its origin, the nucleus.

As a further aside, it is not possible for an electron to exist inside a nucleus—the result of an interesting quantum mechanical phenomenon, so that when it's created, it must immediately exit the nucleus. The neutron that decayed cannot decay simply into an electron for a host of reasons, so it decays into a proton and that emitted electron. The proton, however, is free to remain in the nucleus, which then increases the number of protons and changes the element itself.

Radioactive Decay Laws and Equilibrium

Activity: Consider a number of radioactive nuclei of the same isotope, e.g. Rn-222 which has a half-life of 3.82 days. Let N(t) represent the number of those nuclei that exist at the time "t." The equation which describes the number that exist at the time "t" is given by

$$N(t) = N_i \exp^{(-\lambda t)}$$

Where N_i represents the number of that nuclei that exist initially, at t = 0, and λ is the decay constant, which represents the decay probability for that nuclei, e.g. for Rn-222 its value is 0.181/day. That is, the probability of a given radon atom decaying in one day is 0.181. This decay constant is related to the half-life $t_{1/2}$ by the equation

$$\lambda = \frac{.693}{t_{\frac{1}{2}}}$$

The "activity" of a sample of N(t) radioactive atoms can be calculated from

Activity = λ N(t). This represents the number of radioactive atoms that decay per second or per day. For example, the activity of 1,000,000 radon-222 atoms is

$$\lambda N = .18 \times 1{,}000{,}000 = 180{,}000 atoms / day$$

This can easily be changed to decays per second by converting days to seconds. In this case, the activity becomes about 2 atoms/second. That is, λN , the activity or quantity of a radionuclide, is the number of atoms that are decaying per second at a given time.

Now we can consider equilibrium. If we continue with the radon-222 atom as the example, we can recognize that it decays from radon-222 into Po-218, which has a half-life of 3.1 minutes, or a decay constant, λ_{Po}, of .0037 atoms/second. So it decays rather quickly, at least in comparison to radon-222 which has a decay constant, λ_{Rn}, of 0.000002 atoms/second. So what happens if we start with 1,000,000 radon-222 atoms initially and nothing else in our container? As the radon decays, it becomes Po-218 which then decays further. So initially, the number of radon-222 atoms decreases and the number of Po-218 atoms increases. After a while though, because the Po-218 half-life is short compared to that of Rn-222, the number of Po-218 atoms reaches a maximum and then eventually decreases at the same rate that the Rn-222 decays. This does not mean the half-life of Po-218 has changed, it has not. But the number of new atoms of Po-218 being created by the decay of the Rn-222 and the number of Po-218 atoms decaying yield a net effect that the rate at which the number of Po-218 atoms changes is the same rate with which the number of radon-222 atoms decreases. This is called "secular equilibrium" and occurs when the half-life of the decay product is short compared to that of the parent radionuclide.

This result, can be written as

$$\lambda_{Po} N_{Po} \approx \lambda_{Rn} N_{Rn} .$$

It takes about four hours for all of the short-lived decay products of radon-222 to come into complete secular equilibrium with an initially pure amount of radon.

Radiation Type	Energy content	Range in medium
Radio Waves	1 millionth eV	
Visible Light	1 to 3 eV	
Ultraviolet Light	3 to 10 eV	
X-rays	10 eV to 120 keV	
Gamma rays	Few keV to 10 MeV	Hundreds of miles in air
Beta particles	Few keV to 1 MeV	Dozens of feet in air
Alpha particles	4 to 8 MeV	A few inches in air

Some radiation types with typical energy values and in some cases their range in a given medium.

Plate Out

Radon atoms are typically electrically neutral, that is they have as many electrons surrounding the nucleus as there are protons within the nucleus. Being neutral they are not attracted to materials in their surroundings, such as furniture, walls, carpeting, etc. But this is not the case with the radon progeny such as Po-218 and Pb-214, for example. These progeny may be electrically charged upon their creation during the radioactive decay process and may be attracted to surfaces found within the rooms where the radon decayed into these radionuclides. Therefore, while the radon floats around in the room quite easily, many of the progeny become attached to furniture, etc. and therefore are removed to a large degree from becoming a health hazard.

If there is no plate out then it is generally taken that 100 pCi/l of radon yields 1 working level (WL) of radon progeny in the air. However, with a typical amount of plate out of approximately 50%, then of course one can easily see that it would take 200 pCi/l of radon to produce a concentration of 1 WL of radon progeny in the air.

Plate out can be affected by

a. Attachment rates
b. Ventilation
c. Deposition of unattached progeny

One can easily picture that if there is a modest amount of air movement within a given environment that the progeny will more frequently find themselves in contact with other surfaces in the room, therefore yielding a greater amount of plate out than if there were little air movement within the room.

Thoron

Thoron, the common name for Rn-220 is also a gas and is found in the thorium-232 decay series (see above). Its half-life is 55 seconds and it decays via alpha emission producing an array of radon progeny somewhat like Rn-222. The health risk due to Rn-220, like that of Rn-222, is due mostly to the alpha emission of its progeny.

Because of its short half-life, it has not been considered to be a significant radiobiological hazard. However, there is some research to indicate occasions where that is not the case. Further some "grab-sample" measurements may be made in such a way that thoron has an impact on the concentrations of radon-222 that are reported.

Radon Units

Energy

BTU is defined as the amount of energy needed to raise one pound of water held at one atmosphere pressure by one degree Fahrenheit, from 60 °F to 61 °F.

Calorie is defined as the amount of energy needed to raise one gram of water from 14.5 °C to 15.5 °C at one standard atmosphere of pressure.

Electron volt is defined as the amount of energy by which an electron's energy increases as it passes through one volt of potential difference.

MeV is defined as one million electron volts.

Erg is defined as the amount of work done by a force of one dyne exerted for a distance of one centimeter.

Joule is defined as the amount of energy expended by a force of 1 newton over a distance of one meter.

Disintegration

Each time a radioactive atom decays, that is termed one "disintegration." As an example, radon-222 decays by emitting an alpha particle and becoming polonium-218.

Half-life

If you begin with a number of radon-222 atoms, e.g. 1,000,000, then after 3.82 days you would have only 500,000 radon-222 atoms left and as you watched the number of radon atoms decay, even though their half life is 3.82 days, some would decay every second you are watching them. Hence, we would have a number of disintegrations per second. The number of disintegrations per second is proportional to the number of radon atoms we have at that given second and hence is a measure of the health risk of the radon atoms. So the unit of dis/sec becomes important. The number of disintegrations/second is also called the activity of the sample.

Some other units which are related to dis/sec are:

1 becquerel (Bq)	**= 1 dis/sec**
1 curie (Ci)	**= 3.7 x 10^{10} dis/sec**
1 picocurie (pCi)	**= 0.037 dis/sec**
1 picocurie/liter (pCi/l)	**= 0.037 dis/sec/liter**
1 pCi/l	**= 37 Bq/m^3**

Exposure

> **1 roentgen** is the amount of photon energy (either x-rays or gamma rays) required to produce 1.610 x 10^{12} ion pairs in one cubic centimeter of dry air at 0°C and 760 mm Hg.

The main advantage of this unit is that it is easy to measure directly with a survey meter, as survey meters function on measuring the number of ion pairs produced as x-rays or gamma rays pass through the detector.
The main limitation is that it is valid only for deposition of energy in air.

Obviously, it is more important to recognize the amount of energy absorbed by tissue than by air, so the concept of absorbed dose is developed.

> **1 rad** is defined as 100 ergs/gram and this unit does not depend on the time of radiation depositing that energy nor the material into which that energy is absorbed.

For example, if 100 ergs of energy is deposited by some alphas and betas into one gram of tissue that tissue is said to have absorbed 1 **rad** of radiation.

"It can be shown that one gram of air will absorb 87 ergs of energy and that one gram of soft tissue will absorb 96 ergs of energy when exposed to a radiation field which produces an exposure of one roentgen. This is true to within two percent for gamma energies from 0.1 MeV to 3 MeV. Thus, for many practical health physics problems, over the range of energies usually encountered, the **rad** and **roentgen** are often used interchangeably"[1]

Another unit of absorbed dose is the **gray**:

> **1 gray (Gy)** is defined as one joule/kilogram, and 1 Gy = 100 rad.

The **rem** is a unit designed to take into account the effect that different types of radiation have on tissue.

For radiation protection purposes it is useful to define a quantity, the dose equivalent, which describes the effect of radiation on tissue. Equal absorbed doses of radiation may not always give rise to equal risks of a given biological effect, since the biological effectiveness may be affected by differences in the type of radiation or irradiation conditions. Thus, the **dose equivalent** is defined to be the product of the absorbed dose and a modifying factor or factors:

Dose Equivalent (rem) = Absorbed Dose (rad) x Quality Factor.

Another unit of dose equivalent is the **sievert**:

1 sievert (Sv) = 100 rem.

Dose Equivalent (sievert) = Absorbed Dose (gray) x Quality Factor

where the quality factor, the most common modifying factor, takes into account the relative effectiveness of the radiation in producing a biological effect. The special unit of dose equivalent is the **rem.**

Quality Factor

The values for quality factor given in the table below are those recommended by the International Commission on Radiological Protection in ICRP Publication 26:

Types of Radiation	*Quality Factor (QF)*
x or gamma rays	**1**
beta particles	**1**
***neutrons and protons of unknown energy**	**10**
singly charged particles of unknown energy with rest mass greater then 1 amu	**10**
alpha particles	**20**
particles of multiple or unknown charge of unknown energy	**20**

The value of the quality factor for each type of radiation depends on the distribution of the absorbed energy in a mass of tissue. For example, the increased effectiveness of neutrons relative to gamma rays is believed to be related to the higher specific ionization of the recoil protons liberated by neutron bombardment as compared to the specific ionization of the secondary electrons arising from gamma-ray irradiation. The values of quality factor are known to vary with the biological effect being observed, and in some cases are still a matter of controversy for the same biological effect. (See http://web.princeton.edu/sites/ehs/radsafeguide/rsg_app_e.htm)

Working Level

Radon decay product concentrations are typically measured in the unit of working level (WL).

> **1 working level (WL)** is defined as any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy. The historical more definition of the working level is the potential alpha energy of radon decay products in equilibrium with 100 pCi/L of radon. This value is 128,000 MeV. An excellent reference for this

definition is Evans, R.D. Engineers' guide to the elementary behavior of radon daughters. Health Physics 17(2):229-252, August 1969.
The number 130,000 MeV was chosen for its simplicity and because it is approximately the alpha energy released from the decay products in equilibrium with 100 pCi of Radon-222 per liter of air assuming an equilibrium ratio of 1.0

Working Level Month (WLM): An exposure to a concentration of radon progeny of 1 WL for one working month.

Working Month: For purposes of calculating working level months, a month is 170 working hours.

For example, a worker exposed to a radon progeny concentration of 0.5 WL for a period of 170 hours would have been exposed to 0.5 WL x 1 month = 0.5 working level months. The calculation is simply

$$\#wlms = \#workinglevels \times \#months$$

Worker exposures are measured in working level months (WLM). (See http://www.radon.com/pubs/homprot7.html)

Number of Digits

Radon concentrations are typically reported in pCi/l to one digit to the right of the decimal. For example: 3.7 pCi/l, 0.3pCi/l.

Radon progeny concentrations are typically reported in WL to three digits to the right of the decimal. For example: .002 WL, 1.222 WL.

Equilibrium Ratio

The equilibrium ratio is simply defined as the ratio of the collective concentration of all the short-lived radon progeny to the concentration of the parent radon gas and is defined analytically by the following equation

$$ER = \frac{Daughteractivity(wl) \times 100 \frac{pCi/l}{wl}}{radongasactivity(pCi/l)}$$

For example: Given the radon progeny concentration to be 0.020 WL and the parent activity to be 25 pCi/l, the ER becomes

$$ER = \frac{0.020 \times 100}{25}$$

$$ER = 0.08$$

Generally it is not known what the equilibrium ratio is in a given environment. Current (2009) recommendations suggest using an ER of 0.4 to convert from WL to pCi/l as follows:

$$WL = \frac{ER \times radonconc(pCi/l)}{100 \frac{pCi/l}{wl}}$$

For example, if the equilibrium ratio is 0.4 and the radon concentration is 20 pCi/l, the radon progeny concentration is calculated as:

$$WL = \frac{0.4 \times 20}{100} \text{ wl}$$

$$WL = 0.080 \text{ wl}$$

Clearly, the range of values of the Equilibrium Ratio falls between zero and 1.0. The minimum value of zero would indicate there are no decay products in the environment at that time relative to the parent gas.

An Equilibrium Ratio value of 1.0 indicates that the concentration of each of the radon progeny is equal to the concentration of the parent radon-222. If the radon concentration is 100 pCi/l, then the concentration of each of the decay products is also 100 pCi/l, and the collective concentration of the radon progeny is 1 WL.

Another equivalent view of the ER is sometimes found as:

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 that is present. (This is not the common use of the term within the radon industry.)

At equilibrium (i.e., at an equilibrium ratio of 1.0), 1 WL of RDPs is present when the radon concentration is 100 pCi/l. Although the equilibrium ratio can temporarily be greater than 1.0 as the radon progeny concentrations lag behind a decrease radon concentration, on the average the ratio is never 1.0 in a house. Due to ventilation and plate out, the RDPs never reach equilibrium in a house environment if the radon concentration is stable. A commonly assumed equilibrium ratio is 0.4 (i.e., the progeny are 40% toward equilibrium), in which case 1 WL corresponds to 250 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 have equilibrium ratios less than 0.5. Some factors affecting the equilibrium ratio in a given environment are:

a. Attachment rate
b. Deposition of unattached progeny
c. Ventilation

Clearly the greater the amount of "plate out," the fewer progeny will be in the air and therefore the lower the equilibrium ratio.

Equilibrium ratios for outdoors have been reported in the vicinity of 0.6.

Equilibrium Factor

- **Equilibrium factor (F):** The ratio of the radon progeny concentration in WL actually present to the radon progeny concentration which would be present if the short-lived progeny were in equilibrium with the radon that is present.

This quantity is the same as the equilibrium ratio.

Equilibrium Equivalent Concentration

Equilibrium equivalent concentration (EEC): The concentration of radon that would be present if the radon progeny that are present were in complete equilibrium with the radon that is present (i.e., if the ER were 1.0). The ratio of the EEC to the actual radon concentration is equal to the equilibrium ratio.

Analytically the EEC may be calculated by either

$$EEC = WL_{actual} \times 100$$

or

$$EEC = Rn_{actual}(pCi/l) \times ER$$

Typically, we don't know the ER, so we might take it as 0.4 which yields

$$EEC = Rn_{actual}(pCi/l) \times 0.4$$

For example, assume we know the radon progeny concentration in a room is 1.0 WL. What radon concentration would produce that concentration of radon progeny, assuming no plate out? The answer is of course 100 pCi/l and we can find that using the equation above:

$$EEC = WL_{actual} \times \frac{100\,pCi/l}{wl}$$

$$EEC = 1.000 \times 100 = 100\,pCi/l$$

As a second example: Assume we know that the actual radon concentration is 100 pCi/l, and the equilibrium ratio is 0.4. From our equation for equilibrium ratio above

$$WL = \frac{ER \times radonconc(pCi/l)}{100 \frac{pCi/l}{wl}}$$

we find that the radon progeny concentration is

$$WL = \frac{0.4 \times 100}{100} = 0.4 wl$$

Therefore, we know without plate out, we would need 40 pCi/l, since without plate out 100 pCi/l yields a radon progeny concentration of 1 working level.

We can calculate that radon concentration by using the equation above which reads

$$EEC = Rn_{actual}(pCi/l) \times ER$$

$$EEC = 100 \times 0.4 = 40 pCi/l$$

If one knows the concentrations of the individual radon-222 decay products, then the EEC can be calculated from the following expression:

$$EEC = 0.105 \text{ x } C(^{218}Po) + 0.516 \text{ x } C(^{214}Pb) + 0.379 \text{ x } C(^{214}Bi)$$

where EEC is the equilibrium equivalent radon concentration in pCi/l or Bq/m^3 (depending on the unit used for the decay product concentrations) and C(^{218}Po), C(^{214}Pb) and C(^{214}Bi) are the concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi in pCi/l or Bq/ m^3. Note that the concentration of ^{214}Po is not included in this equation, as it does not contribute significantly to the expression.

PAE Potential Alpha Energy. This quantity is the total alpha energy of an atom of one of the short-lived decay products of radon-222 as it decays to the long-lived decay product ^{210}Pb.

For example, if we have one atom of ^{218}Po, as it decays to ^{210}Pb, the total alpha energy emitted is 13.68 MeV (6.0 MeV from the decay of ^{218}Po + 7.68 MeV from the subsequent decay of ^{214}Po). If we also have at that moment one atom of ^{214}Bi, as it decays to ^{210}Pb, the total alpha energy emitted is 7.68 MeV (from the subsequent decay of ^{214}Po). So, if we have in a given room at a given moment one ^{218}Po atom and one ^{214}Bi atom, the total potential alpha energy emitted as these two atoms decay to ^{210}Pb is the sum of 13.68 MeV and 7.68 MeV, or 21.36 MeV. This total alpha energy is useful in determining health risks. (See Introduction to Radiation Protection dosimetry, Sabol, Weng, Weng.)

PAEC Potential Alpha Energy Concentration, used as a measure of the decay-product concentration. Units used are Working Level, or joules/m^3. This is the sum of all the PAEs of the radon progeny: ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po per unit volume of air. (See Introduction to Radiation Protection dosimetry, Sabol, Weng, Weng.)

If one knows the concentrations of the individual radon-222 decay products, then the PAEC can be calculated from the following expressions:

$$\text{PAEC } (\mu J/m^3) = 0.000578 \times C(^{218}Po) + 0.00285 \times C(^{214}Pb) + 0.000210 \times C(^{214}Bi)$$

where $C(^{218}Po)$, $C(^{214}Pb)$ and $C(^{214}Bi)$ are the concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi in Bq/ m^3,

$$\text{PAEC (WL)} = 0.00103 \times C(^{218}Po) + 0.00507 \times C(^{214}Pb) + 0.00373 \times C(^{214}Bi)$$

where $C(^{218}Po)$, $C(^{214}Pb)$ and $C(^{214}Bi)$ are the concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi in pCi/l.

Derivation of the Relationship of the Concentration of Radon Needed for Its Decay Products to Produce 1 WL

Before we begin this derivation an issue of "units" arises. One often finds in the literature the statement that 100 pCi/l = 1 WL. If we take a careful look at the left-hand side of this equation, pCi is 2.22 disintegrations/min which has units of min^{-1} since the term disintegration is in fact not a "unit," just like atom or nucleus are also not "units," rather just a handle by which it is easier to talk about. For example, if one asks how many atoms there are in a jar, the answer might be 1000 atoms, but the term atom here is not a unit, the answer to that question is most correctly simply "the number is 1000." But, adding the word atom makes it a bit more clear.

So returning to the equation 100 pCi/l = 1 WL, we have on the left side of the equation the unit $min^{-1}\ l^{-1}$, i.e. 1/(min l). On the right we have the "WL" which has units of MeV/l, or energy/l. So, the right side of the equation does not have the same units as the left side leading us to recognize that this is not an equation at all. In particular, if we reduce this equation just a bit we have

$$100 \times 2.22 \frac{1}{\min \bullet l} = 1 \times \frac{1.3 \times 10^5\ MeV}{l}$$

which can be reduced to:

$$\frac{222}{\min} = 1.3 \times 10^5 MeV$$

This makes very little sense. It would be better to write 100pCi/l →1WL, but this has not become the common use, which is unfortunate. We shall use the "→" as it is a more correct notation.

For the case where radon decay products are in equilibrium with radon, it is typically taken that

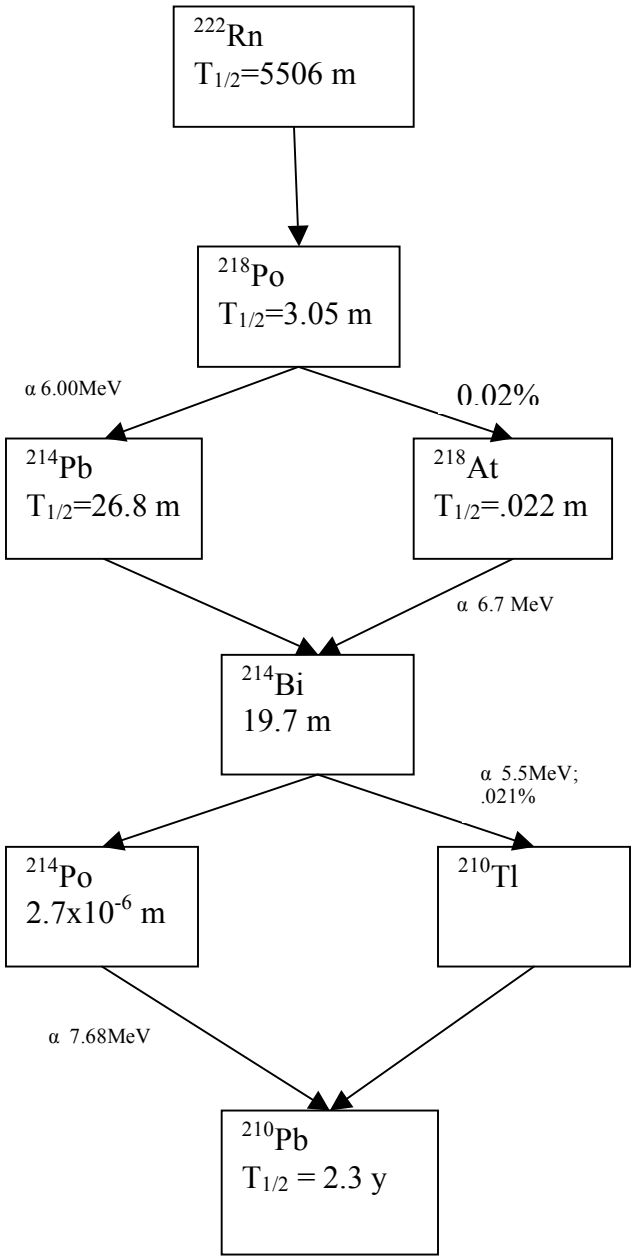
$$100 \frac{pCi}{l} \rightarrow 1WL$$

Its derivation proceeds as follows:

Recognize that the definition of 1 working level is any combination of radon or thoron decay products which will potentially produce 1.30 x 10^5 MeV (more accurately 128,400 MeV) of alpha particles in one liter of air. For the case of radon decay products this is

1.30 x 10^5 MeV of alphas emitted by radon decay products when they're in equilibrium with approximately 100 pCi/l of radon which we show below.

The decay scheme of radon 222 is as follows:



The pertinent alpha emissions and their approximate alpha energies are noted in the drawing and in some cases along with the percentage of that decay branch.

Let's consider a volume of 1 liter and an activity of 100 pCi for radon with its decay products in full equilibrium for the purpose of this derivation. Therefore, at equilibrium the "activity" of each decay product in this 1 liter of air is equal to that of the radon itself, 100 pCi.

In this case, we can calculate the number of atoms of each decay product in that 1-liter volume at that moment of equilibrium as follows:

That is, the number of ^{218}Po atoms is

$$N_{Po} = \frac{\lambda_{Po} N_{Po}}{\lambda_{Po}}$$

Which seems trivially true and where N is the number of atoms and λ is the decay constant ($\lambda = \frac{.693}{t_{\frac{1}{2}}}$) and where $t_{1/2}$ is the half-life.

We now recognize that the activity, $\lambda_{Po} N_{Po}$ is 100 pCi or 220 dis/min.

So $$N_{Po} = \frac{220 dis/\min}{.227 \min^{-1}} = 978 atoms$$

That is we have initially 978 polonium-218 atoms.

Similarly, we can easily show that we also have 8.49 x10^3 ^{214}Pb atoms, and 6.25 x 10^3 ^{214}Bi atoms. We won't take into account here the ^{218}At radionuclide since there are so few of them at 100 pCi (6.9 atoms). Also not entirely surprising the number of ^{214}Po atoms at 100 pCi is less than 1, so we'll take it as zero. Further, we don't need to look down into the decay chain beyond the ^{210}Pb since its half-life is comparatively long. These omissions will have only the slightest impact on the accuracy of our results and the additional detail serves only to detract from the clarity of this derivation.

Next let's consider these 978 ^{218}Po atoms which we have initially in this one-liter volume. Each one of these ^{218}Po atoms will produce one alpha particle of 6.00 MeV as it decays into ^{214}Pb, and then later another alpha of 7.68 MeV as a resulting ^{214}Po atom decays. So each ^{218}Po atom is responsible for two alpha particles, totaling 13.68 MeV, approximately.

Therefore, the entire 978 ^{218}Po atoms yield a total alpha energy of

$$978 \times 12.68 MeV = 1.34 \times 10^4 \; MeV$$

Now we can perform the same calculation for the ^{214}Pb atoms as follows:

The total number of ^{214}Pb atoms is found as before from:

$$N_{Pb} = \frac{\lambda_{Pb} N_{Pb}}{\lambda_{Pb}}$$

$$N_{Pb} = \frac{220 dis / \min}{.0259 \min^{-1}} = 8.49 \times 10^3 atoms$$

Each one of these ^{214}Pb atoms is responsible for one alpha particle of 7.68 MeV when the eventual ^{214}Po atom decays. Hence the total alpha energy released by these 8.49 x 10^3 atoms is

$$8.49 \times 10^3 \times 7.68 MeV = 6.52 \times 10^4 \; MeV$$

Performing a similar calculation for ^{214}Bi yields 6.25 x 10^3 atoms yielding 4.80 x 10^4 MeV.

