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Characterization of Radon Levels in Indoor Air

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The purpose of this paper is to describe the different types of monitoring and sampling techniques that can determine the radiation burden of the general public from radon and its decay products. This is accomplished by measuring the range and distribution of radon and radon decay products through broad surveys using simple and convenient integrating monitoring instruments. For in-depth studies of the behavior of radon decay products and calculation of the radiation dose to the lung, fewer and more intensive and complex measurements of the particle size distribution and respiratory deposition of the radon decay products are required. For diagnostic purposes, the paper describes measurement techniques of the sources and exhalation rate of radon and the air exchange inside buildings. Measurement results from several studies conducted in ordinary buildings in different geographical areas of the United States, using the described monitoring techniques, indicate that the occupants of these buildings are exposed to radon and radon decay product concentrations, varying by as much as a factor of 20.

Introduction

The radon decay products contribute a significant fraction of the natural radiation dose to man. Most of the exposure occurs indoors not only because most people spend the bulk of their time there but also because the radon and radon decay product concentrations within buildings are usually higher than in outside air. Therefore, accurate information on the concentration of radon in buildings is important for the assessment of the radiation dose to man. High air concentrations of these radioisotopes in underground mines have been shown to cause lung cancer in miners. Assuming the incidence of lung cancer is proportional to the indoor airborne concentration times duration of exposure, some individuals may suffer exposures large enough to significantly increase their risk of lung cancer during their lifetime.

Because of the rising cost of energy and the present energy conservation awareness, steps are being taken to make buildings more energy efficient by insulating. As a result the air exchange indoors decreases and this may lead to elevated concentrations of indoor pollutants, such as: formaldehyde from outgassing urea formaldehyde foam insulation and particle board; tobacco smoke; nitrogen dioxide and particulates from cooking gas; carbon monoxide from combustion products; and radon from building materials, underlying soil, rocks and water.

Concentration levels of radon considered to be abnormal have been measured in various parts of the world, particularly during the cold months when homes are kept tight to conserve energy. However, because of the small number of systematic measurements, definitive conclusions on the behavior of indoor radon and its decay products are difficult to make. Future measurement protocols should consider the spatial and temporal concentrations as well as diffusion and ventilation characteristics inside buildings before deciding on the appropriate monitoring technique. The purpose of this paper is to discuss the different types of sampling techniques which, when used properly, can determine the radiation burden of the general public. By measuring radon sources and airborne radon concentration levels in the indoor environment, building standards and control measures can be instituted to minimize the buildup of radon.

Characteristics of Radon and Its Decay Products

Radon-222 is the immediate decay product of ^{226}Ra, a member of the decay chain of uranium, a naturally occurring trace element distributed in soil, rocks, water and as a consequence in building materials. Ordinary soil and rocks contain about 1 pCi of ^{226}Ra per gram. Thus any material containing uranium or radium is a potential source of radon. The decay chain of ^{226}Ra is listed in Table I. Radon-222, because of its relatively long half-life compared to the time air is in the lungs, is not a significant source of exposure. However, its decay daughter products ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po have greater radiological significance, particularly the two alpha emitters ^{218}Po and ^{214}Po. They have short half-lives and exist either as free atoms or ions or may attach to dust particles in air, and may plate out on walls, furniture and other surfaces. Under typical living or working conditions, most of the decay products of radon attach to dust particles in air and about 20-50% of those that are inhaled deposit on the epithelium lining of the lungs.[1] There, they release their energy (called potential alpha energy

in Table I) as alpha radiation. The actual dose from inhaled radon decay products depends on the particle size on which the radon decay products become attached, on the breathing rate, the time spent indoors and on the airborne concentration. The median diameter of the particles onto which radon decay products attach is about 0.1-0.15 μm.[2] The decay chain of ^{226}Ra ends at ^{206}Pb, a stable isotope.

Because of uncertainties in lung dosimetry the concept of the working level (WL) was developed as a measure of exposure to workers in uranium mines, and the common unit of cumulative exposure to