So the total alpha energy eventually released by these atoms in equilibrium with the 100 pCi of radon is

1.34 x 10^4 MeV + 6.52 x 10^4 MeV + 4.80 x 10^4 MeV = 1.27 x 10^5 MeV ≈ 1.30 x 10^5 MeV.

If we compare this calculated value to that of the more correct value of 1.28 x 10^5 MeV value of 1 WL, then the result presented here differs by less than 1%

The discrepancy between the above calculated value and the more commonly reported value is attributed to the approximations used in this derivation.

Derivation of the Relationship of the Concentration of Thoron Needed for Its Decay Products to Produce 1 WL

Before we begin this derivation an issue of "units" arises. One often finds in the literature the statement that 100 pCi/l = 1 WL. If we take a careful look at the left-hand side of this equation, pCi is 2.22 disintegrations/min which has units of min^{-1} since the term disintegration is in fact not a "unit," just like atom or nucleus are also not "units," rather just a handle by which it is easier to talk about. For example, if one asks how many atoms there are in a jar, the answer might be 1000 atoms, but the term atom here is not a unit, the answer to that question is most correctly simply "the number is 1000." But, adding the word atom makes it a bit more clear.

So returning to the equation 100 pCi/l = 1 WL, we have on the left side of the equation the unit $min^{-1}\ l^{-1}$, i.e. 1/(min l). On the right, we have the "WL" which has units of MeV/l, or energy/l. So, the right side of the equation does not have the same units as the left side leading us to recognize that this is not an equation at all. In particular, if we reduce this equation just a bit we have

$$100 \times 2.22 \frac{1}{\min \bullet l} = 1 \times \frac{1.3 \times 10^5\ MeV}{l}$$

which can be reduced to:

$$\frac{222}{\min} = 1.3 \times 10^5 MeV$$

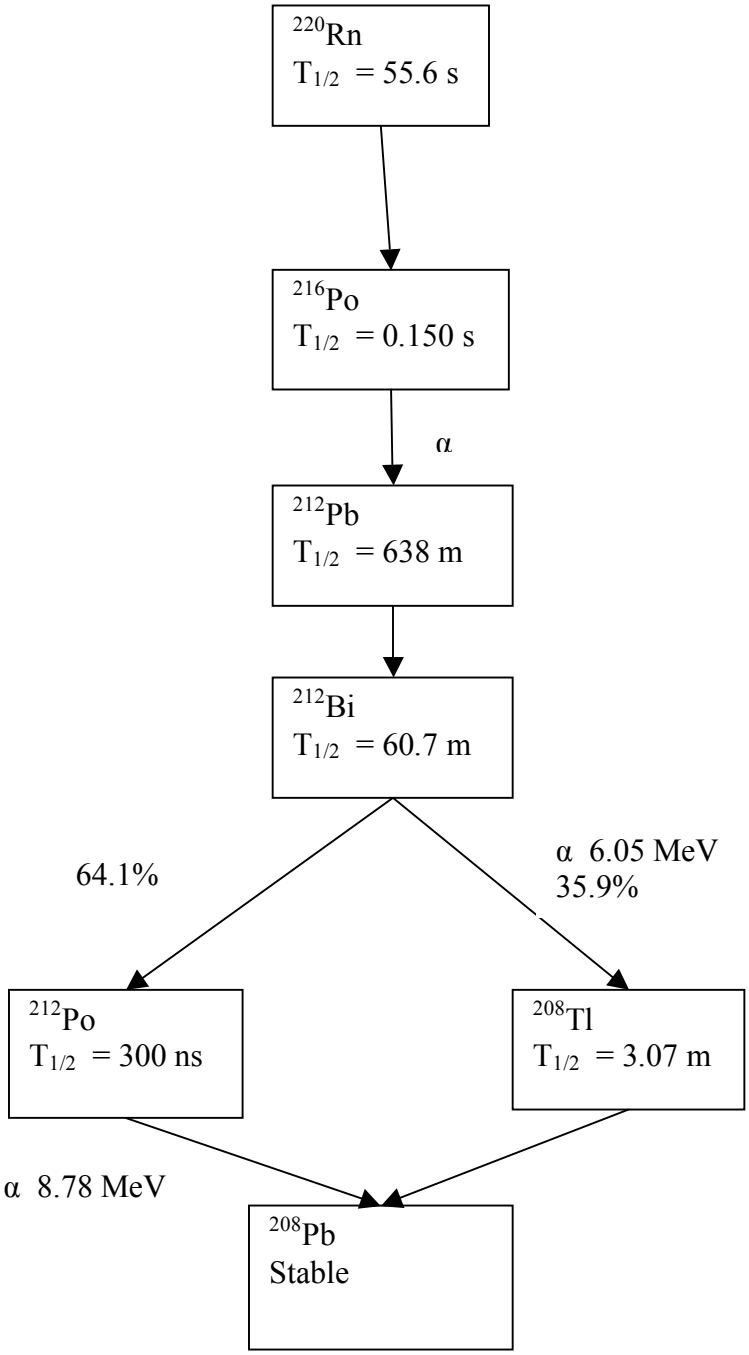
This makes very little sense. It would be better to write 100 pCi/l →1WL, but this has not become the common use, which is unfortunate. (See the definition of WL elsewhere in this manual.) We shall use the '→' as it is the correct notation.

It is interesting to calculate how many pCi/l of thoron (^{220}Rn) are needed for its decay products to produce 130,000 MeV of alpha energy. Recognize that the definition of 1 working level is any combination of radon or thoron decay products which will potentially produce 1.30 x 10^5 MeV (more accurately 128,400 MeV) of alpha particles in one liter of air. For the case of thoron decay products this is 1.30 x 10^5 MeV of alphas emitted by thoron decay products when they're in equilibrium with thoron. (Editor's Note: Thoron progeny cannot come into equilibrium with the parent thoron, because the half-life of thoron is short compared to that of its decay products, namely that of Pb-212 with a half-life of 10.64 h. However, the discussion here is correct if one considers that the thoron and its progeny come into equilibrium with the source of the thoron, Ra-224. Further, because of the short half-lives of thoron and its immediate decay product, Po-216, the concentrations of these two radionuclides are typically significantly reduced at

some sampling point at a practical distance from the source of the thoron. This still does not affect the validity of the discussion here, if one recognizes that the contribution of Po-216 to the PAEC is insignificant.)

The concentration of thoron needed for its decay products to produce 1 WL may be calculated as follows:

The decay scheme of radon-220 is as follows:



The pertinent alpha emissions and their approximate alpha energies are noted in the drawing and in some cases along with the percentage of that decay branch.

We will approach this case slightly differently than the radon case. Here we will calculate the total alpha energy emitted by thoron decay products each with a concentration of 1 pCi in one liter of air. This will provide us with a number of MeV. Then we can easily calculate the number of pCi of thoron decay products needed to produce 1.30 x 10^5 MeV in that one liter of air.

It is important to recognize that the decay products of thoron will be in equilibrium with the thoron in this discussion. Therefore 1 pCi of thoron means we have 1 pCi of each of the thoron decay products. So we will calculate the number of atoms of each thoron decay product assuming there is 1 pCi of each of them. Again, we need to remember we are doing this for one liter of air.

Beginning with ^{216}Po, we will use the equation:

$$N_{Po} = \frac{\lambda_{Po} N_{Po}}{\lambda_{Po}}$$

Which is trivially obvious and where N is the number of atoms and λ is the decay constant ($\lambda = \frac{.693}{t_{\frac{1}{2}}}$) and where $t_{1/2}$ is the half-life.

Recognizing now that the numerator on the right is the activity of the ^{216}Po which is 1 pCi (2.22 dis/min), and that the decay constant of ^{216}Po is 2.77 m^{-1}, we find

$$N_{Po} = \frac{2.22 dis/\min}{277 m^{-1}} = 0.00801 \text{ atoms}$$

We proceed this way to calculate the number of atoms (or nuclei) of each of the other decay products, using their decay constants of 0.00109 m^{-1} for ^{212}Pb, 0.0114 m^{-1} for ^{212}Bi, and 1.39 x 10^8 m^{-1} for ^{212}Po and find

N^{212}_{Pb}= 2040 atoms

N^{216}_{Po}= 0.00801 atoms

N^{212}_{Bi}= 195 atoms

N^{212}_{Po}= 1.60 x 10^{-8} atoms

By looking at the decay chain above, we see for each ^{216}Po atom that exists initially, there will be produced one alpha of 6.78 MeV, 0.359 alphas of 6.05 MeV as the ^{212}Bi decays 35.9% of the time to ^{208}Tl and .641 alphas of 8.78 MeV. (Please note that 64.1% of the

time the ^{212}Bi will decay into ^{212}Po) as the ^{212}Po decays into stable lead. So the total alpha energy emitted in this case by the 0.00801 atoms of ^{216}Po atoms will become

$$8.01x\ 10^{-3}(6.78+.641\ x\ 8.78\ +.359\ x\ 6.05)\ MeV = .117\ MeV$$

For each atom of ^{212}Pb that exists initially, there will be produced .641 alphas of 8.78 MeV, and .359 alphas of 6.05 MeV. This yields for the 2040 ^{212}Pb atoms a total alpha energy of

$$2040\ x\ (.359\ x\ 6.05 + .641\ x\ 8.78)\ MeV = 1.59\ x\ 10^4\ MeV.$$

For each atom of ^{212}Bi that exists initially, there will be produced 0.359 alphas of 6.05 MeV and .641 alphas of 8.78MeV. This yields for the ^{212}195 Bi atoms a total alpha energy of

$$195\ x\ (.359\ x\ 6.05 + .641\ x\ 8.78)\ MeV = 1.52\ x\ 10^3\ MeV.$$

For each atom of ^{212}Po we will find one alpha of 8.78 MeV but this will still yield zero MeV since there are effectively no ^{212}Po atoms in this case.

So, for the entire decay chain for thoron, we see that for 1 pCi of each decay product we will get a total alpha energy of

$$\text{Total alpha energy} = .117\ MeV + 1.59\ x\ 10^4\ MeV + 1.52\ x\ 10^3\ MeV = 1.74\ x\ 10^4\ MeV.$$

We now have that 1 pCi of each of the thoron decay products causes 1.74 x 10^4 MeV of alphas to be emitted. To accumulate 130,000 MeV of alpha energy (1 WL) we would then need

$$\frac{130{,}000 Mev}{1.74x10^4 Mev/pCi} = 7.47\,pCi$$

If we use the more correct value of 1WL, 128,400 MeV, then we would find

$$7.38\frac{pCi}{l} \rightarrow 1WL$$

It is quite common to see the figure quoted as 7.43 pCi/l and the discrepancy between the above calculated value and the more commonly reported value is attributed to the approximations used in this derivation.

If we compare this calculated value with the more commonly quoted value of 7.43 pCi/l, we find the difference to be less than 1%.

It's of some interest to note that it takes approximately 100 pCi/l of radon to produce 1 WL of decay products but only approximately 7.43 pCi/l of thoron to produce 1 WL of its decay products or about 13 times more radon activity than thoron activity.

This is easily explained by comparing the number of atoms of each decay chain for the case of 1 pCi/l of radon and thoron as shown in this table:

Total number of atoms which emit alpha particles for 1 pCi/l of radon or thoron for the case where the decay products are in secular equilibrium.

Radon	Thoron
Po^{218}----------10	Pb^{212}----------2040
Pb^{214}----------85	Po^{216}----------0
Bi^{214}----------62	Bi^{212}----------195
	Po^{212}----------0
Total----------157	Total----------2235

There are more atoms of the decay products for thoron than radon by a factor of almost 14 so 1 pCi/l of thoron decay products yield about 14 times more alpha energy than the decay products of 1 pCi/l of radon. So approximately 14 times less thoron activity is needed to provide the same amount of alpha energy.

Further this is due to the fact that the equation for the number of atoms existing for a given activity "λN" which has been shown above to be

$$N = \frac{\lambda N}{\lambda}$$

Is easily rearranged by recognizing that

$$\lambda = \frac{.693}{t_{\frac{1}{2}}}$$

which yields this expression for N:

$$N = \frac{\lambda N \times t_{\frac{1}{2}}}{.693}$$

And taking as has been done for a given activity of 1 pCi/l, N becomes

$$N = \frac{1 \times t_{\frac{1}{2}}}{.693}$$

which shows that the number of atoms of a given decay product is proportional to its half-life for a given activity which makes sense in that the shorter the half-life the more quickly the atoms decay and hence the more quickly it produces an alpha particle with its attending energy.

The difference in the half-lives of the decay products between the two decay chains is what gives rise to the difference in the number of atoms, and therefore in the amount of alpha energy given off by these decay products.

Radon-222 Dose Calculation

Initial Assumptions:

Equilibrium Factor (EF): 0.4	BEIR VI
Dose Conversion Coefficient 0.54 rad/WLM	UNSCEAR 2006
Occupancy Factor for home: 0.7, or 6136 hr/yr,	BEIR VI
Radiation Weighting Factor (W_r) for Alphas: 20	2005 ICRP Recommendations
Tissue Weighting Factor (W_f), Lung: 0.12 Bronchial Tree: 0.08	2005 ICRP Recommendations (NCRP/ICRP) UNSCEAR 2006

Equations:

WL = (Rn x EF)/ 100

WLM = (WL x Exposure in hrs)/ 170 working hours per month

Now for a problem.

1. 4 pCi/L in home environment

   (4 pCi/L x 0.4)/ 100 = 0.016 WL;

   WLM = (0.016 WL x 6136 hr/yr) / 170 hrs/month = 0.58 WLM/yr

   Now convert to dose equivalent: (WLM/y) (DCC) (W_r) (W_f)

   (0.58 WLM/yr) (0.54 rad/WLM) (20) (0.08) = 0.5 rem/yr, effective whole body dose equivalent

   References:

United Nations Scientific Committee on the Effects of Atomic Radiation, Volume I: Sources, 2006.

National Research Council. Health Effects of Exposure to Radon, BEIR VI. National Academy Press, 1999.

Dosimetry Section

Dosimetry is the calculation of the absorbed dose in matter and tissue resulting from the exposure to indirectly and directly ionizing radiation. The dose to matter is measured in gray (Gy) and the dose to biological tissue in sieverts (Sv), where 1 Gy or 1 Sv is equal to 1 joule per kilogram. The United States does not use the SI units for dose and still uses rad and rem, where 1 Gy = 100 rad, and 1 Sv = 100 rem.

It should be pointed out that we do not measure the dose to the lung tissue, it must be calculated. Additionally, the vast majority of the dose (energy) deposited in the lung tissue is due to the radon progeny and not the radon gas.

The majority of the lung tumors are found in the tracheobronchial region of the lung. The cells at risk in this region of the lung are the basal and secretory cells.

We are exposed to radon gas and to radon progeny, and these are measured in pCi/L and working levels; however, it is the decay products that result in the majority of the dose being delivered to the lung tissue. In calculations of dose, we therefore need a dose conversion factor to convert a cumulative exposure in working level months to rads of absorbed dose in the lung. This dose conversion factor as found in UNSCEAR 2006 is 0.54 rad WLM^{-1} or 9 nGy $(Bq\ h\ m^{-3})^{-1}$.

An example dose calculation follows:

Radon-222 Dose Calculation

Initial Assumptions:

Equilibrium Factor (EF): 0.4	UNSCEAR 2006
Dose Conversion Coefficient 0.54 rad/WLM	UNSCEAR 2006
Occupancy Factor for home: 0.7, or 6136 hr/yr,	BEIR VI
Radiation Weighting Factor (W_r) for Alphas: 20	2005 ICRP Recommendations
Tissue Weighting Factor (W_f), Lung: 0.12	2005 ICRP Recommendations
Bronchial Tree: 0.08	UNSCEAR 2006

Equations:

WL = (Rn x EF)/ 100

WLM = (WL x Exposure in hrs)/ 170 working hours per month

An example problem shows:

2. 4 pCi/L in home environment

   (4 pCi/L x 0.4)/ 100 = 0.016 WL;

   WLM = (0.016 WL x 6136 hr/yr) / 170 hrs/month = 0.58 WLM/yr

   Now convert to dose equivalent: (WLM/y) (DCC) (W_r) (W_f)

   (0.58 WLM/yr) (0.54 rad/WLM) (20) (0.08) = 0.5 rem/yr, effective whole body dose equivalent

References:

United Nations Scientific Committee on the Effects of Atomic Radiation, Volume I: Sources, 2006.

National Research Council. Health Effects of Exposure to Radon, BEIR VI. National Academy Press, 1999.

Effective Whole Body Dose Equivalent
From Exposure to Radon and Radon Progeny in Air
(July 2007)

pCi/L	WLM/year	Rem/year Lungs	Rem/year Whole Body (EDE)	Annual Whole Body Dose Comparison
0.15	0.02	0.23	0.03	Single view Mammogram (10); Cosmic Radioactivity At Earth's Surface (8).
2	0.29	3.12	0.37	Near twice avg. dose for Nuclear Power Plant Worker (6).
4	0.58	6.24	0.75	About 900 Medical X-Rays (7).
8	1.16	12.47	1.50	Between one to two times the dose from a whole body CT Scan. (8).
10	1.44	15.59	1.87	
20	2.89	31.19	3.74	Near Limit of Annual Occ. Exp.– 5.0 Rem (9).
50	7.22	77.96	9.36	
100	14.44	155.93	18.71	
200	28.88	311.85	37.42	

WL = ((pCi/l)(ER))/100. WLM = ((WL)(hrs))/170hrs/month.
WLM/yr = (WLM)(6136hr/yr). EDE = (WLM/y)(DCC)(Wr)(Wf)

Assumptions/references:

1. Occupancy: 70% of time (16.8 hours/day). Ref. BEIR VI Report (1999).
2. Equilibrium Ratio (ER) :0.4, Ref. EPA 402-R-03-003, Assessment of Risks from Radon in Homes (6/2003).
3. Dose Conversion Coefficient (DCC) 0.54 rad/WLM. Ref. UNSCEAR 2000 Report Vol. 1.
4. Weighting factor (Wf) Lung Dose to Whole Body (EDE) = 0.12
5. Radiation Weighting Factor (Wr) for alpha particles = 20 rem/rad.
6. Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities 2005, NUREG 0713, Vol. 27 section 4.4.
7. CRCPD Pub. E-05-2 Nationwide Evaluation of X-ray Trends, Tabular and Graphical Summary of 2001, Survey of Adult Chest Radiography.
8. Radiological Society of North America, Inc. 2007.
9. 10 CFR Part 20 Radiation Protection, 1201.
10. CRCPD Pub. E-03-2 Patient Exposure and Dose Guide (2003).

Risks from Indoor Radon-US EPA

The EPA's revised risk assessment (EPA, 2003) is based on the National Academy of Sciences, BEIR VI report, 1999. This short presentation provides some of the most relevant facts from that assessment.

- The risk estimates are still based solely on the miner data, 11 cohort studies.
- The estimates in BEIR VI are based on an average annual exposure of 0.181 WLM/yr, and this is based on the EPA National Residential Radon Survey value of 1.25 pCi/L for the U.S. housing stock, assuming 70% occupancy and 40% Equilibrium ratio (ER).
- Example Calc.: ((1.25 pCi/L) (0.4))/ 100 = 0.005 WL;
- ((0.005 WL) (6136 hrs/yr))/ 170 working hrs/ mo. = 0.181 WLM/yr

	1992 Assessment	**2003 Assessment**
ER	0.5	0.4
Occupancy Time	75%	70%
Avg. Progeny Exp.	0.242 WLM/yr	0.181 WLM/yr
Risk Estimate	2.24E-4/WLM	5.38E-4/WLM
Mortality Data	1980 data	1990 data
Model used	BEIR IV relative risk model	BEIR VI Age Conc. Relative risk model
Miner Data	4 cohorts	11 cohorts
K-factor	0.7	1.0
Rn Induced LC deaths	13,600	21,100

Note: Changing the exposure from 0.242 to 0.181 has little effect on risk per WLM.

References:

EPA Assessment of Risks from Radon in Homes. EPA 402-R-03-003, June 2003. United States Environmental Protection Agency.

Pawel, D.J. and Puskin, J.S. The U.S. Environmental Protection Agency's Assessment of Risks from Indoor Radon. Health Physics, July 2004, Volume 87, No. 1, pp. 68-74.

Radon-222 and Lung Cancer (LC) Risk Estimates

Below is a compilation of various sources for risk estimates and other useful information for radon-induced LC.

UNSCEAR 2006 Report, Vol. II. Effect of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, Annex E- Sources-to-effects Assessment for radon in Homes and Workplaces.

- Though dated 2006 this report was not officially released until July 2009.
- The report is a review and compilation of all of the most significant work on sources of radon exposure, dosimetry, experimental studies, epidemiological studies of miners, epidemiological studies of residential exposures, effects of radon on organ and tissues other than the lung, and implications of risk assessment.
- The excess relative risk (ERR) per unit exposure from the combined (9) miners studies is 0.59 per 100 WLM, with 95% CI of 0.35 to 1.0.
- At this time adopted the ERR from the pooled European study as an appropriate, though possibly conservative, estimate of lifetime risk at 0.16 per 100 Bq/m^{-3}, with a 95% CI of 0.05 to 0.31. In other words the risk is about 16% for smokers and nonsmokers. It is the baseline risk that is significantly higher for smokers.
- The Committee now believes that risks from residential radon exposure can be directly estimated from the pooled residential case-control studies.
- Found that the excess relative risk of lung cancer from residential radon exposure is about the same for smokers and nonsmokers. This is consistent with the European and North American pooled studies.
- The European, North American, and Chinese pooled case-control residential studies, overall provide for a clear association between the risk of lung cancer and residential radon exposure.

Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. S Darby et al., December 21, 2004, British Medical Journal.

- Absolute risk of LC by age 75 at "usual" radon concentration of 0, 2.7, 10.8 and 21.6 pCi/L would be about 0.4%, 0.5%, 0.7%, and 0.93% respectively, for life-long nonsmokers, and 10%, 12%, 16%, and 21.6% for smokers.
- Relevant exposure for risk of LC was 30 years ending 5 years prior to diagnosis of LC.
- Risk of LC increased by 8.4% per 2.7 pCi/L. This corresponds to an increase of 16% per 2.7 pCi/L in "usual" radon, or an excess relative risk of 1.16.
- Radon poses a much greater absolute hazard to cigarette smokers, and to recent ex-smokers, than to lifelong nonsmokers.

Note: "Usual" radon is radon corrected for the dilution caused by random uncertainties in measuring radon concentrations.

Comparative dosimetry of BEIR VI revisited. A.C. James, A. Birchall, and G. Akabani. Radiation Protection Dosimetry 108:3-26, 2004.

- This paper confirms the BEIR VI Committee's choice of K = 1 for application in their risk extrapolation model.
- K is a dimensionless factor that relates the risk to miners per unit exposure to that for an individual exposed in the home.
- Evidence suggests that most cancers are of monoclonal origin; that is, they originate from damage to a single cell.
- Sensitive targets are assumed to be the nuclei and cytoplasm of the basal cells and the secretory cells in the bronchioles, both located in the epithelial lining of the bronchial tree.
- Dose Conversion Coefficient (dose/WLM) averaged over all target nuclei in the lungs (bronchial, bronchiolar, and alveolar-interstitial regions) for the home environment, without smokers is 0.89 rad/WLM, and for smokers is 0.75 rad/WLM.

EPA Assessment of Risks from Radon in Homes. D. Pawel and J. Puskin. Office of Radiation and Indoor Air, US EPA. June 2003.

- EPA risk assessment update based primarily on BEIR VI.
- Latest risk per unit exposure is 5.38E-4 fatal LC's per WLM.
- This new risk estimate increases the estimated proportion of LC deaths from 8.5% (1992) to 13.4%.
- Previous risk per unit exposure was 2.24E-4 per WLM (EPA 1992)
- Of the 157,400 LC deaths in 1995, 21,100 (13.4%) were radon related.
- Estimated risk from lifetime exposure at 4 pCi/L: 2.3% for entire population, 4.1% for ES, and 0.73% for NS.
- Radon exposure accounts for 1 in 8 ES LC deaths and 1 in 4 NS LC deaths. Thus, the relative risk is higher in NS but the absolute risk is higher in ES.
- For exposure calculations use 70% occupancy factor and 0.4 equilibrium factor.
- Radon induced LC deaths tend to occur earlier than other LC deaths. The average radon induced LC death occurs at ~ 65 y compared to 72 y for all LC deaths.
- There are uncertainties in the estimates of risks from indoor radon; in fact, the BEIR VI committee identified 13 sources of uncertainty.

Residential Radon and Risk of Lung Cancer, A Combined Analysis of 7 North American Case-Control Studies. Krewski, D, Lubin, J, et al. Epidemiology, Volume 16, Number 2, March 2005.

- To date 20 case-control studies of residential radon exposure and LC have been completed.
- The case-control studies to date cannot provide a definitive link between residential radon exposure and an increased risk of LC. Their results reflect a range of LC risks, including the possibility of no risk. The weight of evidence for radon carcinogenicity derives largely from underground miner studies.
- This study focused on the exposure time window of 5 to 30 years prior to diagnosis of LC.
- There was an 11% increase in LC at 2.7 pCi/L.

Health Effects of Exposure to Radon, BEIR VI. Samet, J et al. National Academy of Sciences, 1999.

- Based on 11 major studies of underground miners, which involved about 68,000 men, of whom 2,700 have died of LC.
- Most miners received radon exposures that were, on the average many times larger than those of people in most homes.
- BEIR VI central estimates are about 15,400 or 21,800 LC deaths per year attributed to radon among ever smokers and never smokers, depending on which model is used.
- Most radon-related deaths among smokers would not have occurred if the victims had not smoked.
- At low radon exposures, typical of those in homes, a lung epithelial cell would rarely be traversed by more than one alpha particle per human lifespan.
- Even allowing for a substantial degree of repair, the passage of a single alpha particle has the potential to cause irreparable damage in those cells that are not killed.
- The analysis of smoking and radon indicated a synergistic effect of the two exposures acting together, which was characterized as submultiplicative.

Health Risks of Radon and other Internally Deposited Alpha-Emitters, BEIR IV. Fabrikant, J. I et al. National Academy of Sciences, 1988.

- The Committee used a direct epidemiological approach instead of the dosimetric approach and used the data from four of the principle studies of radon-exposed miners.
- The model used was the modified relative-risk model. In this model radon exposures more distant in time have a smaller impact on the age-specific relative risk than more recent exposures.
- Cigarette smoking and exposure to radon progeny interact multiplicatively.

- Estimate of lifetime risk of LC mortality due to lifetime exposure to radon progeny: 350 deaths/10^6 person WLM.

Evaluation of Occupational and Environmental Exposure to Radon and Radon Daughters in the United States. Harley, N et al. NCRP Report no. 78, 1984.

- Following a latent period, the tumor rate is an exponentially decreasing function of time since exposure.
- Disease rate excess associated with a single exposure increases with age at exposure.
- Lung cancer is rare before the age of 40 years.
- Median age at LC among miners is about 60 yr in nonsmokers and 50 yr or older in smokers.
- The minimal time for tumor growth, from initial cell transformation to clinical detection, is 5 years.
- Derives a lifetime risk of LC of about 1.5 E-4 per WLM

Epidemiology Section

Epidemiology is the study of factors affecting the health and illness of populations.

Epidemiology is the study of patterns of disease in human populations.

The primary source of data for studying exposure to radon and its decay products and lung cancer has been epidemiologic studies of underground miners. It was these studies that were used to provide the downward extrapolation to provide the risk estimates for the residential exposures, even though the miners were exposed to higher exposures for shorter times.

The mean exposure in the miner cohort was 164 WLM (NRC, 1999). A typical residential exposure is about 13 WLM (70 yrs, 1.25 pCi/L, 0.4 ER, 70% time indoors). However, it should be pointed out that there is an overlap of total cumulative exposure between the miner and residential exposures. Some of the lower exposures (~50 WLM) in the miners were similar to some of the higher exposures in homes. For instance, a homeowner exposed to 4 pCi/L for a 70 year lifetime accumulates ~41 WLM.

The data for the miners consisted of 11 cohort studies. Lubin et al. (1994) performed an analysis of the combined data from the 11 cohorts and found that there was conclusive evidence that exposure to high levels of radon is associated with increased risk of lung cancer. The BEIR VI committee (NRC, 1999) then updated the miner studies by reviewing the current molecular and radiobiological basis of radiation effects on cells, examined the exposure differences in mines and homes (the K factor), reviewed the latest information on radon concentrations in U.S. homes and analyzed the properties of alpha particles and cellular interactions. With all this in mind, the committee concluded that 10-15% of the approximately 157,400 lung cancer deaths in the U.S. annually may be due to residential radon exposure.

A growing list (20) of case-control residential radon exposure and lung cancer studies are providing additional evidence for the association of radon exposure and lung cancer. Krewski et al. (2006) provides a good review of the seven North American studies. The individual studies have limited statistical power and their results are inconsistent. However, more recent pooled analysis of various combined studies does provide evidence for a direct association between residential exposure to radon and lung cancer. This no longer necessitates the downward extrapolation from the miner studies to estimate residential risk.

Many epidemiology studies assume that the exposure most relevant to the risk of lung cancer was the 30 years ending five years before the diagnosis of lung cancer.

The latent period is the time from the initial radiological insult to the appearance of a clinically evident cancer. This time period was at least five years for lung cancer in the

uranium miners. Additionally, this latent period may be different for smokers and nonsmokers, with nonsmokers having a longer latent period (Archer, 2004).

BEIR VI report (NRC, 1999):

-Examined 11 major studies of underground miners.
- 68,000 men involved, of which 2,700 died of lung cancer
- Majority of miners were smokers
- Current EPA risks estimates are based on this miner epidemiology
- The miner data showed an inverse exposure-rate effect. For a given dose or cumulative exposure, as the dose rate is lowered, the probability of carcinogenesis increases. However, this does not apply at the more typical residential exposures (~ less than 25-100 WLM) where there is a very low probability of multiple alpha-particle traversals through a cell.

"Of the residential case-control studies to date, 19 of 22 have shown a positive association with radon exposure and lung cancer; however, only five show a significant association. But no study shows a negative association." Quote from R. William Field, Ph.D., University of Iowa, College of Public Health, at the 2008 International Radon Symposium, Las Vegas, NV.

Tables I, II, III below with permission of senior author, Mustafa Al-Zoughool (Al-Zoughool, 2009).

Table I. Types of epidemiological studies used to evaluate the risk of lung cancer due to radon exposure.

Study type	Target population	Main purpose of the study	Method of radon dosimetry	*Major findings/conclusions*
Cohort studies	Miners/occupational exposure.	Determine the risk of lung cancer mortality in exposed miners	Radiation exposure was estimated using job-exposure matrix (JEM) which provides exposure values for potential alpha energy from radon and its progeny in working level months (WLM).	*High levels of radon m exposure were associated with increased cancer risk.*
Case-control studies	The general public/ residential exposure.	Determine the risk of lung cancer in residential settings.	Year-long residential radon levels were measured by a-track detectors and were used to estimate exposure in the 25 years prior to the index date.	*Most studies reported small insignificant association between residential radon exposure and lung cancer, some studies found negative association.*
Pooled analysis of the cohort studies on miners	Miners/occupational exposures.	Obtain summary estimates of the risk of lung cancer in radon-exposed miners using large sample size.	A summary of the WLM exposure was obtained for the total subjects using reported exposure levels in the individual studies.	*A consistent linear relationship for cumulative radon progeny and lung cancer was observed in the range of miner exposures*
Combined analysis of case-control studies	*The general public/ residential exposure in Europe and North America.*	*Obtain accurate estimates of lung cancer risk from residential radon exposure by reducing uncertainty in radon dosimetry.*	*Available radon measurements form individual studies were used to estimate radon exposure for the total individuals in all homes occupied over the past 5–30 years.*	*A significant increase in risk of lung cancer was associated with increased radon exposures with seemingly linear dose-response relationship.*

Table II. Summary of the main characteristics and risk estimates of cohort studies.

Study region (Ref number)	Type of mine	Person-years		Lung cancer deaths		Mean cumulative radon exposure in working level months †	ERR/WLM† (95% confidence interval) ‡
		Exposed	Non-exposed	Exposed	Non-exposed		
Newfoundland, Canada: Extended study (Villeneuve et al. 2007)	Fluorspar	88,842	NA*	191	62	378	0.0043 (0.0023, 0.0062)
Germany (Grosche et al. 2006)	Uranium	1 565 070	236 560	2201	187	241.1	0.0021 (0.0018, 0.0024)
Czech Republic: Extended cohort (Tomasek 2002)	Uranium	127 397	NA*	495	165	NA	0.026 (0.012, 0.041)
France: Extended cohort (Laurier et al. 2004b)	Uranium	50 034	6 338	85	45	71.3	0.006 (0.001, 0.012)
France (Tirmarche et al. 1993)	Uranium	39 487	4556	45	0	70.4	0.0036 (0.001, 0.013)
Yunnan Province, China (Xuan et al. 1993)	Tin	135 357	39,985	936	44	277.4	0.0016 (0.001, 0.002)
W. Bohemia, Czech Republic (Tomasek et al. 1994)	Uranium	10 3652	4,216	656	5	198.7	0.0031 (0.002, 0.006)
Colorado Plateau (Hornung and Meinhardt 1987)	Uranium	73 509	7403	292	2	595.7	0.004 (0.003, 0.007)
Ontario, Canada (Kusiak et al. 1993)	Uranium	319 701	61 017	282	2	30.8	0.0089 (0.005, 0.015)
Newfoundland, Canada (Morrison et al. 1988)	Fluorspar	35 029	13 713	112	6	367.3	0.0076 (0.004, 0.013)
Malmberg, Sweden (Radford and Renard 1984)	Iron	32 452	841	79	0	80.6	0.0095 (0.001, 0.041)
Grants, New Mexico (Samet et al. 1991)	Uranium	46 797	12 152	68	1	110.3	0.0172 (0.006, 0.067)
Port Radium, Canada (Howe et al. 1987)	Uranium	30 454	22 222	39	18	242.8	0.0019 (0.001, 0.006)
Beaverlodge, Canada (Howe et al. 1986)	Uranium	68 040	50 345	56	9	17	2 0.0221 (0.009, 0.056)
Radium Hill, Australia (Woodward et al. 1991)	Uranium	25 549	26 301	32	22	7.6	0.0506 (0.010, 0.122)
Pooled analysis of 11 cohort studies: References 18–28 (Lubin et al. 1995)		907 459	242 332	2597	109	158.0	0.0049 (0.002, 0.010)

*Non-exposed cohort was the general male population in the same region of the study; †Among radon-exposed miners; ‡ERR/WLM, excess relative risk/working level month. Excess relative risk expresses how much increase in the risk of the disease is due to exposure to a given agent. The ERR can be obtained by subtracting one from the relative risk. Working level month is a time-integrated exposure measurement, is the product of time in working months (170 hours) and working-level (WL). One WL equals any combination of radon progeny in 1 l of air that gives the ultimate emission of 130 000 MeV of energy of alpha particles. Consequently, 1 WLM corresponds to 2.08×10^{-5} J/m^3 ×170 hours or 3.5×10^{-3} J-hours/m^3.

Table III. Major characteristics and findings of case-controls studies of residential radon and lung cancer.			
Study (reference)	Cases/Controls	Estimated radon concentration* Bq/m^3	Excess odds ratio† (95% confidence interval)
North America			
New Jersey – I (Schoenberg JB 1992)	480/442	26	0.56 (-0.22, 2.97)
New Jersey – II (Wilcox et al. 2007)	561/740	32	0.05 (-0.14, 0.56)
Winnipeg (Letourneau et al. 1994)	738/738	142	0.02 (-0.05, 0.25)
Missouri (Alavanja et al. 1999)	512/553	56	0.27 (-0.20, 1.53)
Iowa (Field et al. 2000)	413/614	127	0.44 (0.05, 1.59)
Connecticut (Sandler et al. 2006)	963/949	33	0.02 (-0.21, 0.51)
Utah-South Idaho (Sandler et al. 2006)	511/862	57	0.03 (-0.20, 0.55)
Combined analysis of the above studies	*3662/4966*	*70*	0.11 (0.00, 0.28)
(Krewski et al. 2005)			*0.21 (0.03–0.51)‡*
Europe			
Austria (Oberaigner W 2002)	183/188	198	0.46 (< -0.046, >5.00)
Czech Republic (Tomasek et al. 2001)	171/713	500	0.09 (0.02, 0.21)
Finland nationwide(Auvinen et al. 1996)	881/1435	103	0.11 (-0.06, 0.31)
Finland southern (Ruosteenoja et al. 1996)	160/328	215	0.28 (-0.21, 0.78)
France (Baysson et al. 2004)	571/1209	133	0.05 (-0.01, 0.12)
Germany eastern (Wichmann et al. 2005)	945/1516	76	0.08 (-0.03, 0.20)
Germany western (Wichmann et al. 2005)	1323/2146	50	-0.02 (< -0.18, 0.17)
Italy (Bochicchio et al. 2005)	384/405	108	0.14 (-0.11, 0.46)
Spain (Barros-Dios et al. 2002)	156/235	131	< -0.11 (<-0.11, 0.59)
Sweden nationwide (Pershagen et al. 1994)	960/2045	96	0.10 (0.01, 0.22)
Sweden never-Smokers (Lagarde et al. 2001)	258/487	74	0.28 (-0.05, 1.05)
Sweden Stockholm (Pershagen et al. 1992)	196/375	134	0.16 (-0.14, 0.92)
United Kingdom (Darby et al. 1998)	960/3126	55	0.08 (-0.03, 0.20)
Combined analysis of the studies in Europe	*7148/14208*	*105*	0.08 (0.03, 0.15)
(Darby et al. 2005)			*0.16 (0.05–0.31)‡*
China			
Shenyang (Blot et al. 1990)	308/356	85	-0.05 (<0.00, 0.08)
Gansu (Wang et al. 2002)	768/1659	223	0.19 (0.05, 0.47)

*Estimated average residential radon concentration in the 5–30 exposure time window; †The excess relative risk of lung cancer per 100 Bq/m^3 increase in the time-weighted radon concentration; ‡After correction for random uncertainties in radon measurements.

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Lung Cancer Section

Leading cause of cancer-related deaths in the United States

Smoking remains the predominant risk factor for lung cancer. However, only 10-20% of smokers develop lung cancer (Sophie, 2007). According to the U.S. Surgeon General, smoking is also associated with increased risk of at least 15 types of cancer, including lung cancer (PA Dept. Health, 2008).

Cigarette smoking alone still accounts for approximately 30% of all cancer deaths in the United States, despite reductions in smoking prevalence. Most (80%) of these smoking-attributable cancer deaths involve lung cancer; although, smoking causes other cancers (Jemal, 2008).

Interestingly, cigarette smoke can deliver a significant radiation dose to the lung. Radiation "hot spots" may occur at bifurcations of segmental bronchi. The dose to these specific areas for adult smokers may be in the range of 0.8 to 1.0 rad/yr, and if a quality factor of 20 for alpha particles is applied this gives an annual dose equivalent of 16 rem. This is not directly comparable to the effective dose equivalent for radon progeny in that a tissue weighting factor is not available for inhaled cigarette smoke products (NCRP 95, 1987).

Fifteen percent of lung cancers in men and 53% in women are <u>not</u> attributable to smoking; overall accounting for 25% of all lung cancer cases worldwide (Sophie, 2007).

The US EPA estimates that radon exposure accounts for 1 in 8 lung cancer deaths in ever smokers, and 1 in 4 lung cancer deaths in never smokers (EPA, 2003).

For the population as a whole the risk of a fatal lung cancer due to a <u>lifetime exposure</u> of 1 pCi/L is ~ 0.58%, or at the 4 pCi/L action level it is 2.3% (EPA, 2003).

Adenocarcinoma is the most common form of lung cancer in never smokers (Sophie, 2007).

Radon exposure is considered the second leading cause of lung cancer.

Second-hand smoke is also a risk factor.

Types of lung cancer: Small cell (oat cell carcinoma) and nonsmall cell

Nonsmall cell accounts for 85-90% of lung cancer types and this is broken down into:
- Adenocarcinoma (40%)
- Squamous cell carcinoma (25-30%)
- Large cell carcinoma (10-15%)

Small cell carcinoma accounts for 10-15% of all lung cancers. It is almost always caused by smoking (ACS).

U.S. Statistics (2005):

90,139 men and 69,078 women died of lung cancer, for a yearly total of **159,217** (CDC)

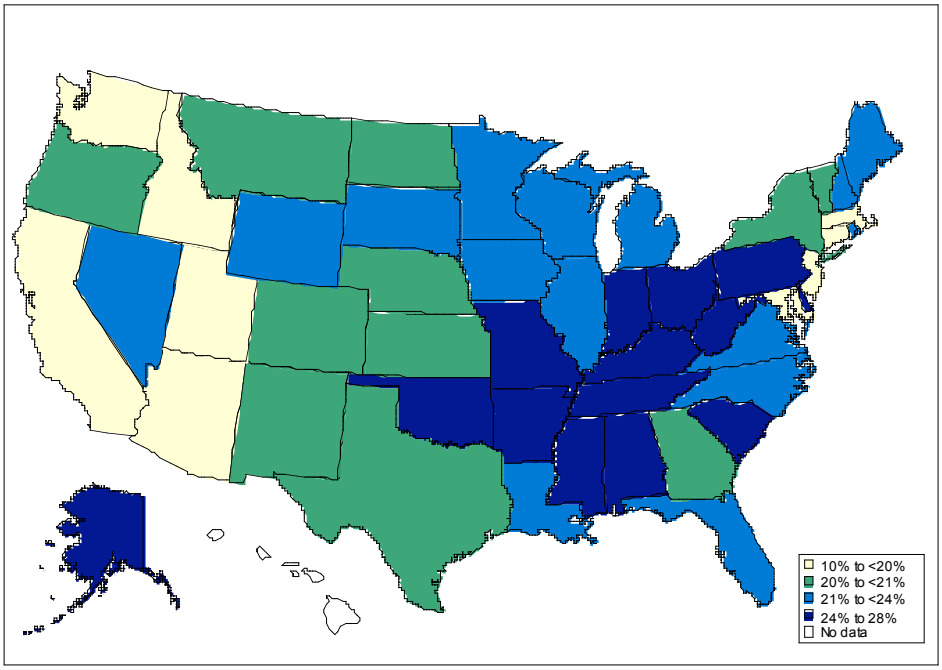
Symptoms of lung cancer:

Shortness of breath
Coughing that does not go away
Wheezing
Coughing up blood
Chest pain
Fever
Weight loss

Currently there is no major organization that recommends screening for early detection of lung cancer (Collins, 2007). However, a New England Journal of Medicine article in October 2006 found that lung cancer could be detected in 85% of patients in its earliest stage by the use of "annual low-dose CT screening (Henschke, 2006)."

Map 1 (9)

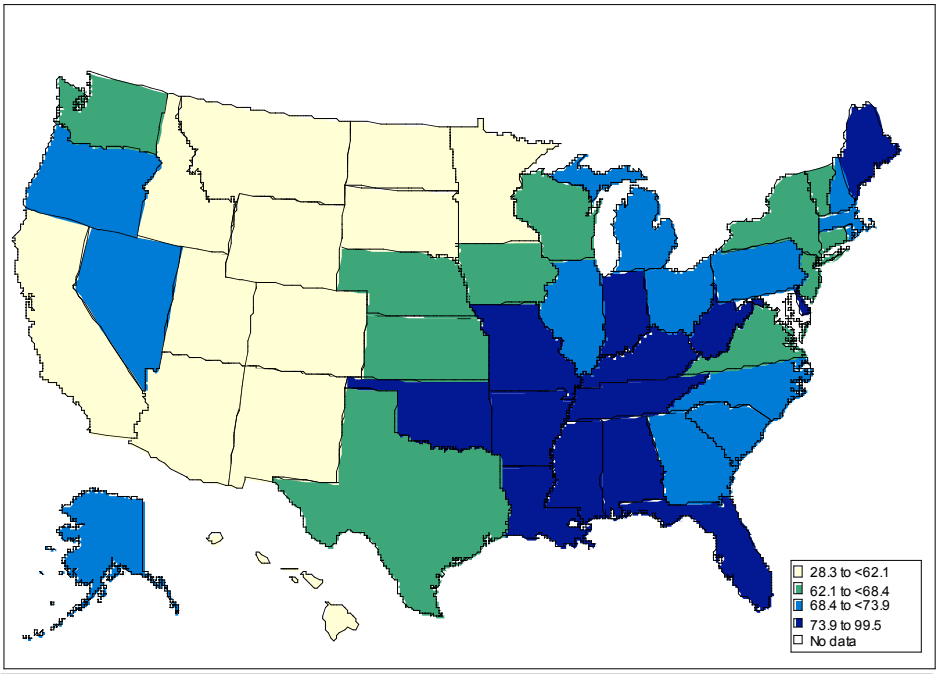
Prevalence of Cigarette Smoking - Adults - 2004
(age-adjusted, aged 18 years and over)



Source: DATA2010 …the Healthy People 2010 Database - March, 2008 Edition: Objective: 27-01a

Map 2 (9)

Lung and Bronchus Incidence Rates - 2004
(age-adjusted, per 100,000)



Source: U.S. Cancer Statistics Working Group. United States Cancer Statistics: 1999–2004 Incidence and Mortality Web-based Report. Atlanta: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention and National Cancer Institute; 2007. Available at: www.cdc.gov/uscs.

Notes: Incidence rates (cases per 100,000) are age-adjusted to the 2000 US standard million population. All in situ cancer incidence cases are excluded.

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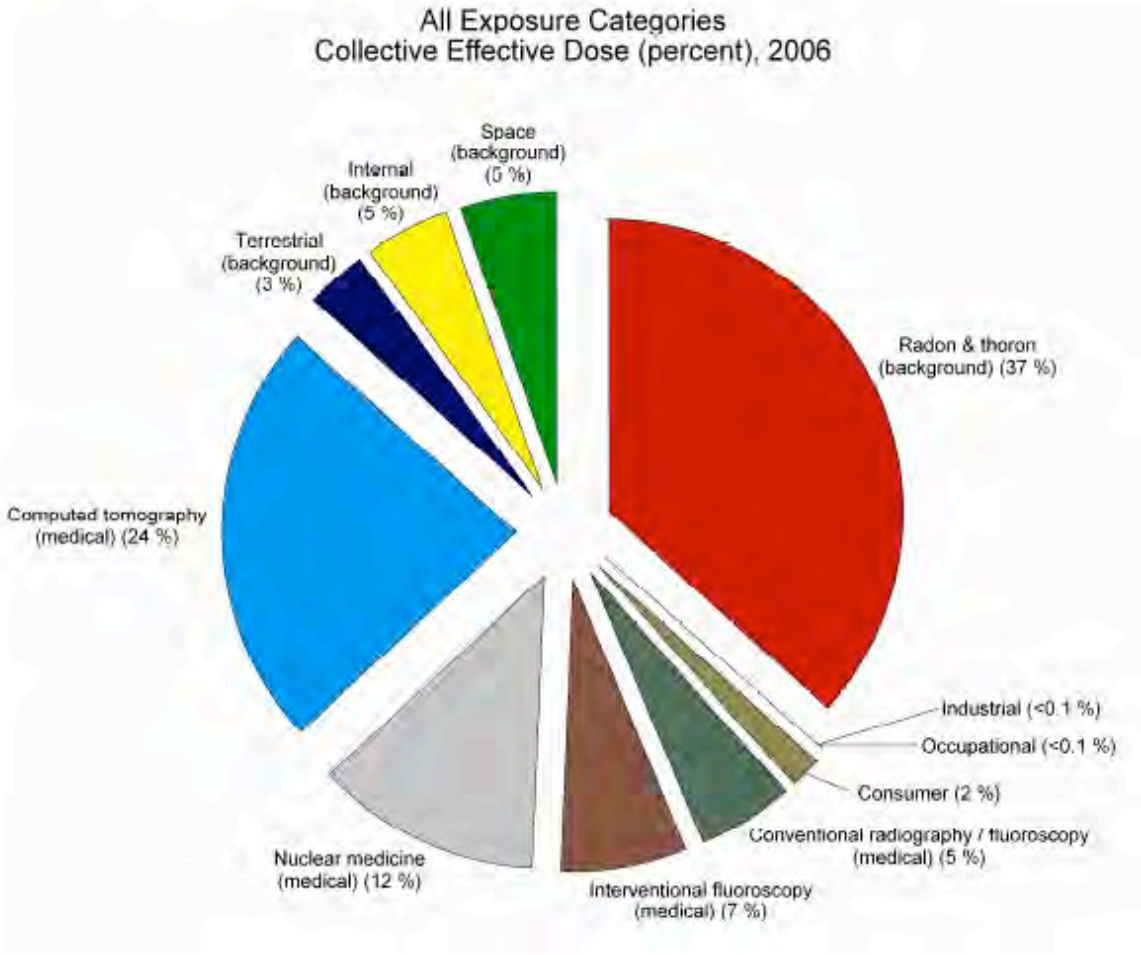
Lung/Bronchus Cancer Incidence Rates by State

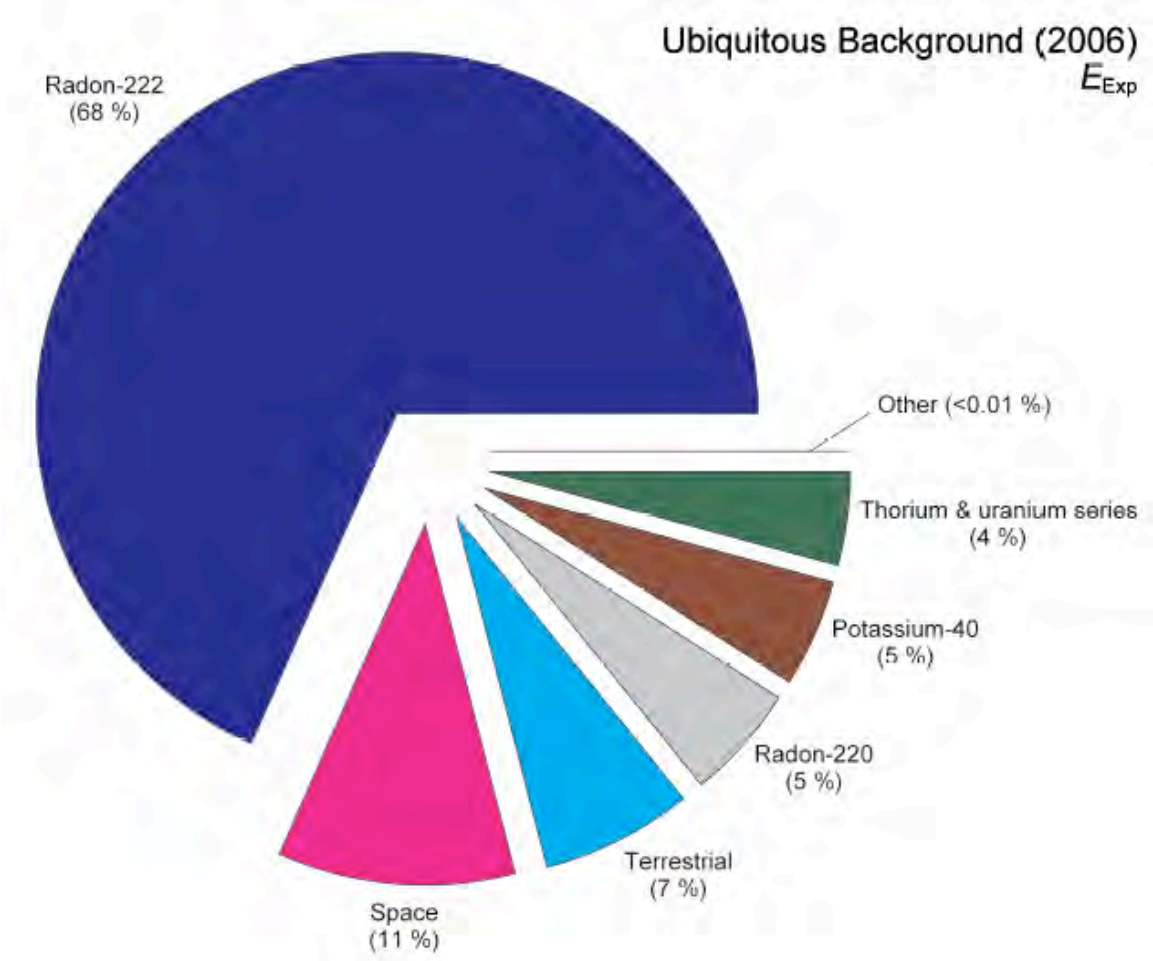
State	Rate	State	Rate
AL	77.0	MT	61.9
AK	70.7	NE	64.9
AZ	55.4	NV	72.6
CA	53.5	NH	70.9
CO	50.8	NJ	62.1
CT	64.5	NM	45.3
DE	80.0	NY	63.5
DC	56.9	NC	72.9
FL	73.9	ND	56.1
GA	72.8	OH	72.9
HI	54.2	OK	78.5
ID	57.8	OR	68.4
IL	69.3	PA	68.4
IN	76.1	RI	73.5
IA	65.2	SC	69.6
KS	65.2	SD	59.0
KY	99.5	TN	82.2
LA	79.9	TX	65.9
ME	79.1	UT	28.3
MD	53.2	VT	62.8
MA	69.7	VA	67.6
MI	71.4	WA	67.1
MN	58.6	WV	85.6
MS	77.5	WI	62.6
MO	77.4	WY	53.6

Age-adjusted rate per 100,000 for both males and females. Age-adjusted to the 2000 U.S. Standard population. **U.S. Average is 67.4.**

Source: Centers for Disease Control, National Program of Cancer Registries, U.S. Cancer Statistics. 2004.

September 14, 2009


All Exposure Categories
Collective Effective Dose (percent), 2006
Space (background) (0 %)
Internal (background) (5 %)
Terrestrial (background) (3 %)
Radon & thoron (background) (37 %)
Computed tomography (medical) (24 %)
Industrial (<0.1 %)
Occupational (<0.1 %)
Consumer (2 %)
Conventional radiography / fluoroscopy (medical) (5 %)
Nuclear medicine (medical) (12 %)
Interventional fluoroscopy (medical) (7 %)



The above two pie charts from the National Council on Radiation Protection and Measurements (NCRP) shows the breakdown of radiation exposure to the U.S. population. The first pie chart shows the exposure from all significant sources, primarily background and medical. The two most significant aspects of this chart are the seven-fold increase in medical exposure, since the early 1980's, primarily from CT scans and nuclear medicine, and the inclusion of thoron with the radon exposure. This first pie chart shows that radon/thoron contribute 37% of the total collective effective radiation dose to the general population.

The second pie chart excludes medical exposures and just shows the background radiation exposures, of which radon-222 contributes 68%, and thoron-220 contributes 5%.

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September 14, 2009

A Brief History of the Rn-222 Occupational Limits

Much of the federal guidance given below was based on studies starting in the early 50's of uranium mines on the Colorado Plateau. The U.S. Public Health Service, primarily led by Duncan Holaday and his colleagues were the first group to raise concern about the potential health effects from exposure to radon decay products in the mines. There was already evidence coming from the "European Experience" where increased lung cancer rates were seen in the miners. However, there was great reluctance by the miners to take radon seriously, they were making good money. The mine operators were also reluctant to disturb operations. However, in spite of the reluctance, the Public Health Service was able to start getting into mines to take samples and have physical exams performed on many of the miners. It was too early yet to see any malignancies in the miners; however, the air samples were certainly alarming. One sample at a working face in a Utah mine showed 26,900 pCi/L, another at the entrance incline was 14,000 pCi/L. These samples are compared to what was seen in some German and Czechoslovakian mines with 1,000 and 1,500 pCi/L, respectively. It was becoming obvious that something had to be done. The Public Health Service estimated that a maximum allowable concentration of 100 pCi/L of radon would be safe in a mine. This was also the European standard. The only radiation standards at the time were those established by the NCRP in 1940. Finally, in the early 1950's William Bale from the University of Rochester, and Dr. John Harley at the Health and Safety Laboratory found that it was not the radon but the radon decay products that were the significant health concern. It would be up to the Atomic Energy Commission to set the standard, see below.

December 1968 the Federal Radiation Council (FRC) submitted three memorandums to the President concerning radiation protection guidance for federal agencies. The recommendations contained in the memorandums were based on FRC Report No. 8, "Guidance for the control of radiation hazards in uranium mining," September 1967.

The first memorandum was published in the Federal Register on August 1, 1967. The FRC considered exposure guidance of 36, 12, and 4 WLM per year. Based on a balance between risks to miners and exposure control capability in the mines they choose the 12 WLM per year limit.

The second memorandum was published in the Federal Register on January 15, 1969. In this memorandum, the FRC gave guidance to federal agencies concerning underground uranium mining. They put forth eight recommendations, two of which are most important to this discussion. 1) Occupational exposure to radon decay products in underground mines shall not exceed 12 WLM in any consecutive 12-month period, and 2) The uranium mining industry is urged to continue to lower exposures so that the anticipated 4 WLM per year standard can be attained by January 1, 1971.

In the May 25, 1971 Federal Register the Environmental Protection Agency (EPA) provided further guidance to federal agencies concerning underground mining of uranium ore. They concluded that 4 WLM per year was technically feasible, that the 4-WLM standard would not have a severe impact on the uranium mining community and that a standard greater than 4 WLM would probably result in dosages greater than those permitted for other occupational exposure situations. This recommendation of 4 WLM per year was approved by the President and published in the January 15, 1969 Federal Register and was to become effective January 1, 1971. This date was later extended to July 1, 1971.

Based upon the May 25, 1971 Federal Register announcement by EPA of the 4-WLM/yr standard, public comments were received. The EPA responded to those comments as published in the July 9, 1971 Federal Register and concluded that no change would be made to the 4-WLM/yr standard.

In the June 24, 1974 Federal Register, the Atomic Energy Commission (AEC) considered an occupational concentration value for Rn-222 **decay products** in their Table 1, Appendix B. The limit for Rn-222 (gas) would be replaced by a limit for the decay products since they are the major health hazard. This change would bring the limit to 4 WLM/yr as recommended by the EPA, which is about 1/3 of the then-current 10 CFR 20 value. This change was in conformance with the ICRP Publication 2, "Report of Committee II on Permissible Dose for Internal Radiation," published in 1959, which recommended a limit on Rn-222 of 3E-8 μCi/ml (30 pCi/L) with decay products present. NCRP also recommended the same limit in their NBS Handbook 69, 1959.

The AEC considered expressing the concentration of the Rn-222 decay products in terms of working level but rejected this because it would add a new unit to the table and add confusion. It was therefore proposed and amended that the current Appendix B, Table 1 limit for Rn-222 be deleted and a new line for Rn-222 decay products be added beneath the Rn-222 line. The limiting value for Rn-222 decay products would be 7E-8 μCi/ml (70 pCi/L). This limit is based on a one-week average. For this value, see Fed. Reg. Vol. 39 No. 122 Monday June 24, 1974.

As published in the October 31, 1975 Federal Register, the AEC decided to express both radon and its decay products in conventional ways. Thus, the Federal Register announcement of June 24, 1974 was amended to show a Rn-222 concentration limit of 3E-8 μCi/ml (30 pCi/L). A footnote gave an alternate limit of 1/3 WL for decay products. This amendment became effective January 29, 1976.

The Nuclear Regulatory Commission changed the averaging period for the Rn-222 limit from one week to one year in the July 7, 1978 Federal Register.

The Rn-222 limit of 30 pCi/L (0.33 WL) that became effective on January 29, 1976 did not appear in the 10 CFR 20 Appendix B table until the 1979 edition. Prior to that, it had been 100 pCi/L.

The value of 30 pCi/L (0.33 WL) is still the current US NRC occupational exposure limit for radon-222. This value is also known as the DAC value, for Derived Air Concentration. The other value for radon-222 in 10 CFR 20 Appendix B, Table 1, is the ALI or Annual Limit of Intake, being 4 WLM for radon decay products.

Radon and Geology

Rocks most likely to cause radon problems and the uranium and radium sources they host. Table below from L.C.S. Gundersen and others.

Rock Type	Uranium and Radium Sources
Black Shales, Lignite, Coal	Uranium-bearing organic compounds; autinite, tyuyamunite
Glauconitic sandstones	Radium- and uranium-bearing iron oxides; heavy minerals
Fluvial and lacustrine sandstones	Roll-front deposits, which include uraninite, coffinite, pitchblende, secondary uranium minerals (tyuyamunite, carnotite, uranophane, and other uranyl vanadates); uranium and radium adsorbed onto organic material; iron and titanium oxides, placer deposits, which include heavy minerals.
Phosphorite and phosphate	Phosphate complexes; apatite
Chalk and marl	Phosphate complexes; apatite
Carbonates	Uranium and radium adsorbed onto iron-oxide coatings; radium with organic material in soils; tyuyamunite, carnotite, and uranophane in karst and caves
Glacial deposits	Bedrock-derived clasts that comprise the glacial deposits are usually the principle source of radioactivity; uranium- and radium-bearing iron oxide and carbonate coatings on clasts are common
Granites and granitic gneiss	Heavy minerals; uraninite; brannerite; apatite, monazite, allanite
Volcanic rocks	Heavy minerals; uranosilicates
Faulted rocks Graphitic schist's and gneisses, some of which are metamorphosed black shale and	Heavy minerals; uraninite; uranium precipitated with hematite and titanium oxide; minerals found in uranium vein deposits

Rock Type	Uranium and Radium Sources
siltstone	
Vein and vein-like deposits	Many kinds of uranium minerals; heavy minerals
Syenites, carbonatites, pegmatites	Uraninite; other uranium minerals; heavy minerals
Bauxite	Heavy minerals

One scheme for the classification of radon-risk areas is based on the geological criteria as follows:

Classification	**Criteria**
High-risk areas	Rn in soil gas Conc. >than 1350 pCi/L
	Uranium-rich granites and gneisses. Contacts of oxidizing (red) and reducing (black) sedimentary rocks.
	Pegmatites (granitic)
	Alum shale
	Highly permeable soils
Normal-risk areas	Rn in soil gas conc. 270 to 1350 pCi/L
	Rocks and soils with low or normal uranium and radium content
	Soils with average permeability
Low-risk areas	Rn in soil gas conc. < 270 pCi/L
	Rocks and soils with very low uranium content.
	Limestone
	Sandstone
	Basic and ultrabasic, such as serpentinite igneous and volcanic rocks
	Soils with very low permeability, such as water saturated

C.R. Cothern and J.E. Smith, Jr. Environmental Radon. Environmental Science Research, Volume 35. Plenum Press, 1987.

As with most any classification system there will be exceptions to the generalizations in the above table.

EPA's Map of Radon Zones

A map(s) of the US on a county-by-county basis identifying areas of highest radon potential (>4 pCi/L).

Designed for federal, state and local governments to design and assist in outreach programs and resource management. Also to be used for targeting local municipalities and builders for the incorporation of radon-resistant new construction practices.

Not to be used to make predictions about individual homes.

The Radon Zone map is based on the work done by the USGS in cooperation with the US EPA to provide a radon potential for the US. That work resulted in ten separate booklets, for instance "The Geologic Radon Potential of EPA Region 3", which includes PA, DE, WV, VA, and MD.

The map assigns each of the 3141 counties in the US to a radon potential zone, Zone 1, Zone 2 or Zone 3.

- Zone 1 counties have predicted average indoor screening level > 4 pCi/L
- Zone 2 counties have predicted average indoor screening level ≥ 2 pCi/l and ≤ 4 pCi/L
- Zone 3 counties have predicted average indoor screening level < 2 pCi/L

Note some important words above; they are **predicted** - foretell on the basis of observation, experience or scientific reason. They are **average** - thus some will be higher and some lower. They are for **indoor** radon levels. They indicate **screening** levels, which implies lowest livable level of home.

The USGS identified 360 separate geologic radon provinces for the US. These provinces were then categorized by five factors considered most important in assessing radon potential: existing indoor radon concentrations, geology, aerial radioactivity, soil parameters and foundation types.

Observations from US Radon map: In general, coastal areas do not have high radon potential. Radon potential does vary throughout the US. Thus, we do not need the same level of effort in Texas as we do in Pennsylvania.

NURE: National Uranium Resource Evaluation

This project was sponsored originally by the U.S. Atomic Energy Commission and then later by the Department of Energy. It systematically evaluated the uranium resources of the United States. The project ran from 1974 to 1980. The project included water and stream-sediment sampling, rock sampling and analysis, airborne radiometric and magnetic surveying, geologic mapping and subsurface geologic investigations.

The data from the NURE mapping was organized onto the USGS National Topographic Map Series 1:250,000 scale. Of most interest to this program are the aerial radiometric data. More than 1.1 million line-miles of surveys were flown to determine the presence of potassium, uranium and thorium. In the western U.S. flight-line spacing was 3 miles and in the eastern U.S. flight-line spacing was 6 miles. Flight lines were either east-west or north-south, and at a nominal ground clearance of 400 feet.

A gamma-ray spectrometer pointed toward the ground detected the 1.764-MeV gamma ray from Bi-214. Bi-214 is one of the progeny of radon-222.

The key information gained from the NURE program was the identification of areas favorable for uranium exploration and mining, with grades of at least 0.01 percent U_3O_8 . This information ended up on color-coded maps of the U.S. and the individual states. The maps showed a color scale typically from 0.5 to 5.5 ppm eU, where the e means radiometric equivalent uranium. Radiometric equivalent, because it was not measured directly but calculated. R.T. Peake considered rocks with >3 ppm uranium as being of high radon potential. Rocks with less than 1.5 ppm uranium may be considered low, and rocks with uranium between 1.5 and greater than 2.5 may be considered intermediate.

How do the NURE data relate to radon? The NURE data give an indication of near-surface uranium concentrations. The uranium concentration can be mathematically converted to radium-226 concentrations in picocuries per gram by the conversion: 1 ppm eU is equal to 0.33267 pCi/g Ra-226. Now with the radium concentration we have the direct parent of radon. Additionally, the radium content of the soil and rocks is one of the four primary factors to consider for an area's radon potential, the other three being emanating power, soil permeability and soil moisture. A radium content of less than 0.5 pCi/g is generally considered low, moderate concentrations are in the range of 0.5 to 1.0 pCi/g, and high concentrations > 1.0 pCi/g.

The NURE data are most useful for radon prediction when augmented with geologic and soil data.

The NURE data typically do not provide useful information on a small-scale basis.

Peake, R.T. Radon and Geology in the United States. Radiation Protection Dosimetry, 24: 173-178, 1988.

Introduction to Soils

Soils have two major volume fractions. The **solid fraction** consists mainly of mineral grains of a wide range of sizes and also includes a small amount of organic matter. The **void fraction** consists of fluid usually water and gas (similar in composition to air). The void fraction is also known as the **soil porosity**. The volume fraction of water is often called the **moisture content**.

Soils are classified according to the size distribution of the solid grains.

Clays - grain size < 2 micrometer, porosity 0.6

Silt - grain size 2 - 60 micrometer, porosity 0.5

Sand - grain size 60 - 2000 micrometer, porosity 0.4

Moisture Content

Moisture content is a very important factor for radon emanation and migration in soil. For a well-drained soil, the void volume contains water in the smaller pores and air in the larger pores. Capillary water increases the radon emanation fraction by absorbing the recoil energy of the newly formed atom. However, this water does not increase the resistance of the soil to airflow to a great degree since it is the larger pores that make the dominant contribution to airflow.

Permeability

The velocity of fluid flow through the soil pores in response to the pressure gradient.

The importance of permeability in relation to indoor radon arises from its very broad range of values.

Range of permeability's: higher (gravel) 10^{-7} m^2 to lower (clays) 10^{-16} m^2; permeability is also described in terms of a rate (inches/hr):

Impermeable----------	<0.0015 in/hr		
Very slow----------	0.0015	to	0.06
Slow ----------	0.06	to	0.2
Moderately slow----------	0.2	to	0.6
Moderate----------	0.6	to	2.0
Moderately rapid----------	2.0	to	6.0
Rapid----------	6.0	to	20.0
Very rapid----------	> 20.0		

Since convective flow rate increases with increasing permeability, and since the radon entry rate increases with the convective flow of soil air into the structure, the potential for radon entry is expected to increase monotonically with permeability for large-grained soils. According to R.T. Peake soils with high permeability (>6 in/hr) may contribute to elevated indoor radon, even when the soil radium concentration is low.

Convective vs. Diffusive flow and permeability

Diffusive flow through soil predominates when permeability's are less than ~ 1E-7 cm^2, and convective flow predominates when the permeability's are greater than ~ 1E-7 cm^2 (Tanner, 1964).

This can lead to radon diffusion lengths of less than 1 cm for low-permeability, saturated soils to about 1 m for low-permeability, dry soils, and to as much as ~ 5 m by convective flow for higher-permeability soils. Thus, well-drained soils such as those found on hilltops may yield high indoor radon.

Thus, on-site measurements or published data of soil permeability may be useful for identifying buildings with high radon concentrations.

Radon Production in Soil

This is a function of the radium content of the soil, which in turn depends on the radium content of the rocks from which the soil was formed.

Emanation Coefficient or Emanation factor - Only a fraction of the radon generated in soil ever leaves the solid grains and enters the pore space of the soil. This fraction is known as the emanation coefficient or emanation fraction.

Typical range of values for the emanation coefficient are 0.05 to 0.7 for soil.

The emanation coefficient is largely controlled by the size of the mineral grains and the distribution of radium within the material. Where the radium is disseminated throughout the volume of the grain, the emanation coefficient is low; when radium is coating the mineral grains near the pore space, the emanation coefficient is high.

During radon production, a radium atom decays via alpha decay into a radon atom. This radon atom has a recoil range of about 0.02 to 0.07 micrometers in common minerals; 0.1 micrometer in water, 63 micrometers in air.

Now, there are three outcomes after this radium decay:

1. The radon atom stops in the fluid-filled pore space
2. The radon atom leaves one mineral grain and is trapped in another grain.
3. The radon atom begins and ends its recoil within a single grain.

Important: Only radium atoms within the recoil range of the surface generate radon atoms that have any possibility of escaping the grain.

Combining numerous factors suggests that radon release from the soil is maximal when the soil is moist.

In summary, if we were going to try to characterize a geographical area for radon potential several factors we would consider are:

1. Radium content of soil
2. Temporal state of the soil, particularly moisture
3. Soil permeability
4. Weather - temperature, wind, rain fall

References:

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Radon Decay Products (RDP)

RDP: Po-218 → Pb-214→ Bi-214→ Po-214→ Pb-210→ Bi-210→ Po-210

Synonymous with Radon Decay Products are "Radon Daughters" and "Radon Progeny." Note: The Health Physics Society no longer uses or permits the use of the term "Radon Daughters" in its keywords or publications.

Radon Decay Products are the radionuclides that follow the decay of radon-222 in the uranium-238 decay series.

Radon Decay Products are principally distinguished from radon by their chemical activity; whereas, radon-222 is chemically inert for all practical purposes.

RDP's are originally formed as positive ions or neutral atoms.

First decay product Po-218 is formed in positive state 80% of time.
Single, positive charge is assumed.
Positive charge acquired by stripping electrons by departing alpha or as a result of recoil.
Probably no negatively charged Po-218.
Po-218 undergoes ~ 1 trillion collisions until it thermalizes (nsec), it may still have a charge after thermalization. It finally does become neutral by scavenging electrons from its recoil path.

Second decay product Pb-214, results from alpha decay of unattached or attached Po-218.
Pb-214 may remain attached or due to recoil energy (100 KeV) become unattached.

Third decay product Bi-214, results from beta decay of Pb-214.
Bi-214 typically remains in attached state since recoil energy of beta is only a few electron volts. This is not sufficient to promote detachment.

Radon Decay Products are classed into size distributions:

- -Unattached Fraction (ultrafine aerosol mode)- 0.5 to 5.0 nm in diameter.
- -Unattached Fraction mostly consists of "free" Po-218 atoms. A few water molecules may also be attached. (Hopke, 1992)
- -Unattached Fraction due to high diffusivity and high deposition rate in the tracheobronchial region delivers a higher dose per unit exposure than attached fraction.
- -Unattached Fraction comprises about 5% of total Radon Decay Products in houses. (UNSCEAR, 2000)
- -Unattached Fraction dose conversion factor around 10 to 20 rad/WLM
- -Unattached fraction has diffusion coefficient of 0.054 cm^2/sec.

-Attached Fraction- 20 to 500 nm in diameter.
-Attached Fraction dose conversion factor around 0.2 to 1.3 rad/WLM.
-Attachment process is due to two main mechanisms; classical diffusion and gas kinetics

The fate of the decay products: Decay, Attachment, Deposition, Recoil and Resuspension.

Radioactive Decay is a physical characteristic unique to each radionuclide and not affected by circumstances, such as temperature, pressure, or chemical environment.

Attachment is the process whereby an unattached radon progeny atom or cluster, strikes and sticks to an aerosol particle. Most radon progeny activity will be found attached to particles in the size range 100 to 200 nm in diameter.

Deposition describes the process whereby attached or unattached progeny stick to surfaces exposed to the air. The term "plateout" is often used for this phenomenon. The deposition onto surfaces is described by the deposition velocity. All to be said regarding this is that the deposition velocity for the unattached progeny is about 100 times greater than that of the attached progeny.

Resuspension occurs when a previously deposited radon progeny (unattached or attached) recoils from the surface back into the air space.

References:

Nazaroff, W.W. and Nero, A.V. Radon and its Decay Products in Indoor Air. John Wiley & Sons. 1988.

Cavallo, A., Hutter, A., and Shebell, P. Radon Progeny Unattached Fraction in an Atmosphere Far from Radioactive Equilibrium. Health Physics, 76(5):532-536; 1999.

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United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2000, Volume 1: Sources.

Hopke, P.K. Harmonization of Radon Jargon and Units. Health Physics, Volume 64, page 459, 1993.

Radon Variability

That radon concentration does vary with time is well documented. Over short periods of time a change in concentration of a factor of five is not uncommon. One NJ residence had basement radon variations of a factor of 15 over a two-month period (Hernandez, et al., 1984).

One interesting comment that Allan Tanner made while performing a bibliography search was that "nearly all papers discuss the effects of meteorological variables. Owing to nonideal conditions in the various test areas and to the understandable difficulty of isolating the effects of different variables, the results of these investigations do not present a very coherent picture; the variable inferred to dominate in one investigation is found to be of little significance in another." This comment was made in 1964, however.

Four factors that influence radon concentrations indoors are properties of the building material and ground; building construction; meteorological conditions; and occupant activities. Building materials can have varying concentrations of radium-bearing material and different diffusion properties. The ground surrounding the structure can have varying radium content, different porosity's and permeability's. The structure can be slab-on-grade, full basement, crawl space or some combination. A floating slab may exist or the pour may be monolithic. Wind, rain, temperature and barometric pressure all factor into affecting indoor concentrations. Operation of HVAC systems and window opening would probably be the major factors due to occupants.

The sources of radon in the home environment are soil gas (90%), domestic water and underground wells (8-9%) and building materials (1-2%). There is a wide range of variability in the radon source materials that can add to the variability of the radon concentration in the home. The source material variability in decreasing order is ground water (1000X), soil and geologic substrate (20X or more), meteorological conditions (10X if short-term measurements are used), building materials (5X in most cases) and ventilation rate (usually less than 3X) (Mueller Associates, 1986).

Meteorological factors are often interrelated in their influence on indoor radon concentrations. Some researchers have suggested that lower air exchange rates may cause higher radon concentrations. However, the forces that cause higher air exchange rates (winds and temperature differences) also cause an increase in the soil gas entry and may cause higher indoor radon concentrations.

Soil moisture and its effect on radon emanation runs the gamut. At very low moisture content the radon atom has little opportunity to come to a stop in the open pore space, and it may become embedded in the mineral, moist soil conditions seems to lead to optimal emanation, and high soil moisture causes decreased diffusion and again low emanation.

Even "general weather effects" can have substantial effects on short-term radon measurements. These weather effects should be considered as factors, which can compromise short-term measurement results (Hoffman, 1995).

Radon Entry Dynamics

For a given radon entry rate, the indoor concentration depends on the ventilation rate. Infiltration, the uncontrolled leakage of air, is the dominant mechanism for ventilation when windows and doors are normally closed. In typical U.S. housing stock, rates range from 0.3 to 1.5 ACH, but new construction techniques have reduced this value to 0.1 ACH. However, the broad range of indoor radon concentration is due primarily to differences in radon entry rate as compared to differences in ventilation rates. This as been confirmed in numerous studies where a weak correlation has been found between air exchange rate and indoor radon concentration.

Radon entry into homes is via diffusion from soil and building materials, via off gassing from radon in water and via pressure-driven flow of soil gas. Pressure-driven (advective) flow is the predominant entry mechanism. This flow is driven by depressurization of the below-grade portion of the building relative to the soil. Temperature differences, wind speed, and barometric pressure changes may all induce this depressurization. At least one author (Minkin, 2008) believes that pressure-driven entry does not totally explain radon entry, particularly during the times when stack effect would be reversed as during warm weather. He has proposed an entry mechanism of thermodiffusion, whereby a temperature difference can induce mass transport.

Soil gas entry is through cracks and gaps in the foundation structure, and these openings typically provide little resistance to flow. Soil permeability to air is therefore the major factor governing indoor radon concentrations. Soil-gas entry is essentially proportional to permeability (Garbesi, et al 1999).

Recent research has suggested that diffusion can be a significant contributor to indoor radon, particularly at low indoor concentrations where advection may only account for 20% of the radon entry (Renken et al., 1995).

Soils: Nazaroff and Nero 1988

Soil and rock act as the main source for generation of radon. The radium content of soil reflects the radium content of the rocks from which the soil formed. However, some locations can have soils that have been transported from distant locations and therefore the underlying rock type may not reflect the prevailing soil. The average radium-226 content of Pennsylvania surface soils is about 1 pCi/g. Movement of radon within the soil is restricted to several meters or less; therefore, a foundation would not draw radon from very distant locations.

Two processes; convective flow and diffusion govern the exchange of gas between the soil and the atmosphere. Convective flow is due to pressure differences

between the soil and the atmosphere. These pressure differences can be induced by soil and air temperature differences, barometric pressure and wind movements. The upper few inches of soil may show significant diurnal temperature changes resulting in convective flow; however, most gas exchange occurs via diffusion (Brady, 1974).

Some important characteristics of soil that are discussed below are grain size, permeability, porosity and moisture content. These characteristics have a large influence on radon transport within the soil. The soil is divided into two major volume fractions; the solid fraction composed mainly of mineral grains and the void fraction (also known as **soil porosity**), which usually consists of water and air. The volume fraction of water is called the moisture content. A soil is saturated when the moisture content equals the porosity. Soil porosities are commonly in the vicinity of 0.5. **Grain sizes** range from clays at <2 μm, to silt at 2-60 μm, to sand at 60-2000 μm.

Moisture content is a very important factor for radon emanation and migration in soil. For a well-drained soil, the void volume contains water in the smaller pores and air in the larger pores. Capillary water is held in the small pores and in a film around the surface of soil particles. This capillary water increases the radon emanation fraction by absorbing the recoil energy of the newly formed radon atom. However, this water does not increase the resistance of the soil to airflow to a great degree since it is the larger pores that make the dominant contribution to airflow within the soil.

Permeability describes how readily a fluid can flow through a soil. It relates the fluid flow through the soil pores to the pressure gradient. Its importance in the study of radon arises from the very broad range of permeability's found in soil. Common soils range from 10^{-8} m^2 (clean gravel) to 10^{-16} m^2 (clay). Larger grained soils generally have higher permeability's. At the low end of this range, molecular diffusion is the dominant process, at the upper end convective flow is the dominant transport process.

Diffusivity, owing to random molecular motion, is the tendency for a substance to migrate down its concentration gradient in a material. The term used to describe this flux is the **diffusion coefficient**. In a porous medium (soil), it is a property of the fluid (radon) in the pores. The movement of radon from soil to the atmosphere appears to be primarily due to molecular diffusion. The radon diffusion coefficient in air is 1.2E-5 m^2/sec; the radon diffusion coefficient in soil of low moisture content is 1E-6 m^2/sec.

Water plays an important role in influencing the radon diffusion coefficient in soil. In saturated soil, the radon diffusion coefficient may be reduced to 2E-10 m^2/sec. This value is so much lower than for that in air that we can view the effect of water on the radon diffusion in soil as blocking a fraction of the available pore space.

Emanation coefficient is the fraction of radon generated that leaves the solid grains and enters the pore volume of the soil. Only radium atoms within the recoil range of the surface (0.02-0.07 μm for common minerals) have any possibility of escaping the mineral grain; maybe around 25%. Radon atoms in the deeper regions of the crystals are unavailable to the pore space without the development of a large internal surface, such as

may result from chemical corrosion, weathering, or intensive fracturing on a microscopic scale (Tanner, 1964). Moisture content of soil has a large impact on the emanation coefficient. A radon atom entering a pore space partially filled with water has a high probability of stopping in the water, and from there it readily transfers (~0.1 sec) to air in the pore. This suggests that radon release from soil, combining emanation and transport, is maximal when soil is moist.

One important consideration must be kept in mind when considering the above soil characteristics and radon transport. The presence of a house may influence the spatial distribution of soil moisture and, thereby, the emanation and migration of radon. The house acts as an umbrella to precipitation whereby the soil surrounding the house is more affected than the soil beneath the structure.

A **wind** of 6.7 mph can induce a pressure difference across the soil and substructure on the windward side of about 2 Pa. This pressure difference varies as the square of the wind speed; therefore, much larger pressure differences are possible. Since wind-induced pressures can fluctuate rapidly, do they have time to be transmitted through the soil? This depends on the soil permeability. For this wind-induced pressure to be transmitted 1 meter through the soil in clay takes 10 days, in silt it takes 30 minutes and in gravel it takes 0.01 seconds. In addition to wind speed, wind direction can also affect radon entry in the absence of other factors.

A definite trend indicates that high **wind** speeds produce a depletion of radon concentration in soil gas down to 44" (Kraner, 1964).

This brings up a good point. Someone calls you up and asks about a radon test they had performed during some windy conditions. Did the wind have any effect on my results? From the above it would seem to depend on soil permeability, which we obviously don't know. Thus, it is not easy to answer the question.

Besides its effect on soil, **temperature** would also act to produce a stack effect in the building since a pressure difference exists across any vertical wall separating air masses of different temperature. The temperature creates a convective loop that carries air into the building near the ground and out of the building toward the top of the structure. Stack effect is primarily a function of temperature difference and height of building. It has been demonstrated that temperature differences associated with extreme weather conditions can generate pressure differences of several pascals, which contribute to radon driving forces and indoor radon concentrations (Al-Ahmady, 1994). There is a strong correlation between the indoor-outdoor pressure differences and the indoor-outdoor temperature differences. It is the temperature difference, which causes air volume movements, which consequently cause the pressure difference.

Regarding radon exhalation rates from soil Kojima and Nagano, 2000 found that wind, which is often associated with decreasing barometric pressure, had a significant effect; whereas, temperature had only a minor effect on soil exhalation rates. The wind

velocity induces negative pressure difference by lowering surface pressure, the effect results in the increasing upward flow of soil gas.

Compared with the pressure changes associated with wind and temperature differences, the magnitude of **barometric pressure** change is large, with excursions from the long-term average routinely exceeding 100 Pa. Over a three-year period of measurement Hoffman, 1995 found barometric pressure swings as much as 336 Pa. However, this only leads to soil gas flow into the building if this large pressure difference causes a sustained pressure difference between basement and the pore air of nearby soil. A barometric pressure drop alone does not appear to affect basement radon concentration as much as a barometric pressure drop plus rainfall (Harley, et al., 1984).

Kraner et. al., 1964 described the changing **barometric pressure** effects using a piston analogy of the atmosphere. This produced a short-range displacement of soil gas, moving under the influence of a pressure differential between the atmosphere and soil gas at depth.

The effects of **precipitation** showed radon-laden soil-gas increases at depth owing to a "capping effect," in which the moisture significantly reduces vertical porosity of the surface layers. This effect continues while the soil is extremely moist (Kraner, 1964).

Well-**frozen ground** appears only to reduce the soil-gas flux. A 40% reduction in flux was seen with ground frozen to 6" compared to average summertime values (Kraner, 1964).

For a house with a basement on relatively permeable soil, and the surface of the **soil frozen**, a barometric pressure change could lead to a flow of soil gas that is funneled through the basement as a result of the reduced permeability of the frozen soil. A similar situation might exist for buildings immediately following a **heavy rain**. Harley noted that enough rain to "plug" the soil surface may inhibit surface release and lead to a build-up of radon at depth.

Tanner 1964

The three factors most commonly observed to have pronounced effects on radon concentration and exhalation are rainfall, freezing and snow cover. Both transport and diffusion are affected. With heavy rainfall, the soil gases near the surface tend to be displaced upward, carrying radon with them and increasing the exhalation rate temporarily. Thereafter, the reduced diffusion coefficient and reduced permeability of the wet ground restrict migration by both mechanisms. Exhalation of radon is markedly reduced, with a commensurate increase of radon in the soil.

Fleischer et al. 1983

Summer radon levels are usually substantially different from winter. The reasons for this variability include increased ventilation of the homes during summer (open windows) and lack of operation of central heating systems that circulate air.

Grainger et al., 2000 found that on the Isle of Man (UK) radon concentrations were highest during the winter months indoors and highest during the summer months outdoors. No explanation was given.

Majborn 1990, in Denmark, found the "normal" **seasonal variation** of highs in winter and lows in summer in a study of 10 single-family houses. He found a strong positive correlation between average indoor-outdoor temperature difference and indoor radon. He also found that radon in basements during winter was about 35% higher than radon in basements during the summer.

Growing information on karst geology areas suggests this to be another source of variability for radon occurrence. The tendency in these areas is for a reverse of the "normal" pattern of winter high and summer low radon occurrence. However, even in karst areas not all homes are affected by this "reversal effect." Which homes are affected may depend on their degree of connection to the karst solution cavities and their location in relation to topographic features (Smithard, 2009 and McNees and Roberts, 2004).

Arvela et al. 1994

Radon in Eskers in Finland. Eskers are long narrow steep-sided ridges formed by glacial streams. The soil is permeable sand and gravel, which allows significant soil gas flow. In these areas air above 0 degrees C flows out of the ground in the winter and into the ground in the summer.

Indoor radon is affected by permeable soil, subterranean airflows and wind effects hitting the slope. During the summer, the ambient air is warm and the subterranean air is cool, thus the airflow is from top of the slope to bottom. During the winter, the ambient air is cold and the subterranean air is warmer, thus the airflow is from bottom of slope towards top. Large errors can occur in predicting indoor radon if you measure the homes at the bottom of the slope in the wintertime (underestimate by factor of 3-4) and the homes at the top of the slope in the summertime (2-10% of annual average).

Thus, radon variability is complex; permeable soil, wind effects; location on slope and temperature, all affect variability; however, temperature is the dominant factor affecting airflows in the eskers and the annual variations in the indoor radon concentration.

Valen et al., 2000

Found the same effect in Norway in a glacial valley. There is a movement of relatively warm soil air towards the higher areas during winter giving rise to high radon content in the ground in the topographical elevated areas, while the lower areas are aerated. In summertime, the process is reversed, giving rise to high radon content in the lower parts of the area.

Nero et al, 1983

No correlation was seen between radon concentration and air change rate in three groups of houses. Differences of radon concentration among the group are due to source strength. However, for a given source strength, the indoor concentration can be expected to depend largely on the ventilation rate. This correlation does not hold up in the real world, because there are so many other variables; source strength, soil characteristics, foundation type, house characteristics, ventilation rate and meteorological conditions.

Nazaroff et al, 1985

In a house with a crawl space, a modest drop in barometric pressure and a period of **heavy rain** caused the indoor radon and crawl space radon to rise to its highest level during a 5-week measurement period. The rain may be acting in one of two ways; it could act by funneling the radon from the soil into the crawl space: with heavy rain, the permeability of the soil surrounding the house is greatly reduced while the permeability of the soil beneath the house remains unchanged; as the barometric pressure falls, soil gas then flows into the crawl space at a higher rate then it does out of the soil surrounding the house. The alternative explanation is that the downward movement of water through the soil may act like a piston and displace the radon, which then flows into the crawl space.

Soil moisture: Radon emanation from soil grains and its transport through interstitial spaces are significantly affected by soil moisture content. Radon exhalation from a completely dry soil was at its lowest due to the reduced emanation coefficient, and was at its lowest for saturated soil, due to its low diffusion coefficient. Thus, it would seem that somewhere in between you would have the highest exhalation rate.

Other factors affecting radon exhalation from soil are meteorological variables (barometric pressure, wind speed, relative humidity), vegetative cover, pressure effects, particularly the pressure difference between pore space air and outside air. A 1% difference in barometric pressure results in a 60% change in the exhalation rate. **Temperature effects** produce two types of behavior in soils; the first type is the widely observed diurnal variations that result from competition of convective flow due to temperature differences in soil from day to night and from turbulent mixing in the atmosphere, which leads to an increase in exhalation in daytime and a reduction at night. The second type of behavior results from the direct heating of the soil (Collé et al., 1981). Stranden et al., 1984 also found a temperature effect on soil radon exhalation, with an

increase in exhalation with increasing temperature. Physical adsorption of gases on solids is known to be temperature dependent; therefore, an increase in temperature caused a decrease in the adsorption of radon on the soil grains, with an increase in exhalation. This effect is not as significant as the moisture effect on exhalation. A good value to quote for radon exhalation from soil is 0.43 $pCi/m^2/sec$. However, meteorological variables play only a minor role in soil radon exhalation compared to the soil characteristics.

Stranden et al., 1984

Three major effects of soil moisture causing an **increase** in radon exhalation; the direct recoil fraction of the emanation power is increased when there is a fluid present in the internal pores of the material, the fluid may hinder adsorption of radon gas on internal surfaces of the material, and with a soil moisture content gradient in the sample, active transport of radon on water molecules may take place.

On the other hand, water present in the internal pores reduces the diffusion of radon out of the material. The radon diffusion coefficient for water is 0.00001 $cm^2\ sec^{-1}$ compared to the radon diffusion coefficient for air, which is 0.01 $cm^2\ sec^{-1}$.

Thus, up to a certain point of soil moisture content the increasing effects are dominating. After an optimum moisture content the reduced diffusion due to the water will dominate, and exhalation will decrease.

Schubert, M. et al., 2002

Radon at the soil-air interface. Again, **soil moisture** is found to be a crucial factor in radon variation, and soil moisture is affected by meteorological conditions. The highest radon concentrations at the soil-air interface, and at depth of 5 cm, was found in early morning hours, and lowest values emerge in the afternoon. These highs and lows are due to temperature gradient at air-soil interface and to wind speed. The highest wind speeds appear at about noon and in the early afternoon and the lowest ones at about midnight and in the early morning hours. During the night and early morning hours, the temperature difference between soil and air is positive, that is the soil is warmer than the air directly above it, thus an upward directed convective radon flux enhances the overall diffusive transport leading to the early morning maximum. As soon as the outside air temperature is higher than the soil-gas temperature the situation is reversed, because the convective flux is now downward and this reduces the upward diffusive flux, leading to the minimum radon concentrations in early afternoon. This occurs only at the soil-air interface and at very shallow depths. Below ~ 30 cm no diurnal effects are seen.

Levesque, B. et al. 1997

894 Quebec residences show a lognormal distribution and summer values are lower than winter values. Concentrations found in basements are clearly higher than those found on first floors. First floor to basement ratio is 0.59, i.e. basement 10 pCi/L

first floor 5.9 pCi/L. They did not see any difference between first floor and second floor.

Two other factors contributed to increased radon; building on hilly terrain and a fireplace increased radon in basements.

Fisher et al., 1998 found in Iowa homes that the first floor/basement ratio is slightly different for one- and two-story homes; 0.61 and 0.53, respectively. For two-story homes, the second floor was about equal to the first floor, with a second floor/first floor ratio of 1.02.

Lenzen, M. et. al. 1999

Showed a direct connection between radon-222 concentration and the **earth tides** at a period of 12.4 hours, showing a positive correlation. This relation may be due to a compression of the pore space due to the tidal compression, causing a porous flow of radon-bearing gas across the rock-air interface. This was observed in a gypsum mine in Luxembourg.

Diurnal tides run on a 12-hour cycle with a high and low.

Marley, 2001

Investigated several homes on British Isles. Found **seasonal variability** contrary to most, where radon was higher in the summer than in the winter by a factor of two to three times. This study found radon variability is primarily dependent on barometric pressure, vapor pressure and wind variation (including direction relative to the building concerned), with barometric pressure being the primary factor.

Hintenlang, et al., 1992

It is typically assumed that radon entry is due to pressure-driven flow with indoor pressure being lower than sub-slab pressure. Circumstances can occur where the highest concentration of indoor radon will correspond when the house is under neutral pressure conditions.

A semidiurnal variation of barometric pressure is a well documented result of **atmospheric tides** resulting from solar heating and coriolis forces (an apparent force that as a result of the earth's rotation deflects moving objects) on the earth. These barometric pressure changes are not related to changing meteorological conditions. This oscillation of barometric pressure produces a natural pumping action on soil gas into houses by inducing small indoor/sub-slab pressure differentials. This mechanism provides a means of pumping radon into a house without depressurizing the interior of the house relative to the outdoors. Additionally, since the indoor/outdoor pressure equalizes so quickly there is little infiltration of outdoor air.

Steck, 1992

This author found that a significant **spatial variation** can exist within a house. The most significant spatial variation was found in basements, most likely due to point sources. Much less variation was found on first and second floor.

Marley, 1999

Radon variability can to some degree reflect **occupancy** of a building. Consider a school HVAC operation. Unit ventilators typically come on an hour or two prior to start of class and then shut down around 4 PM during the weekdays. On the weekends, the units may not operate at all. Intermittent operation of the AC system reduced radon by a factor of four, and operation of the central heating (CH) reduced radon by 40%. The operation of the CH had the effect of increasing the internal temperature with a corresponding small increase in pressure. If these two mechanical devices were not present, the radon variability would be more directly and consistently determined by general atmospheric conditions. In the summer, the AC air is more dense then outdoor air. In theory, flow-reversal due to a gravity-driven outflow of air may reduce radon influx. However, this pressure difference is very small and could be easily overshadowed by meteorological factors (Hoffman, 1995).

We have not mentioned anything about progeny; however, mechanical devices would have a pronounced effect on progeny distribution.

Matthews et al., 1990 found that operation of heating and air-conditioning systems in two unoccupied houses resulted in a three-fold increase in transport rate of tracer gas from crawl space to living area.

Nazaroff et al., 1985 has shown that **fireplace** operation can lead to house depressurization and increased radon entry but that effect can be masked by geological factors affecting the availability of radon in the near-surface soil.

Chittaporn, et al.

Showed that variability of basement radon was associated with **air exchange rate**. The lowest air exchange rate was during highest outdoor temperature (summer) and the basement radon was the highest. Conversely, colder outdoor temperatures yielded larger pressure differences yet lower basement radon concentrations. It was also found that drops in barometric pressure caused transient radon surges into the basement.

Cohen, et al., 1988

A very large sample size showed **winter radon** about 60% higher than **summer radon** for the living areas of the home. Spring and fall radon were about 40% higher than summer radon. The winter/summer ratio (living area) for PA was 1.86. Basements

were about 2.5 times higher than other rooms, with this difference being larger in the summer and smaller in the winter.

Miles, 1998

A 2000 house survey in the UK showed a clear pattern of high indoor radon in **winter** months and lower radon during **summer** months. A similar result was found in Swedish homes. However, in both cases, some houses showed just the opposite effect, but this was only in a small number of homes.

Hans, et al., 1985

A study of homes (68) in Butte, MT presented some limited data showing **daily cycle** of radon with indoor minimums during daylight hours and maximums during nighttime hours. This cycle was more pronounced in the summer and less pronounced in the winter. The occurrence of the large cycles was caused principally by alteration of the ventilation rates.

Hans, et al., 1986 EPA Report

Found the low to occur during the warmer months, corresponding to increased ventilation rates and possibly due to less radon in the soil gas due to more exhalation to the atmosphere. **Ground freezing** lowers radon exhalation rates, which increases below-grade concentrations available for transport and diffusion into homes. The maximum indoor concentration was found to occur in December and the minimum in August. The study included twenty homes in Butte, MT.

Borak, et al., 1989

A survey of 110 homes in Fort Collins, CO found radon in **summer** to be about 40% of the annual average, and radon in the **winter** was about 1.7 times higher than the annual average. The radon concentration in basements was two times higher than on ground floors; however, there were no differences between ground floors and second floors.

Porstendorfer, et al., 1994

Outdoor radon also shows a diurnal cycle, with its highest activity during the night and early morning hours when the atmosphere is most stable. At noon and early afternoon, the mixing of the lower atmosphere is strongest and radon concentration is lowest. Indoor radon is mainly influenced by source strength and air change rate, and both of these factors can change with meteorological conditions, occupant activities, mechanical ventilation and heating systems.

Conclusions

A lot of information has been presented. Sometimes there are differences from one study to another, and sometimes one variable is looked at more closely than another. The above information has come from research studies, conducted usually with relatively small sample size and at different locations in the country and throughout the world. There can certainly always be exceptions to the conclusions drawn regarding radon variation from one house to another and under different meteorological and occupant conditions. Below is a general compilation of the variables that affect radon variability.

Soil moisture: The moisture content of soil and its affect on radon exhalation run from dry soil where exhalation is reduced, to saturated soil where exhalation is also reduced, to moist soil where radon exhalation is optimal.

Wind: Wind can affect both the structure and the soil-gas concentration. Wind can have a depressurizing effect on the basement, with soil-gas entry being dependent on soil permeability. Wind can also induce convective flux of soil gas out of the soil causing a depletion zone.

Temperature: Temperature, like wind, can affect both the structure and soil-gas concentrations. Inside/outside temperature difference across the building shell results in a stack effect. A type of "stack effect" also operates in soil where in the early morning, when the soil is warmer than the air, there is an upward convective flow. The opposite also occurs when air is warmer than the soil. Increased soil temperature would tend to decrease adsorption of radon on soil grains and cause increased exhalation.

Barometric Pressure: A decrease in barometric pressure allows more radon to easily exhale from the soil surface. However, this drop may not affect the basement radon concentration unless the pressure drop is sustained long enough to affect the soil pore air space below the foundation. A barometric-pressure drop plus rain seems to affect basement radon more than just a barometric-pressure drop.

Rain: Enough rain to saturate soil, after some time, reduces surface exhalation and leads to increased radon concentration at depth.

Frozen Ground: Primarily reduces soil-gas flux, but does not stop flux completely.

Seasonal Variation: Generally, indoor radon is higher in winter and lower in summer.

Diurnal Variation: The indoor radon concentration tends to be higher during the night and early morning and lower radon during noon to early afternoon.

House Level: Basement concentration is about twice what is found on the first floor. First floor and second floor are about equal. The basement to first floor ratio does change slightly with season.

This paper identified about thirteen factors that can affect radon variation in the soil and house environment. The thirteen factors being soil moisture content, soil permeability, wind, temperature, barometric pressure, rainfall, frozen ground, snow cover, earth tides, atmospheric tides, occupancy factors, season and time of day. One can see the complexity of understanding and studying radon variability in homes.

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Radon in the Workplace

OSHA's primary mission is to provide for the safety of the American workers. OSHA regulations do not apply to the residential environment.

OSHA Ionizing Radiation Regulations: 29 CFR 1910.1096

Exposure Limit for Rn-222 in a restricted area: **100 pCi/L** (this is the value found in the 1970, 10CFR20, Appendix B, Table 1, Column 1, for occupational exposure).

Exposure limit is based on average conc. for 40-hour week.

May be proportionally increased or decreased, depending on the 40-hour work week.

The employer shall perform surveys and measure the concentration of radioactive material present, where employees are exposed to said radioactive material.

Posting Requirements:

A room with concentration in excess of 100 pCi/L, or an occupied room with average conc. during occupancy > 25 pCi/L, shall be conspicuously posted, **"Caution, Airborne Radioactivity Area."**

Personnel monitoring equipment is required in restricted areas if the employee is likely to receive in any calendar quarter a whole body dose in excess of 0.31 rem (25% of the calendar quarter limit of 1.25 rem).

Personnel monitoring would also require that the employer maintain records of personnel radiation exposure.

Types of Areas:

Unrestricted Area: < 3 pCi/L

Where an employee continuously present would not receive in any one hour a dose in excess of 2 mrem or a dose in any seven consecutive days of greater than 100 mrem.

Where airborne radioactive material does not exceed the limits found in 10 CFR 20, Appendix B, Table 2, Column 1, 1970 for effluent releases). This value may be averaged over a period of not greater than one year.

Restricted Area: > 3 pCi/L.

Any area for which access is controlled by the employer for purposes of protection of individuals from exposure to radiation or radioactive materials 1910.1096(a)(3).

No individual in a restricted area may receive, in any period of one calendar quarter, a dose in excess of 1.25 rem to the whole body, head and trunk, active blood forming organs, lens of eyes, or gonads; 18.75 rem to the hands and forearms, or feet and ankles; 7.5 rem to the skin of the whole body 1910.1096(b)(1). These values may be exempted if during any calendar quarter the dose to the whole body does not exceed 3 rems; and the dose to the whole body, when added to the accumulated occupational dose to the whole body, shall not exceed 5(N-18) rems, where "N" is the individuals age in years. The employer must also maintain past and current exposure records 1910.1096 (b)(2) (i,ii,iii). No one under 18 years of age may receive in one calendar quarter a dose in excess of 10% of the limits specified above (1.25, 18.75, and 7.5 rem) in a restricted area.

No employee shall be exposed to airborne radioactive material in an average concentration in excess of the limits specified in Table 1 of Appendix B to 10 CFR Part 20, in a restricted area. For radon-222 this is 100 pCi/L averaged over a 40-hour workweek 1910.1096(c)(1).

No one under 18 years of age may be exposed to airborne radioactive material in an average concentration in excess of the limits specified in Table II of Appendix B to 10 CFR part 20, in a restricted area 1910.1096(c)(2). For radon-222 this is 3 pCi/L averaged over a period not greater than one week.

An employee who enters a restricted area who receives or is likely to receive a dose in any calendar quarter in excess of 25% of the values specified above (1.25, 18.75, and 7.5 rem) shall wear personnel monitoring equipment for the purpose of measuring the dose received 1910.1096(d)(2)(i).

Radiation Area: > 5 mR/hr

High Radiation Area: > 100 mR/hr

Airborne Radioactive Area: >100 pCi/L or > 25 pCi/L (occupied area). This area shall be conspicuously posted, **"Caution, Airborne Radioactivity Area."**

Diagnostics

Diagnostics (our definition): A series of questions, observations and measurements designed to assess the cause of a problem.

Visual Inspection
Homeowner Questions
Building Material Surface Radon Flux
Radon in Water
Grab Samples
PFE Mapping
Air-Flow Measurements
Blower-Door Tests
Photos

Potential Failure Modes: Inadequate PFE, Untreated Sources, Reentrainment, Fan failure, Radon in Water, Building Materials, Outdoor Radon.

One of main entry points of radon into homes is via the wall/floor joint. Studies have shown that once the gap width exceeds 0.5 mm (~1/32"), there is no longer a significant increase in radon entry, with increasing gap width (UNSCEAR, 2000).

Forced air distribution systems can influence radon in at least two ways (Turk, 1988):

1. Leaky returns in basement have been observed to depressurize basement as much as 10 Pa.
2. They can transfer large amounts of basement radon to the upper floors.

The soil temperature surrounding the building foundation significantly influences (positively and negatively) the pressure difference that drives radon into buildings (Turk, 1988).

Stack Effect:

The movement of air into and out of buildings, driven by the buoyancy of air. Buoyancy occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences. The movement of air in the building can be either up or down. The driving force for air movement is the pressure difference between the inside and outside of the building. That pressure difference can be calculated with the following equation:

$P_s = 0.52\ PH\ (1/T_o - 1/T_i)$ where

P_s = Total pressure difference caused by stack effect, inches of water column.
P = Ambient pressure, psia
H = Building height, ft
T_o = Absolute temperature outside, in Kelvin
T_i = Absolute temperature inside, in Kelvin

The neutral pressure plane is where the inside and outside pressures are equal.

The neutral pressure plane can shift up or down depending on how the leakage openings of the building are distributed, top to bottom.

Infiltration occurs below the neutral plane and exfiltration occurs above it.

Interestingly, in the summer, when the outside air temperature is higher than that inside the pattern of pressure differences and air flow is the reverse of that during the winter. Infiltration occurs at the upper floors, and exfiltration at the lower levels, with air flowing downward within the building. The stack effect is much reduced (Wilson, 2004).

Pressure Field Extension (PFE): The maximum distance from a suction point where the sub-slab volume remains depressurized to a magnitude capable of preventing soil-gas flow into the building (Hintenlang, 1991).

PFE is a function of applied pressure at the suction point, pit size and sub-slab permeability (Hintenlang, 1991).

In soils with poor communication (low permeability) the pressure field may take minutes to hours to extend to its fullest point (Hintenlang, 1991).

The creation of the suction pit, immediately below the suction pipe, has been empirically demonstrated to enhance pressure field extension (Hintenlang, 1991).

If you double the applied pressure at a suction point you will approximately double the pressure at a given test hole some distance away. However, you will not appreciably increase the distance of the pressure field. To do this you most likely need to add another suction point (Hintenlang, 1991).

Radon diffusion through concrete can be a source of indoor radon. Radon can diffuse through intact concrete at a rate of about 1/10,000,000 to 1/100,000,000 per meter squared per second. Diffusion may be more significant in low-permeability soils, where there is less air-driven seepage through cracks (Rogers, 1994).

On the Subject of U-tubes

I recently had a useful conversation with a mitigator looking for help with diagnostics on a home he was working on. This contractor made the comment that he was looking at the U-tube and then making a decision on what to do with the current fan he was using. This got me thinking about U-tubes.

First, U-tubes should not be used to make decisions about fan choice.

The primary function of the U-tube is as an indicator device, primarily for the homeowner. The contractor should mark the U-tube reading just after installation and note this on the label. The homeowner then has a reference value with which to compare future readings.

Let's look at the two extremes:

1. You have a U-tube reading that is very "high." Let's say 2" WC.

   This does not necessarily mean that you are using the wrong fan. It could mean that that the pipe has fallen down and embedded in the soil and cut off all of your flow. In this case, you obviously don't need a different fan, you just need to remove the blockage.

   It could also mean that you are dealing with very low-permeability soil. This would result in very low flows and high vacuum readings. This may suggest a higher vacuum fan, but other things should also be done with pit size and additional suction points.

2. Now we have a U-tube reading that is very "low." Let's say 0.1" WC.

   This could mean that you have very high-permeability soil. This would probably mean that you want a fan to move more air.

   You could have leaks in the piping system or the foundation. This would result in high airflows and low vacuum readings. Obviously sealing the leaks would help with this problem.

   You could have short-circuiting from a suction point through a footer at the walkout side of a basement. This would suggest that you want to move the suction point to a more central location.

So, as you can see there can be multiple reasons for high or low U-tube vacuum readings, and some of them have nothing to do with the fan.

These examples are good. You could elaborate further by pointing out that changes in the u-tube reading over time do not necessarily indicate whether the changes in conditions, which have resulted in the u-tube change, are favorable or unfavorable in terms of system effectiveness. What I like to focus on when explaining the usefulness of looking at the u-tube is that there is no particular relationship between the u-tube reading and the effectiveness (radon control) of the system(or of the PFE values) . This is true not only from one system to another, but for a particular system from one time to another. The strength and extent of the pressure field is far more indicative of potential effectiveness, and that is the pressure value mitigators should focus on, whether in system design or troubleshooting. (Personal communication, Jack Hughes, Southern Regional Radon Training Center)

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Fan Selection

The fan must be able to maintain an appropriate suction by producing an adequate airflow in the system. Typical airflows for residential applications range from ~ 20 to 100 cfm. The ideal situation is to have a tight foundation, with a good aggregate layer below the slab, and a fairly impermeable soil around the foundation. In this situation, fairly low airflows may be required to control soil gas entry. This ideal situation would probably require a very low system to produce the necessary airflow.

The fan is the integral part of the sub-slab depressurization system providing the work of moving air from one location (under the slab) to another location (the atmosphere). This movement of air creates a low-pressure area under the slab relative to the basement.

Fan selection involves comparing fan operating characteristics with the performance requirements (required airflow) and resistance characteristics of the system. One does not want to consider just flow or just pressure when deciding on a fan. The use of a fan curve and system curve supplied by the manufacturer will allow for appropriate fan selection. However, few mitigators take the time to produce a system curve. Be aware that the manufacturer fan curves are derived under laboratory conditions. At least one experienced mitigator believes that the quantitative diagnostics is by far the most appropriate approach to fan selection and total system design. This leaves one with two other options for fan selection; manufacturer-supplied qualitative information and field experience. The manufacturer's information may state, "good for low-flow applications," "prepiped new construction," "good communication and small foot print," etc. Field experience comes from installations in a given area and your success with a certain fan. This method may provide for good radon control, but it may not provide for the most appropriate system, i.e. those that produce the required indoor radon reduction without creating unnecessary system or building operating costs, or creating other safety hazards or detrimental conditions (Hughes, 2009).

Fan selection continued; **Manufacturer's Information**

Dave Kapturowski of RadonAway:

For *good communication*, where you are ventilating the soil and typically moving *less than 100 cfm* of air the RP or XP series fans should fit the bill. All of the current RP and XP fans will move this amount of air. Since they should all do the job, you may want to also consider the physical size of the fan and its power consumption to narrow your choice. **XP 151, XP 201, XR 261, RP 140, RP 145**. 3" pipe OK

For *good communication*, but where you may encounter flows *greater than 100 cfm*, such as a walkout basement or basements where foundation openings cannot be sealed, then go with the **RP 260 or RP 265**. 4" pipe preferred

A very good choice for *RRNC* would be the low-power **RP 140,** it is very quiet**.**

For *tight soil* and poor communication, where you may be moving less than 20 cfm of air, you are trying to establish a pressure field, where more static pressure is needed. You most likely will also have *multiple suction points*. **GP201, GP301, GP401, GP501**.

RadonAway Manufacturer Data

Fan	Max. Pres./Flow	Power Consumption
RP140	0.5”/134 cfm	14-20 W
RP145	2”/173 cfm	37-71 W
RP260	1.5”/275 cfm	52-72 W
RP265	2”/327 cfm	86-140 W
XP151	1.6”/180 cfm	45-60 W
XP201	1.9”/125 cfm	45-60 W
XR261	1.8”/230 cfm	65-105 W
GP201	2”/82 cfm	40-60 W
GP301	2.5”/92 cfm	55-90 W
GP401	3”/93 cfm	60-110 W
GP501	4”/95 cfm	70-140 W

All above fans ETL listed for outdoor use.

Fantech Manufacturer Data

HP2133 ----- Low power and low flow, good communication and low radon

HP2190 ----- Similar to HP190, but smaller housing

HP175 ------- Good communication, lower radon, small footprint, RRNC, lower wattage than HP190

HP190 ------- Good overall choice, moderate radon, multiple suction points, medium footprint

HP220 ------- High radon, high flow, multiple suction points, large footprint, moderate communication

Fan	Max. Pres./Flow	Power Consumption
HP2133	0.84”/134 cfm	14-20 W
HP2190	1.93”/163 cfm	60-85 W
HP175	1.66”/151 cfm	44-65 W
HP190	2”/157 cfm	60-89 W
HP220	2.4”/344 cfm	85-152 W

All HP series UL listed for outdoor use

Final method of fan selection is to generate a “system curve” and then plot this on graph paper that has multiple fan curves already plotted. See which fan curve intersects the system curve at the appropriate position. Ideally, you would pick a fan for which the system curve intersected the fan curve roughly in the middle of the fan curve. The basis for this selection is that the fan would be operating at a comfortable point, and could handle increases or decreases in flow over time that may occur as the soil dries out or becomes saturated.

The above method may be more complex, but it provides for a much more “appropriate” selection and may save contractor costs by using smaller fans and homeowner costs in utility bills over the many years of operation. One would also need a pitot tube, several magnehelics or a digital micromanometer.

Below are presented some anecdotal information from some local radon mitigation contractors on their experiences with fans: Please be aware that these approaches are obviously qualitative.

Field Experience 1

- I use a lot of RP-145’s and RP-140”s.
- Poured concrete foundations and stone under slab RP-140 works well
- Wattage should be considered. Over ten years costs can add up.

Field Experience 2

- Basically use two fans RP-145 and RP-140.
- For RRNC RP-140 is good choice, unless you encounter a lot of airflow that can’t be sealed.

- For existing homes will often perform diagnostics during install. Cut 5" hole, put RP-145 on hole, measure PFE at distant points. If measured PFE is > 5 Pa, then figure RP-140 will give about 2.5 Pa, which should be enough. If < 5 Pa, use RP-145.
- Often can get a 50-Pa differential pressure with RP-140.
- Sometimes just take a chance and guess; however, fan choice ideally depends on diagnostics.
- Very occasionally (10-12/yr) will use HP-220 or RP-265 for high-flow applications.
- Only very occasionally will use GP-501. Seldom need to draw 4" of vacuum. Too expensive.

Field Experience 3

- First dig hole to see what is under slab.
- Use two fans; XP-151 and GP-501.
- Lots of gravel and loose fill use XP-151.
- Tight soil use GP-501.
- The ultimate determination is the reading on the U-tube.
- Sometimes for lots of airflow and higher vacuum use RP-265.
- For RRNC, with sub-slab loop use XP-151.
- When doing the installation it's a seat of the pants thing.
- The bottom line is the confirming test. Sometimes I will change a fan to get to the right number.

Field Experience 4

- Use XR-261 94% of time, existing homes and RRNC.
- Use RP-265 2% of time, where I need more airflow than XR-261.
- Use GP-501 0.5% of time, where low permeability fill and/or finished basement. Where you can't place suctions points where you want.
- Use GP-401 3.5% of time, usually older homes, and > 10 pCi/L.
- Crews rate sub-slab permeability on scale of 1 to 10. 1 is damp clay, 10 is abundant, clean large gravel.
- XR-261: 6 to 10
- RP-265: 6 to 10, large area, high air flow
- GP-401: 2 to 5, tight substrate
- GP-501: 1, very tight substrate
- GP-501 not often used by experienced mitigator
- Noise: XR-261*, RP-265***, GP-401**, GP-501*****

Some Fan Facts

Maximum fan pressure is often stated two ways; maximum fan pressure and maximum fan operating pressure. Maximum fan pressure is the reading on the u-tube when the fan is not moving any air. This will cause the fan to run hotter and shorten life. Maximum fan operating pressure is the reading on the u-tube when about 20 cfm of air is moving through the fan. This airflow will help extract heat from the fan. Every fan should be operating below its specified maximum fan operating pressure. If a fan is operating at its maximum fan pressure, steps should be taken to introduce air into the system.

Within a certain range for each fan model, **fan power consumption** is determined by the amount of air the fan is moving. The more air moving through the fan the more power required. When there is no air moving through the fan blades, the motor is coasting.

When given a range of fan power consumptions (i.e. 60 to 90 watts), this means that at maximum suction the fan will consume 60 watts, because it is doing the least amount of work, and at maximum flow it will consume 90 watts, because it requires more power to move air.

One can get a very rough idea of fan power consumption from the u-tube, and the above relation. Say a fan is rated from 0 to 2" WC, and 60 to 90 watts. If the u-tube was showing zero, there was basically no vacuum and the fan would be moving the most amount of air; therefore, the power consumption would be closer to 90 watts. If the u-tube was showing 2" WC, there would be very little airflow and the fan would be consuming closer to 60 watts.

Stacking fans, that is running them in series, can be done in field applications when additional airflow is required and higher vacuum is needed to produce that airflow. When you stack two fans you will double the maximum static pressure that one fan would produce, but the actual static pressure developed and the airflow increase will vary. You may only increase the airflow a small amount. This is because airflow is dependent on other things besides the fan; such as, sub-slab material, foundation openings and suction-point location. Stacking fans can be useful in dealing with tight soil.

When stacking two fans you want to use identical fans. Using different fans can cause cavitation problems and nonlaminar flow problems, both of which can cause inefficiency problems. Also, leave about 15 pipe diameters of separation between the two fans that will be stacked. This also helps preserve laminar flow.

Condensation can be the single most significant factor in fan failure. According to Dave Kapturowski of RadonAway the amount of condensation produced is dependent on the climate, soil conditions, ducting above the fan and the ducting material. In fact, Dave has calculated that under certain conditions the typical residential system can produce about one gallon of water per day due to condensation.

How to deal with condensation: Mount the fan in a location that minimizes the length of ducting above the fan, use the least amount of pipe in unconditioned spaces, consider using schedule 40 piping, or even insulated piping, be careful not to create any low spot in your piping network, assure that there is adequate slope on piping for condensation to drain back to the soil and use a condensate bypass mechanism for condensation to drain down and around the fan. Fantech has recently (6/09) announced a new fan with a condensate bypass built in.

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Kapturowski, D. Radon Today. Fall Issue 2004

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Kapturowski, D. Radon Today. Summer Issue 2005

Radon Fan Comparison List

MANUFACTURER	MODEL	WATTS	Fan Duct Dia. (in.)	HP	CFM @ 0"WC	"WC @ 0 CFM
RadonAway	RP140	14-20	4	0.019-0.027	134	0.8
RadonAway	RP145	37-71	4	0.050-0.095	173	2.1
RadonAway	RP260	52-72	6	0.070-0.095	275	1.8
RadonAway	RP265	86-140	6	0.115-0.188	327	2.5
RadonAway	RP380	103-156	8	0.138-0.209	510	2.2
RadonAway	XR161*	48-75		0.064-0.100	215	2.1
RadonAway	XR261	65-105	6	0.087-0.141	230	1.8
RadonAway	XP101*	40-49		0.053-0.065	125	1.2
RadonAway	XP151	45-60	4	0.060-0.080	180	1.6
RadonAway	XP201	45-66	4	0.060-0.087	125	2.0
RadonAway	GP201	40-60	3	0.053-0.080	82	2.0
RadonAway	GP301	55-90	3	0.073-0.121	92	2.6
RadonAway	GP401	60-110	3	0.080-0.148	93	3.4
RadonAway	GP501	70-140	3	0.080-0.188	95	4.2
RadonAway	GP500	70-130	3	0.094-0.174	~90's	4.39 (flat box)
RadonAway	HS2000	150-270	3 inlet/2 out	0.201-0.362	110	18 (high suction)
RadonAway	HS3000	105-195	3 inlet/2 out	0.141-0.261	40	27 (high suction)
RadonAway	HS5000	180-320	3 inlet/2 out	0.241-0.429	53	50 (high suction)
Fantech	HP-2133	14-20	4	0.019-0.027	134	0.84
Fantech	LV-2133 DC	14-20	4	0.019-0.027	134	0.84
Fantech	HP-2190	60-85	4	0.080-0.114	163	1.93
Fantech	HP175	44-65	4	0.061-0.090	151	1.66
Fantech	HP190	60-85	4	0.080-0.114	157	2.01
Fantech	HP220	85-152	6	0.114-0.204	344	2.46
Fantech	FR100	13-19	4	0.044-0.056	122	0.87
Fantech	FR110	58-75	4	0.078-0.100	167	1.6
Fantech	FR125	15-18	5	0.020-0.024	148	0.79
Fantech	FR140	45-60	6	0.060-0.080	214	1.15
Fantech	FR150	54-72	6	0.097-0.125	263	1.58
Fantech	FR150 DC	54-72	6	0.097-0.125	263	1.58
Fantech	FR160	103-130	6	0.130-0.174	289	2.32
Fantech	FR160 DC	103-130	6	0.130-0.174	289	2.32
Fantech	FR200	106-128	8	0.142-0.172	408	2.14 (high flow)
Fantech	FR225	111-152	8	0.149-0.204	429	2.48 (high flow)
Fantech	FR250	146-248	10	0.196-0.333	649	2.58 (high flow)
Fantech	ECL452	110		0.148	134	1.26
KTA	KTA150 DC	54-72	6	0.097-0.125	263	1.58
AMG	Spirit	20	3	0.027	121	0.9
AMG	Maverick	75	4	0.114	221	1.88
AMG	Hawk	75	6	0.114	295	1.6
AMG	Prowler	130	3	0.174	163	2.71
AMG	Legend	150	6	0.201	353	2.6
AMG	Eagle	160	3	0.215	124	4.0
AMG	Fury	175	8	0.235	544	2.48
AMG	Force	302	4	0.188	240	5.51
RAM/GAM Eng.	RAM II 24VDC	38 max	4	0.051	195	1.9
RAM/GAM Eng.	RAM 8 24VDC	40 max	2	0.060	70	8.0
RAM/GAM Eng.	Mini RAM 115VAC	20 max	4	0.107	124	1.2
RAM/GAM Eng.	RAM II 115VAC	81 max	4	0.107	195	1.6
RAM/GAM Eng.	Grand RAM 230VAC	250 max	6	0.335	430	2.6
Rosenberg *	R100	50		0.067		
Rosenberg *	R125	50		0.067		
Rosenberg *	R150	90		0.121		
Rosenberg *	R160	90		0.121	Rosenberg lists their watts as input watts.	
Rosenberg *	R200	125		0.167		
Rosenberg *	R200L	210		0.281		
Rosenberg *	R250	330		0.442		

* Models no longer sold. Note: Check manufacturer for exact specs. Prepared by Matt Shields, PA DEP Revised 3/09

1 atmosphere = 1.013255x10^6 dynes/cm^2
14.696 psia
29.921” Hg
1013 mbar
760 Torr
760 mm Hg
406.782” WC
10.3355 meters WC
33.899 ft WC
101,325 Pa

14.696 psia = 406.782 inches WC

1 psia = 27.680 “ WC

1” WC = 249.09 Pa

1” WC = 2.5 mbar

1” WC = 0.074” Hg

1 mbar = 0.4” WC

1 psia = 6894.7 Pa

4 pCi/l = 0.00002 ppm = 0.02 ppb = 148 Bq/m^3

Post-Mitigation Radon Data
Year-long ATD Data

Below is a compilation of PA Radon Division long-term ATD data obtained from our Remedial Program. Our Remedial Program sends out a charcoal and an ATD to homeowners who have provided us proof of having installed an active radon mitigation system. The charcoals are analyzed in our Radon Division lab, and the alpha tracks are analyzed by the alpha-track lab. For this current data set, all of the ATD results were from Landauer. The homeowners are told to initially expose the charcoal in the basement, and if that result comes back less than 4.0 pCi/L, then expose the ATD for one full year. Some do not expose the ATD for a whole year, but most do. This compilation of data is from 1999 to 2008.

Post-mitigation, year-long, radon test results

	Basement	**First Floor**
Mean +/- 1 SD	2.1 ± 1.9 pCi/L	1.0 ± 1.4 pCi/L
Median	1.5 pCi/L	0.5 pCi/L
Sample Size	435	158
Range	0 to 14.7 pCi/L	0 to 11 pCi/L

The above table clearly shows that on the average the active radon mitigation systems are doing a very good job of radon reduction. Actually, for the case of a lognormal distribution the median is the more appropriate statistic. The sample size is fairly decent for this type of data. The first floor/basement ratio shows 1.0/2.1 = 0.476, which is relatively close to the value we previously determined from the Radon Analyzer data of 0.5. The interesting aspect is that the 0.5 value (radon analyzer data) was mostly from nonmitigated homes; whereas, these data are all post-mitigation data, and the ratio stays very similar.

A review of the range values above shows some rather high results for year-long post-mitigation data. From our data we have no information on the installed system and what has transpired in the home, except that is was an active ASD. For the basement results the data show that 88.4% of the results are below 4.0 pCi/L, and 11.5% above. The first-floor data show 96.2% of results below 4.0 pCi/L, and 3.8% above. We do not know what transpired with the results greater than 4.0 pCi/L. It is presumed that homeowners would have called the contractor back for necessary modifications.

The above data impliy that most active ASD systems can reduce basement radon concentrations to the range of 1.5 to 2.0 pCi/L, and that the systems are initially effective (<4 pCi/L) about 90% of the time.

We will attempt to do some further data analysis with pre- and post-mitigation charcoal results and from the pre- and post-mitigation data in Oracle, in the future.

Dr. Daniel Steck (Steck, 2008) of St. John's University, MN provides some similar data for post-mitigation radon concentrations in Minnesota homes. The data below come from his Table 2. Landauer Radtrack ATD's were used. The measurement period for these ATD's was one-half of the winter season and the spring.

	Primary Site
Average	0.84 pCi/L
Median	0.3 pCi/L
Sample Size	132

The primary site is composed of 90% basement and 10% first-floor readings. This data set shows both average and median values less the PA Radon Division data from above.

Brodhead (Brodhead, 1995), in a survey of nationwide mitigation contractors, found that 94% of survey participants (n= 226) who deployed an alpha-track detector had post-mitigation results less than 4.0 pCi/L, and 70% of the survey participants had results less than 2.0 pCi/L. However, measurement location is not given and the measurement period is for three months.

References

Brodhead, B. Nationwide Survey of RCP Listed Mitigation Contractors. Proceedings of the 1995 International Radon Symposium, Nashville, TN.

Steck, D. Post-mitigation Radon Concentrations in Minnesota Homes. Proceedings of the 2008 International Radon Symposium, Las Vegas, NV.

Ambient Radon

Factors affecting ambient concentrations:

Snow cover- likely to depress radon gas release into the atmosphere (Steck, 1999).

Soil moisture content- 40 to 60% can produce high radon emanation and diffusion from soil (Steck, 1999).

Wind direction- This would tend to suggest a change of source with changes in wind direction (Steck, 1999).

Soil cover or lack of cover. i.e. bare tilled soil. The air permeabilities of plowed soils are 4 to 1000 times greater than corresponding compacted samples (Steck, 1999 and Ball, 1981).

Seasonality- maximum in winter (dry season) and minimum in summer months (wet season), in Brazil. Other data from Japan shows similar pattern. U.S. data show minima during spring, and maxima in late summer and fall (Gesell, 1983). Seasonality effects are primarily related to precipitation, relating to soil moisture, and prevailing winds.

Atmospheric conditions- early morning atmospheric temperature inversions lead to a stable atmosphere that restricts vertical mixing. This results in maximum ambient radon during these times. With sunrise, solar radiation heats the ground and causes lower atmospheric warming. This increases vertical mixing, with a decline in radon concentration in the afternoon (Magalhaes, 2003).

Local geology- outdoor concentrations can be correlated with different concentrations of radon in soils and uranium and its progeny in rocks.

Height above ground- Some (Price, 1994) saw indistinguishable radon values at 0.5, 1.0, and 2.0 meters, others (Moses, 1960 saw a gradient from ground level (0.032 m) and a height of 0.97 m, with values decreasing with increasing height.

Soil characteristics such as grain size, mineralogy, porosity and permeability affect how much radon enters the soil gas. There is a mild correlation between soil-gas concentration and radon in ambient air (Price, 1994).

Soil-gas concentration- Concentration of radon in air is governed by the source term, which is the concentration in the soil (Gesell, 1983).

Barometric Pressure- A 1% fall in barometric pressure can double the emanation rate, which in turn would increase the radon concentration close to the ground surface (NCRP, 1975).

Ambient radon concentration and elevation

Radon enters the atmosphere at the soil-air interface.

Radon concentration in the atmosphere is governed by the source term and dilution factors.

Atmospheric radon exhibits a vertical concentration profile, being highest at the soil-air interface and being immeasurably low in the stratosphere.

Over Land vs. Over Oceans

Due to the low radium content of the oceans, the ambient radon will always be lower over the oceans than over the land surfaces (NCRP, 1975). Ambient radon concentration over oceans have been measured at 0.001 pCi/L (Wilkening, 1990).

Daytime vs. Nighttime

Overall averages tend to show that nighttime concentrations are a few times higher than those existing during the day, primarily due to atmospheric stability (NCRP, 1975).

Maximum and Minimum ambient Radon-222 concentrations

D. Steck found high of 1.5 pCi/L (Measurements in Iowa and Minnesota)
D. Hopper found high of 1.1 pCi/L during the national survey.

Fisenne and Harley found a low of 0.015 pCi/L in NYC.
UNSCEAR 2000 shows a low of 0.001 pCi/L

"Typical" Ambient Radon-222 Values

D. Hopper established a U.S. median value of 0.39 pCi/L
J. Price found median for Nevada of 0.4 pCi/L
D. Steck found geometric mean of 0.67 pCi/L for IA and MN.
M. Magalhaes found mean Rn-222 EEC of 0.3 pCi/L for Rio de Janeiro
T. Borak found geometric mean of 0.4 pCi/L in Ft. Collins, CO.
UNSCEAR 2000 reports 0.27 pCi/L as compilation of numerous studies.

Ambient Radon-220 Concentrations

Very limited data.
UNSCEAR 2000 reports value of 0.27 pCi/L similar to the Rn-222 value.
D.Steck also shows value of 0.27 pCi/L from IA and MN.
M. Doi found 0.25 pCi/L in Chiba City, 50 km east of Tokyo
N. Harley measured 0.4 for Central Park and 0.48 for Northern NJ. NRE VII

Radon-222 Equilibrium ratio in outdoor air

UNSCEAR 2000 uses rounded value of 0.6, but with a range from 0.2 to 1.0.

References

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Wilkening, M. Radon in the environment: Studies in environmental science. No. 40. Amsterdam, Elsevier, 1990.

Radon Statistics

The data below are from an unpublished report titled A Statistical Report of Pennsylvania- Radon-222, April 2007. These data were compiled from the PA DEP, Radon Division Radon Analyzer (Lewis, 2007), which is a web-enabled, multi-dimensional database that presummarizes all of the data from radon testing records into predefined logical categories such as zip code, test values, measurement location in building, house type, etc.

Table 1 below shows the evolution, at least from 1990, of the different measurement methods over time. One can see that the activated charcoal (AC) starts out in 1990 with a significant lead, only to be surpassed by the short-term electrets in the mid to late nineties.

Table 1

		Measurement Method Results by Year					
Year	**All Msmt Types**	**CR**	**AT**	**AC**	**ES**	**EL**	**LS**
1990	33,351	1,771	613	22,365	8,562	40	---
1991	37,308	1,795	4,127	18,239	13,029	114	4
1992	41,666	2,273	2,711	19,103	17,313	266	---
1993	43,956	3,260	2,250	18,177	19,866	394	9
1994	48,179	2,526	1,404	24,828	18,969	444	8
1995	57,744	2,988	731	29,640	24,026	356	3
1996	64,138	4,998	1,014	26,917	30,701	457	51
1997	65,600	6,199	838	22,582	33,207	521	2,253
1998	81,666	6,006	844	34,778	37,302	511	2,225
1999	75,026	10,754	1,108	24,184	35,999	471	2,510
2000	74,091	13,129	1,212	20,174	32,188	347	7,041
2001	75,988	14,195	967	21,666	31,144	271	7,745
2002	84,473	16,210	828	22,709	35,567	274	8,885
2003	75,416	17,071	1,027	21,991	24,835	150	10,342
Total	858,602	103,175	19,674	327,353	362,708	4,616	41,076

Qualifications: Table 1 uses all house types, all building locations, all counties, and years 1990 to 2003.

Table 2 shows the number of measurements in a particular house location and the associated average radon concentration. The average for the third floor of 4.28 pCi/L is the most difficult to explain. It may be due to the relatively small sample size (n= 1601).

Table 2

Sample Size by Measurement Location		
Location	**Sample Size**	**Average Result (pCi/L)**
Basement	599,580	7.11
First Floor	156,502	3.6
Second Floor	30,930	2.82
Third Floor	1,601	4.28
Slab-on-grade	44,525	4.73
Above Crawl Space	6,385	2.5

Qualifications: Years 1990 to 2003, all counties, all house types, all measurement types. The results from basements and first floors may not be simultaneous measurements from the same homes.

Table 3 shows the distribution of our measurement data by house type. One will note the large sample size (n=273,327) for the "Unknown" building type. This is due to the radon reports being sent to the Department, where for some reason the tester or lab has not annotated a house type. We are forced to classify it as "unknown."

Table 3

Number of Measurement Results by Housing Type			
Building Type	**Number of Results**	**Percent**	**Avg. pCi/L**
2-Story House	355,356	41.6%	5.4
3-Story House	31,656	3.7%	8.5
Ranch	65,015	7.6%	6.6
Split Level	26,931	3.2%	4.4
Bi-Level	10,994	1.3%	5.6
Cape Cod	16,965	2.0%	5.2
Townhouse	55,254	6.5%	2.8
Contemporary	8,161	0.9%	6.4
Raised Ranch	2,100	0.25%	6.0
Commercial Bldg.	6,926	0.8%	3.4
Public Bldg	334	0.04%	3.7
Unknown	273,327	32%	
	N= 853,019		

Qualification: All counties, all years 1990-2003, all measurement types, all-building locations.

Table 4 shows both basement and first-floor measurements by month of year. These data are presented below in a graphical format.

Table 4, Average Radon by Month, Basement and First Floor

Month	Bsmt Avg	Count	1st Fl Avg.	Count	1st fl/Bsmt
January	9.3	40,435	5.1	12,630	0.55
February	8.1	42,944	4.9	13,812	0.6
March	7.6	53,670	4.4	17,355	0.58
April	7.3	52,277	3.7	17,210	0.51
May	6.6	49,948	3.7	17,157	0.55
June	6.1	46,620	3.2	16,079	0.53
July	5.5	46,029	3.0	14,829	0.53
August	5.9	43,388	3.2	14,232	0.55
September	7.0	40,424	3.8	12,339	0.53
October	8.0	49,284	4.5	13,686	0.56
November	8.6	47,533	5.2	13,310	0.60
December	8.9	35,856	5.1	10,897	0.57
Avg or Total	7.4	548,408	4.1	173,536	0.56

Qualifications: All short-term test methods included (AC, CR, LS, ES). All single-family house types included plus unknown category. For 1st-floor average, first floors and slab-on-grade were used, second floor was not used. The basement and first-floor measurements are not necessarily simultaneous measurements from the same house.

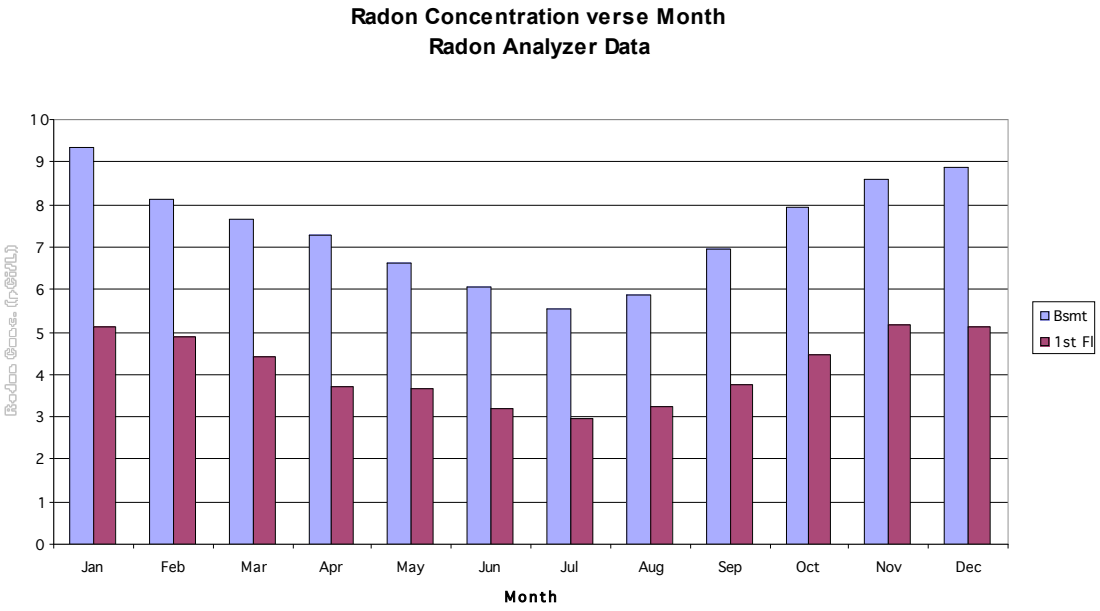


Table 5 shows a breakdown of data by two six-month seasons. These two time periods were chosen only because Rhode Island had done a similar analysis, and we then had some data with which to compare. They also represent warm and cold weather periods, at least in Pennsylvania.

Table 5

Residential Data, Basement and First Floor, Grouped by Season		
Season	**Sample Size**	**Average (pCi/L)**
April thru September	348,240	5.72
October thru March	335,565	7.63

Table 6 gives a finer resolution on the Table 5 above.

Table 6

Residential Data, Basement and First Floor, Grouped by Season		
Season	**Sample Size**	**Average (pCi/L)**
Jan, Feb, Mar	172,600	7.56
Apr, May, Jun	187,051	5.95
Jul, Aug, Sep	161,189	5.45
Oct, Nov, Dec	162,965	7.72

Now if we look at the extremes of winter (7.56) to summer (5.45) months we see a percent difference of 32%, almost identical to the October to March six-month period of Table 7. We then see much less of a difference if we look at adjoining seasons. Spring (5.95) to summer (5.45) shows an 8.7% difference and fall (7.72) to winter (7.56) shows only a 2.1% difference. Winter (7.56) to spring (5.95) shows a 23.8% difference and summer (5.45) to fall (7.72) shows a 34.5% difference.

References

Lewis, R. A Statistical Report of Pennsylvania, Radon-222. Unpublished report. Pennsylvania Department of Environmental Protection, Bureau of Radiation Protection, Radon Division, 2007.

State Radon Data

We had data provided to us by two of the larger charcoal testing laboratories in the country. One of the labs provided the data in the breakdown as seen in the below tables, the other lab provided just raw data for each state by date and result. Due to time constraints, we used just the one data set with the already presummarized data.

The below four tables are an arrangement of radon testing data as provided by this private testing laboratory. Obviously, this laboratory is supplying test kits to all 50 states and the District of Columbia. Data qualifications are 2- to 7-day charcoal, basement and first-floor results, all states, all seasons, years 2000 to 2009 and a total sample size of 718,615. It should also be understood that this data set is not a random distribution. Many states may even use this lab to conduct specific surveys in concentrated areas of their state with known high radon concentrations. This may tend to bias these data high. Also being a private laboratory there may be a large proportion of sales directly to private homeowners, with the potential for improper testing protocols being followed.

The testing data were broken down into four tables simply by sorting the data on (1) sample size for each state (Table 1), (2) average radon concentration for each state (Table 2), (3) the maximum test result (Table 3) and (4) by the percent of test results greater than or equal 4.0 pCi/L (Table 4). The column of interest is highlighted in red.

Sample size for the states shows a large range, and could be due to very low radon activity in a particular state, or a very active state happening to use this particular lab for numerous types of in state surveys.

Table 1, State Ranking by Sample Size

State	N=	AVG	MAX	< 4.0 pCi/L	4-9.9 pCi/L	10-19.9 pCi/L	20-49.9	50-100	>100	< 4.0 pCi/L
HI	18	0.1	0.7	18	0	0	0	0	0	100%
MS	170	1.4	11.8	159	8	3	0	0	0	94%
LA	244	0.6	21.4	239	3	1	1	0	0	98%
DC	302	1.9	22.5	265	31	4	2	0	0	88%
AR	322	3	75.1	276	31	7	5	3	0	86%
AK	373	6.4	273.1	268	59	18	21	5	2	72%
OK	397	2.3	59.3	350	26	11	9	1	0	88%
NV	837	2.7	72.8	693	107	25	10	2	0	83%
AZ	1148	2.3	73.4	984	121	31	10	2	0	86%
ME	1192	6.7	321.2	685	313	123	49	18	4	58%
VT	1222	3.6	110.1	933	198	59	25	5	2	76%
NJ	1245	3.1	71.3	948	218	67	10	2	0	76%
SD	1586	8.1	279.9	663	548	261	96	11	7	42%
TX	1973	2.2	145	1813	105	29	9	6	11	92%
DE	2114	2.4	46.9	1697	360	52	5	0	0	80%
AL	3050	3.9	1383.9	2423	432	117	58	19	1	79%
IN	4133	4.6	616.6	2647	1049	317	111	8	1	64%
WA	4167	5.3	260.6	2927	673	340	171	43	13	70%
NM	4425	3.8	103.4	3125	1012	219	60	8	1	71%
OR	4882	3.7	121.2	3519	923	323	110	6	1	72%
CA	5129	1.6	166.9	4653	370	87	11	7	1	91%
WV	5136	6.6	1228.8	3233	1083	491	252	58	19	63%
RI	5302	4.4	229.7	3552	1283	315	132	17	3	67%
ND	6285	6	181.5	3055	2271	743	189	20	7	49%
MD	6817	5.1	355.4	4555	1495	462	250	38	17	67%
MT	7397	7.3	2574.3	4056	2072	829	363	57	20	55%
NE	7444	5	202.9	4080	2421	766	172	3	2	55%
UT	7444	4.4	542.3	4918	1844	500	163	12	7	66%
ID	7455	6.1	357.1	4722	1660	611	363	78	21	63%
MA	8160	4.1	183.4	5822	1608	512	176	31	11	71%
WY	8539	5.4	240.2	4849	2630	796	235	20	9	57%
KY	9623	8.2	334.9	5170	2277	1215	759	165	37	54%
CT	10010	3.9	309.5	7292	1968	511	198	31	10	73%
SC	10689	2.9	79.3	8359	1775	456	86	13	0	78%
MO	11010	4.6	249.6	7094	2814	805	267	25	5	64%
FL	11205	1.8	342.7	10089	882	161	56	14	3	90%
GA	12843	2.5	90.4	10503	1958	314	65	3	0	82%
NH	13853	5.1	278.8	9287	2976	972	502	88	28	67%
TN	13961	4.3	367.8	9660	3000	905	335	57	4	69%
VA	15558	3.2	165.5	11766	2926	673	169	23	1	76%
KS	15857	5.3	104.5	8646	4999	1760	416	35	1	55%
NY	25634	4.1	318.6	19387	3873	1507	698	136	33	76%
WI	35087	6.2	686.9	19538	10333	3561	1330	230	95	56%
CO	36169	6.1	1618.3	18976	11627	4092	1265	159	50	53%
NC	36775	3.5	1167.3	27229	7184	1786	497	53	26	74%
IL	37427	5	826	22012	10790	3625	909	74	17	59%
OH	44059	8.5	844.2	22223	12929	5279	2688	617	323	50%
IA	47800	6.4	870.6	23512	14987	6916	2223	137	25	49%
PA	57709	8.5	747.2	31639	13693	6736	4195	1080	366	55%
MN	79421	4.7	849.7	45396	26724	6093	1094	86	28	57%
MI	85010	3.4	458	62955	16731	4078	1112	101	33	74%

Table 2, State Ranking by Average Radon

State	N=	AVG	MAX	< 4.0 pCi/L	4-9.9 pCi/L	10-19.9 pCi/L	20-49.9	50-100	>100	< 4.0 pCi/L
HI	18	0.1	0.7	18	0	0	0	0	0	100%
LA	244	0.6	21.4	239	3	1	1	0	0	98%
MS	170	1.4	11.8	159	8	3	0	0	0	94%
CA	5129	1.6	166.9	4653	370	87	11	7	1	91%
FL	11205	1.8	342.7	10089	882	161	56	14	3	90%
DC	302	1.9	22.5	265	31	4	2	0	0	88%
TX	1973	2.2	145	1813	105	29	9	6	11	92%
OK	397	2.3	59.3	350	26	11	9	1	0	88%
AZ	1148	2.3	73.4	984	121	31	10	2	0	86%
DE	2114	2.4	46.9	1697	360	52	5	0	0	80%
GA	12843	2.5	90.4	10503	1958	314	65	3	0	82%
NV	837	2.7	72.8	693	107	25	10	2	0	83%
SC	10689	2.9	79.3	8359	1775	456	86	13	0	78%
AR	322	3	75.1	276	31	7	5	3	0	86%
NJ	1245	3.1	71.3	948	218	67	10	2	0	76%
VA	15558	3.2	165.5	11766	2926	673	169	23	1	76%
MI	85010	3.4	458	62955	16731	4078	1112	101	33	74%
NC	36775	3.5	1167.3	27229	7184	1786	497	53	26	74%
VT	1222	3.6	110.1	933	198	59	25	5	2	76%
OR	4882	3.7	121.2	3519	923	323	110	6	1	72%
NM	4425	3.8	103.4	3125	1012	219	60	8	1	71%
AL	3050	3.9	1383.9	2423	432	117	58	19	1	79%
CT	10010	3.9	309.5	7292	1968	511	198	31	10	73%
MA	8160	4.1	183.4	5822	1608	512	176	31	11	71%
NY	25634	4.1	318.6	19387	3873	1507	698	136	33	76%
TN	13961	4.3	367.8	9660	3000	905	335	57	4	69%
RI	5302	4.4	229.7	3552	1283	315	132	17	3	67%
UT	7444	4.4	542.3	4918	1844	500	163	12	7	66%
IN	4133	4.6	616.6	2647	1049	317	111	8	1	64%
MO	11010	4.6	249.6	7094	2814	805	267	25	5	64%
MN	79421	4.7	849.7	45396	26724	6093	1094	86	28	57%
NE	7444	5	202.9	4080	2421	766	172	3	2	55%
IL	37427	5	826	22012	10790	3625	909	74	17	59%
MD	6817	5.1	355.4	4555	1495	462	250	38	17	67%
NH	13853	5.1	278.8	9287	2976	972	502	88	28	67%
WA	4167	5.3	260.6	2927	673	340	171	43	13	70%
KS	15857	5.3	104.5	8646	4999	1760	416	35	1	55%
WY	8539	5.4	240.2	4849	2630	796	235	20	9	57%
ND	6285	6	181.5	3055	2271	743	189	20	7	49%
ID	7455	6.1	357.1	4722	1660	611	363	78	21	63%
CO	36169	6.1	1618.3	18976	11627	4092	1265	159	50	53%
WI	35087	6.2	686.9	19538	10333	3561	1330	230	95	56%
AK	373	6.4	273.1	268	59	18	21	5	2	72%
IA	47800	6.4	870.6	23512	14987	6916	2223	137	25	49%
WV	5136	6.6	1228.8	3233	1083	491	252	58	19	63%
ME	1192	6.7	321.2	685	313	123	49	18	4	58%
MT	7397	7.3	2574.3	4056	2072	829	363	57	20	55%
SD	1586	8.1	279.9	663	548	261	96	11	7	42%
KY	9623	8.2	334.9	5170	2277	1215	759	165	37	54%
OH	44059	8.5	844.2	22223	12929	5279	2688	617	323	50%
PA	57709	8.5	747.2	31639	13693	6736	4195	1080	366	55%

Table 3, State Ranking by Maximum Radon Value

State	N=	AVG	MAX	< 4.0 pCi/L	4-9.9 pCi/L	10-19.9 pCi/L	20-49.9	50-100	>100	< 4.0 pCi/L
HI	18	0.1	0.7	18	0	0	0	0	0	100%
MS	170	1.4	11.8	159	8	3	0	0	0	94%
LA	244	0.6	21.4	239	3	1	1	0	0	98%
DC	302	1.9	22.5	265	31	4	2	0	0	88%
DE	2114	2.4	46.9	1697	360	52	5	0	0	80%
OK	397	2.3	59.3	350	26	11	9	1	0	88%
NJ	1245	3.1	71.3	948	218	67	10	2	0	76%
NV	837	2.7	72.8	693	107	25	10	2	0	83%
AZ	1148	2.3	73.4	984	121	31	10	2	0	86%
AR	322	3	75.1	276	31	7	5	3	0	86%
SC	10689	2.9	79.3	8359	1775	456	86	13	0	78%
GA	12843	2.5	90.4	10503	1958	314	65	3	0	82%
NM	4425	3.8	103.4	3125	1012	219	60	8	1	71%
KS	15857	5.3	104.5	8646	4999	1760	416	35	1	55%
VT	1222	3.6	110.1	933	198	59	25	5	2	76%
OR	4882	3.7	121.2	3519	923	323	110	6	1	72%
TX	1973	2.2	145	1813	105	29	9	6	11	92%
VA	15558	3.2	165.5	11766	2926	673	169	23	1	76%
CA	5129	1.6	166.9	4653	370	87	11	7	1	91%
ND	6285	6	181.5	3055	2271	743	189	20	7	49%
MA	8160	4.1	183.4	5822	1608	512	176	31	11	71%
NE	7444	5	202.9	4080	2421	766	172	3	2	55%
RI	5302	4.4	229.7	3552	1283	315	132	17	3	67%
WY	8539	5.4	240.2	4849	2630	796	235	20	9	57%
MO	11010	4.6	249.6	7094	2814	805	267	25	5	64%
WA	4167	5.3	260.6	2927	673	340	171	43	13	70%
AK	373	6.4	273.1	268	59	18	21	5	2	72%
NH	13853	5.1	278.8	9287	2976	972	502	88	28	67%
SD	1586	8.1	279.9	663	548	261	96	11	7	42%
CT	10010	3.9	309.5	7292	1968	511	198	31	10	73%
NY	25634	4.1	318.6	19387	3873	1507	698	136	33	76%
ME	1192	6.7	321.2	685	313	123	49	18	4	58%
KY	9623	8.2	334.9	5170	2277	1215	759	165	37	54%
FL	11205	1.8	342.7	10089	882	161	56	14	3	90%
MD	6817	5.1	355.4	4555	1495	462	250	38	17	67%
ID	7455	6.1	357.1	4722	1660	611	363	78	21	63%
TN	13961	4.3	367.8	9660	3000	905	335	57	4	69%
MI	85010	3.4	458	62955	16731	4078	1112	101	33	74%
UT	7444	4.4	542.3	4918	1844	500	163	12	7	66%
IN	4133	4.6	616.6	2647	1049	317	111	8	1	64%
WI	35087	6.2	686.9	19538	10333	3561	1330	230	95	56%
PA	57709	8.5	747.2	31639	13693	6736	4195	1080	366	55%
IL	37427	5	826	22012	10790	3625	909	74	17	59%
OH	44059	8.5	844.2	22223	12929	5279	2688	617	323	50%
MN	79421	4.7	849.7	45396	26724	6093	1094	86	28	57%
IA	47800	6.4	870.6	23512	14987	6916	2223	137	25	49%
NC	36775	3.5	1167.3	27229	7184	1786	497	53	26	74%
WV	5136	6.6	1228.8	3233	1083	491	252	58	19	63%
AL	3050	3.9	1383.9	2423	432	117	58	19	1	79%
CO	36169	6.1	1618.3	18976	11627	4092	1265	159	50	53%
MT	7397	7.3	2574.3	4056	2072	829	363	57	20	55%

Table 4, State Ranking by Percent Radon Results greater than or equal 4 pCi/L

State	N=	AVG	MAX	< 4.0 pCi/L	4-9.9 pCi/L	10-19.9 pCi/L	20-49.9	50-100	>100	> 4.0 pCi/L
HI	18	0.1	0.7	18	0	0	0	0	0	0%
LA	244	0.6	21.4	239	3	1	1	0	0	2%
MS	170	1.4	11.8	159	8	3	0	0	0	7%
TX	1973	2.2	145	1813	105	29	9	6	11	8%
CA	5129	1.6	166.9	4653	370	87	11	7	1	9%
FL	11205	1.8	342.7	10089	882	161	56	14	3	10%
OK	397	2.3	59.3	350	26	11	9	1	0	12%
DC	302	1.9	22.5	265	31	4	2	0	0	12%
AZ	1148	2.3	73.4	984	121	31	10	2	0	14%
AR	322	3	75.1	276	31	7	5	3	0	14%
NV	837	2.7	72.8	693	107	25	10	2	0	17%
GA	12843	2.5	90.4	10503	1958	314	65	3	0	18%
DE	2114	2.4	46.9	1697	360	52	5	0	0	20%
AL	3050	3.9	1383.9	2423	432	117	58	19	1	21%
SC	10689	2.9	79.3	8359	1775	456	86	13	0	22%
VT	1222	3.6	110.1	933	198	59	25	5	2	24%
NJ	1245	3.1	71.3	948	218	67	10	2	0	24%
VA	15558	3.2	165.5	11766	2926	673	169	23	1	24%
NY	25634	4.1	318.6	19387	3873	1507	698	136	33	24%
MI	85010	3.4	458	62955	16731	4078	1112	101	33	26%
NC	36775	3.5	1167.3	27229	7184	1786	497	53	26	26%
CT	10010	3.9	309.5	7292	1968	511	198	31	10	27%
OR	4882	3.7	121.2	3519	923	323	110	6	1	28%
AK	373	6.4	273.1	268	59	18	21	5	2	28%
MA	8160	4.1	183.4	5822	1608	512	176	31	11	29%
NM	4425	3.8	103.4	3125	1012	219	60	8	1	29%
WA	4167	5.3	260.6	2927	673	340	171	43	13	30%
TN	13961	4.3	367.8	9660	3000	905	335	57	4	31%
RI	5302	4.4	229.7	3552	1283	315	132	17	3	33%
NH	13853	5.1	278.8	9287	2976	972	502	88	28	33%
MD	6817	5.1	355.4	4555	1495	462	250	38	17	33%
UT	7444	4.4	542.3	4918	1844	500	163	12	7	34%
MO	11010	4.6	249.6	7094	2814	805	267	25	5	36%
IN	4133	4.6	616.6	2647	1049	317	111	8	1	36%
ID	7455	6.1	357.1	4722	1660	611	363	78	21	37%
WV	5136	6.6	1228.8	3233	1083	491	252	58	19	37%
IL	37427	5	826	22012	10790	3625	909	74	17	41%
ME	1192	6.7	321.2	685	313	123	49	18	4	43%
MN	79421	4.7	849.7	45396	26724	6093	1094	86	28	43%
WY	8539	5.4	240.2	4849	2630	796	235	20	9	43%
WI	35087	6.2	686.9	19538	10333	3561	1330	230	95	44%
NE	7444	5	202.9	4080	2421	766	172	3	2	45%
PA	57709	8.5	747.2	31639	13693	6736	4195	1080	366	45%
MT	7397	7.3	2574.3	4056	2072	829	363	57	20	45%
KS	15857	5.3	104.5	8646	4999	1760	416	35	1	46%
KY	9623	8.2	334.9	5170	2277	1215	759	165	37	46%
CO	36169	6.1	1618.3	18976	11627	4092	1265	159	50	48%
OH	44059	8.5	844.2	22223	12929	5279	2688	617	323	50%
IA	47800	6.4	870.6	23512	14987	6916	2223	137	25	51%
ND	6285	6	181.5	3055	2271	743	189	20	7	51%
SD	1586	8.1	279.9	663	548	261	96	11	7	58%

Table 5 below gives a summary of the four tables above. It is provided for states to compare their data to this large data set. We then provide Table 6 as another means of comparison with the states ranked by percent of readings greater than 10 pCi/L.

Table 5

State	N=	Avg.	Max.	%<4	% 4-9.9	% 10-19.9	% 20-49.9	% 50-100	%> 100	%>4
U.S.	718608	5.2	2574	63	25	8.3	3.1	0.5	0.17	37

Table 6

State	% >10 pCi/L	State	% > 10 pCi/L
HI	0%	UT	9%
LA	1%	MN	9%
MS	2%	NY	9%
DC	2%	TN	9%
CA	2%	MO	10%
FL	2%	IN	11%
DE	3%	MD	11%
TX	3%	NH	11%
GA	3%	AK	12%
AZ	4%	IL	12%
NV	4%	WY	12%
AR	5%	NE	13%
SC	5%	WA	14%
OK	5%	KS	14%
VA	6%	ID	14%
MI	6%	WI	15%
NJ	6%	ND	15%
AL	6%	CO	15%
NC	6%	WV	16%
NM	7%	ME	!6%
VT	7%	MT	17%
CT	7%	IA	19%
RI	9%	OH	20%
MA	9%	PA	21%
OR	9%	KY	23%
		SD	24%
U.S.	**12%**		

State Radon Rankings

This analysis of state radon potential is based on the private lab data provided to us. Qualifications for this lab data are found in the State Radon Data section of this report. We present these data cautiously in that we know there can always be problems or disagreements in what to use and how to use it for the purpose of ranking. Please remember that this ranking is designed to give an indication of which states have the most severe radon problems in terms of the total number of people affected, as well as the magnitude and percentages of radon occurrences. Conversely, the states with the least severe radon problems can also be considered.

We took the data and then ranked the states using nine categories; average radon concentration, maximum radon value, percent of test results greater than 4 pCi/L, percent of test results in the 4 to 10 range, in the 10 to 20 range, in the 20 to 50 range, in the 50 to 100 range, in the greater than 100 range and a final category that considered state average radon and state population. After the state ranking in each category, we then assigned a number, starting with 50 for the "worst" state. For instance, Montana had the highest radon measurement result from this data set and they were given 50 points. Colorado had the next highest maximum radon value and they were given 49 points. Where there was a tie between states, each state received the same score. We then assigned a score for all 50 states plus the District of Columbia. After each state was given a score for each of the nine categories, we then simply added up all the scores for each state. The state with the highest number was considered the state with the most "severe" radon problems; conversely, the state with the lowest score was considered the state with the least "severe' radon problems. Below is the tabulation of state rankings.

State	Score	State	Score
Hawaii	132	North Carolina	296
Louisiana	145	New Hampshire	300
Mississippi	153	New York	301
District of Columbia	160	Wyoming	308
Delaware	183	Utah	308
Oklahoma	199	Tennessee	309
Nevada	202	Missouri	315
South Carolina	205	Nebraska	319
Arizona	207	Kansas	325
Arkansas	211	Washington	329
Georgia	214	North Dakota	332
California	215	Maryland	332
Texas	221	Indiana	334
Florida	227	Idaho	339
Vermont	228	Minnesota	340
New Jersey	242	Maine	354
Virginia	248	West Virginia	356
New Mexico	251	Illinois	358
Oregon	265	Montana	371

State	Score	State	Score
Connecticut	276	South Dakota	372
Rhode Island	278	Wisconsin	380
Alabama	280	Iowa	384
Massachusetts	285	Colorado	388
Michigan	286	Kentucky	397
Alaska	291	Pennsylvania	411
		Ohio	422

We have also received radon testing data from ten state radon coordinators: California, Colorado, Idaho, Minnesota, Nevada, New York, Ohio, Pennsylvania, Utah and Wyoming. Since we had these data, we decided to compare them to the private-lab data from the four tables above. Sometimes the comparisons may not be most appropriate since the qualifications on each data set are different. We also do not know the source of the results from the state radon coordinators; it could be any one of a number of private labs or possibly a state radiation lab. These data may be most useful to those state radon coordinators who supplied these data. The data qualifications for the state-provided data are immediately below each table, where supplied by the state radon coordinator.

Range	OH-State data*	OH- Lab data
<4	51.4%	50.4%
4 to 10	27.8%	29.3%
10.1 to 20	12.2%	12%
20.1 to 50	7%	6.1%
50.1 to 100	1.1%	1.4%
>100	0.53%	0.7%
N=	134,833	44,059

*All house levels, all Measurement types, all seasons, 1986-2007.

Range	NV-State data*	NV-Lab data
<4	75%	83%
4 to 10	18.8%	12.7%
10.1 to 20	4.2%	3%
20.1 to 50	1.3%	1.2%
50.1 to 100	0.2%	0.2%
>100	0.2%	0%
N=	2,274	837

* Lowest Floor, Short-term only, 2003 to 2008

Range	NY-State data*	NY-Lab data
<4	66.1%	75.6%
4 to 10	18.3%	15.1%
10.1 to 20	8.6%	5.9%
20.1 to 50	5.5%	2.7%
50.1 to 100	1.1%	0.5%
>100	0.3%	0.1%
N=	39,715	25,634

* Charcoal, Basement and First Floor, 1990 to 1999.

Range	MN-State data*	MN-Lab data
<4	59.3%	57%
4 to 10	33%	33.6%
10.1 to 20	6.5%	7.6%
20.1 to 50	1.2%	1.4%
50.1 to 100	0.1%	0.1%
>100	0.0003%	0.04%
N=	41,123	79,421

* Basement and First Floor, 1990 to 2000

Range	WY-State data*	WY-Lab data
<4	64%	56.7%
4 to 10	26%	30.7%
10.1 to 20	7%	9.3%
20.1 to 50	2%	2.8%
50.1 to 100	0.3%	0.2%
>100	0.1%	0.1%
N=	18,574	8,539

* All levels, 1990 to 2009, short-term

Range	CA-State data*	CA-Lab data
<4	91.4%	90.7%
4 to 10	6.5%	7.2%
10.1 to 20	1.3%	1.7%
20.1 to 50	0.5%	0.2%
50.1 to 100	0.14%	0.13%
>100	0.09%	0.02%
N=	14,282	5,129

*Short- and long-term, basement and first floor, 1990 to 2000

Range	UT-State data*	UT-Lab data
<4	66%	66%
4 to 10	24%	24.7%
10.1 to 20	7%	6.7%
20.1 to 50	3%	2.2%
50.1 to 100		0.16%
>100		0.09%
N=	12,925	7,444

*1994 to 2009, basement and main floor.

Range	ID-State data*	ID-Lab data
<4	66.8%	63.3%
4 to 10	21%	22.2%
10.1 to 20	7.2%	8.2%
20.1 to 50	4%	4.8%
50.1 to 100	0.7%	1.0%
>100	0.3%	0.3%
N=	3,551	7,455

*1990 to 2000, basement and first floor.

Range	CO-State data*	CO-Lab data
<4	51.5%	52.4%
4 to 10	32.2%	32.1%
10.1 to 20	11.7%	11.3%
20.1 to 50	3.9%	3.5%
50.1 to 100	0.5%	0.4%
>100	0.1%	0.13%
N=	61,767	36,169

*Years 2005 to 2008

Range	PA-State data*	PA-Lab data
<4	61%	55%
4 to 10	23%	24%
10.1 to 20	9%	12%
20.1 to 50	5%	7%
50.1 to 100	1%	2%
>100	0.4%	0.6%
N=	878,600	57,709

*Short- and long-term, basement and first floor, all house types.

Range	MI-State data*	MI-Lab data
<4	75%	74%
4 to 10	19%	19.7%
10.1 to 20	4.7%	4.8%
20.1 to 50	1.4%	1.3%
50.1 to 100	0.1%	0.1%
>100	0.04%	0.03%
N=	96,353	85,010

*Basement, first floor, other floors, activated carbon, short-term, 1993 to 2009.

Acknowledgements

We wish to thank and acknowledge the following individuals for supplying the above data. From Air Chek Shawn Price and Michael DeVaynes, from Michigan Sue Hendershott, from Colorado Chrystine Kelley, from Idaho Megan Keating, from Utah John Hultquist, from California George Faggella, from Wyoming Steve Melia, from Minnesota Andrew Gilbert, from Ohio Chuck McCracken, from Nevada Susan Roberts and from New York Jerry Collins.

EPA State Rankings

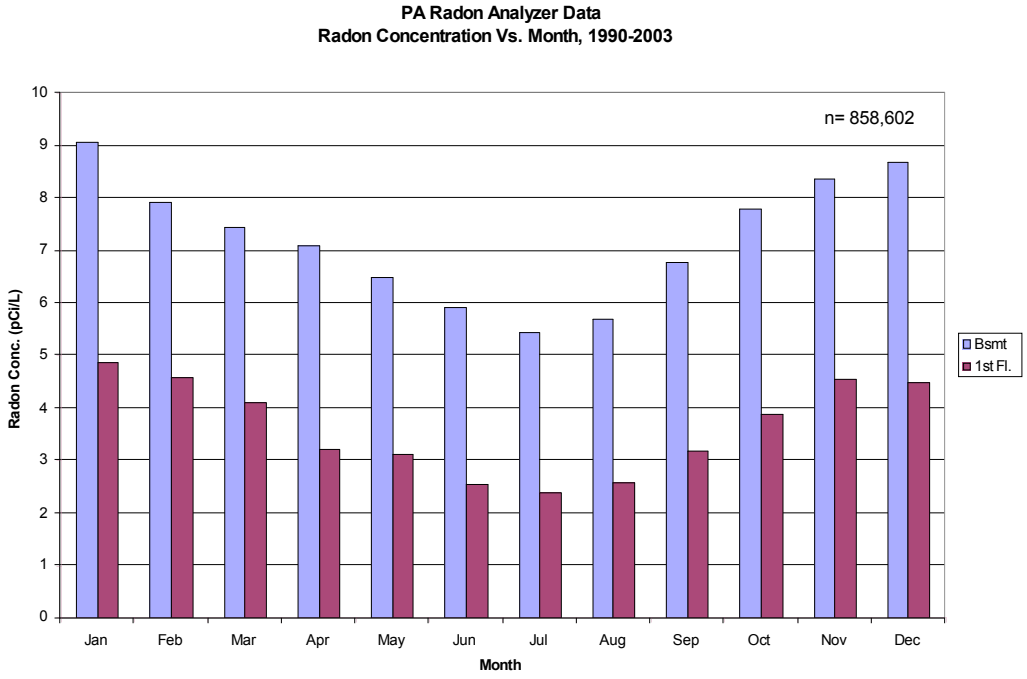
The data in the below table are based on US EPA State Radon Residential Survey. The survey covered single-family detached homes, multi-unit structures and mobile homes. Testing used short-term tests, in lowest-livable level, during winter heating seasons. The states are ranked by the two categories shown; percent of homes above 20 pCi/L, and percent of homes above 4 pCi/L.

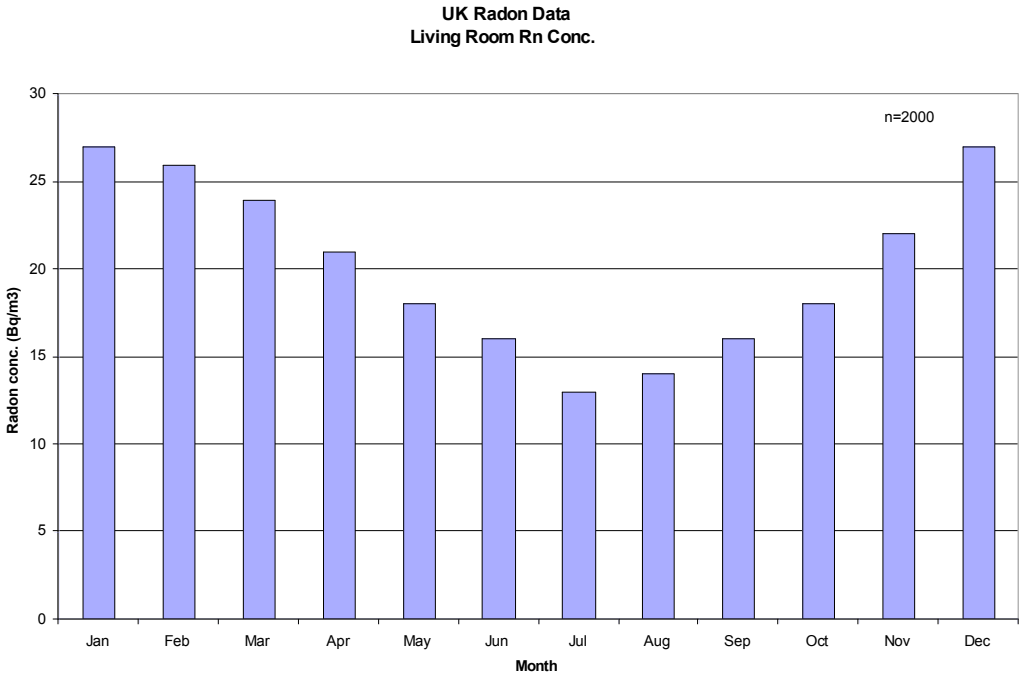
State	Source	% of Homes Greater than 20 pCi/L	State	% Homes Greater than 4.0 pCi/L
PA	EPA/State	7.9	IA	71.0
IA	EPA/State	7.5	ND	60.7
NY	State	5.1	NE	53.5
MT	EPA/State	4.7	MN	45.4
NJ	State	4.6	MT	42.2
ND	EPA/State	4.3	CO	41.5
NH	State	3.7	PA	40.5
OH	EPA/State	2.8	NY	32.8
CO	EPA/State	2.7	NJ	32.5
NE	EPA/State	1.9	OH	29.0
RI	EPA/State	1.9	NH	27.4
ME	EPA/State	1.9	WI	26.6
WY	EPA/State	1.8	IN	26.5
IN	EPA/State	1.5	WY	26.2
KY	EPA/State	1.5	MA	22.7
MN	EPA/State	1.4	KS	22.5
MD	EPA/State	1.4	NM	21.8
WA	EPA/State	1.3	RI	20.6
MA	EPA/State	1.3	ID	20.3
TN	EPA/State	1.3	ME	20.0
UT	State	1.3	KY	17.1
VA	EPA/State	1.2	MO	17.0
ID	EPA/State	1.1	CT	16.5
DC	State	1.0	VT	15.9
CT	EPA/State	0.9	MD	15.9
VT	EPA/State	0.9	TN	15.8
IL	EPA/State	0.8	WV	15.7
NV	EPA/State	0.8	UT	14.0
KS	EPA/State	0.7	VA	13.9
MO	EPA/State	0.7	DC	13.0
AK	EPA/State	0.6	IL	12.0
WI	EPA/State	0.6	MI	11.7
NM	EPA/State	0.6	NV	10.2

State	Source	% of Homes Greater than 20 pCi/L	State	% Homes Greater than 4.0 pCi/L
WV	EPA/State	0.5	WA	8.6
MI	EPA/State	0.4	AK	7.7
NC	EPA/State	0.3	GA	7.5
AL	EPA/State	0.3	NC	6.7
SC	EPA/State	0.3	AZ	6.5
TX	EPA/State	0.2	AL	6.4
AZ	EPA/State	0.1	AR	5.0
CA	EPA/State	0.1	FL	4.0
MS	EPA/State	0.1	SC	3.7
GA	EPA/State	0	TX	3.6
FL	State	0	OR	3.6
OR	State	0	OK	3.3
OK	EPA/State	0	CA	2.4
LA	EPA/State	0	MS	2.2
HI	EPA/State	0	LA	0.6
SD	None	Not available	SD	Not available
DE	State	0	DE	Not available

PA Radon Analyzer Data vs. UK Data

Comparison of two data sets, United Kingdom and U.S. (PA), shows radon variability versus month of the year. The two data sets are in different units, pCi/L and Bq m^{-3}, and the UK data are just from living rooms, which I assume to be first-floor measurements. These two graphs do show a very similar pattern of radon variability over time from two different parts of the world.





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International Radon Section

Table 1. Domestic radon concentrations and Action Levels in different countries

Country	Average radon concentration in homes (Bq/m^3)	Action Level (Bq/m^3)
Australia	*	200
Belgium	*	400
Czech Republic	140	200
Finland	123	400
Germany	50	250
Ireland	60	200
Israel	*	200
Lithuania	37	100
Luxembourg	*	250
Netherlands	*	20
Norway	51-60	200
Poland	*	400
Russia	19-250	*
Sweden	108	400
Switzerland	70	1000
United Kingdom	20	200
European Community	*	400
USA	46	150
Canada	*	200

Taken from the web site for WHO. (As of 5/29/2009)

Comparison of International Radon Action Levels

Country	Existing Dwellings	New Buildings
Canada	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

http://www.co.jefferson.co.us/health/health_T111_R42.htm

10 CFR 20 Appendix B, Table 1 & 2

Concentration in air and water above natural background

Radon-222

Year	Maximum permissible concentrations				
	For 40 hour week (Occupational Exposure)		For 168 hour week (Nonoccupational Exposure)		
1959	MPC_w	MPC_a	MPC_w	MPC_a	
	-----	30 pCi/L	-----	10 pCi/L	

Taken from ICRP 2, 1959 The subscripts "w" and "a" stand for water and air.

Year	Table I		Table II		
	Restricted Areas		Unrestricted Areas		
	Col. 1 (air)	Col. 2 (water)	Col. 1 (air)	Col. 2 (water)	
1970	100 pCi/L	-----	3 pCi/L	-----	
Table I based on exposure to conc. specified for 40 hours in any 7-day period.					
Table II Conc. may be averaged over period not greater than 1 year.					
1975	100 pCi/L	-----	3 pCi/L	-----	
Table I based on exposure to conc. specified for 40 hours in any 7-day period.					
Table II Conc. may be averaged over period not greater than 1 year.					
1977	100 pCi/L	-----	3 pCi/L	-----	
Table I based on annual average					
Table II Conc. may be average over a period not greater than 1 year.					
1979	30 pCi/L	-----	10 pCi/L	-----	
Table I based on annual average					
Table II Conc. may be average over a period not greater than 1 year.					
1980	30 pCi/L	-----	3 pCi/L	-----	
Table I based on annual average					
Table II Conc. may be average over a period not greater than 1 year.					

1985	30 pCi/L	-----	3 pCi/L	-----	
Table I based on annual average					
Table II Conc. may be averaged over a period not greater than 1 year.					

Taken from NRC 10 CFR20, App. B
MPC values based on ICRP 2 switched to DAC values based on ICRP26/30 in 1991.

Year	Table 1 Occupational Values			Table 2 Effluent Conc.	
		Inhalation			
	Col. 1 (oral)	Col. 2 (ALI)	Col. 3 (DAC)	Col. 1 (air)	Col. 2 (water)
1998	-----	4 WLM	30 pCi/L or 0.33 WL	0.1 pCi/L	-----
Table 1 Based on annual average					
Table 2 Based on annual average					
2003	-----	4 WLM	30 pCi/L or 0.33 WL	0.1 pCi/L	-----
Table 1 Based on annual average					
Table 2 Based on annual average					

The tables above show the evolution of the radon-222 occupational standard over time. The first table is from the International Commission on Radiological Protection, ICRP 2, 1959. This data also occur in National Bureau of Standards (NBS), Handbook 69, August 1963. The two other tables are both from Nuclear Regulatory Commission (NRC), 10 CFR 20, Appendix B. These three tables cover a time period of 46 years, from 1963 to the current, since the standards in 2003 are still in effect today. The tables obviously do not cover all years; they show a representation of limits over time, as well as the time periods upon which the limits were based.

The interesting observation from the tables is the change in the maximum permissible air concentration value from 30 pCi/L to 100 pCi/L, than back to 30 pCi/L.

The earliest NBS table uses the concept of the Maximum Permissible Concentration (MPC) for its limiting values in the table. The MPC values are based on occupational values, above background, that would limit a whole body dose to less than 5 rem, or 15 rems to the lung (the critical organ for radon). Radon-222 is interesting in that the decay products are considered present in the state of equilibrium typical of that attained in ordinary air. A quality factor of 10 was used for alpha particles in the NBS tables.

The column in the first table listed as "168 hour week" is for the nonoccupational exposure. It is analogous in the other two tables to "Unrestricted Areas," and "Effluent Concentrations."

The two NRC tables are divided into two basic columns, one for occupational exposures (Restricted areas), and one for nonoccupational exposures (Unrestricted areas). The occupational exposures would occur on the job site on any NRC licensed facility where the radioactive materials exist. The nonoccupational exposures are applicable to the assessment and control of radioactive dose to the general public.

In the early seventies, the NRC also used the concept of the Maximum Permissible Concentration (MPC) to describe the limiting amount of radioactive material to which individuals could be exposed. They changed over to the current concept of the DAC and ALI in 1991.

The ALI or Annual Limit of Intake is an amount of radioactive material ingested or inhaled, which would result in either (1) a committed effective dose equivalent (CEDE) of 5 rems or (2) a committed dose equivalent (CDE) of 50 rems to an organ or tissue.

The values of DAC or Derived Air Concentration are limits intended to control chronic occupational exposures. The DAC is the concentration of radioactive material in air and the time of exposure to that radionuclide in hours. For the particular case of Rn-222 the most current version of 10 CFR 20 lists two values for both the DAC and ALI, one with decay products removed and one with decay products present. For the case of parent radon-222 plus decay products present at 100 percent equilibrium, the values are as listed in the above table for the year 2003. The DAC value then assumes that the worker is immersed in the pure parent plus all of the decay products in equilibrium.

Not to add more confusion to the tables above, but we can also mention the U.S. Department of Energy (DOE) and its occupational dose limits as found in 10 CFR 835. It also publishes Derived Air Concentration values for numerous radionuclides; of interest to this manual are the Rn-222 and Rn-220 values. It has recently updated (effective July 9, 2007) both values based on the dose conversion convention of 0.5 rem per WLM, found in ICRP 65, Protection Against Radon-222 at Home and at Work (ICRP, 1994). The Rn-222 progeny annual exposure limit went from 4 WLM to 10 WLM, and the Rn-220 progeny limit went from 12 WLM per year to 30 WLM per year. The corresponding DAC values are 80 pCi/L or 0.83 WL for Rn-222 and 10 pCi/L or 2.5 WL for Rn-220. Even these increases above the previous values still carry the same risk as 5 rems of total effective dose equivalent, according to ICRP 65.

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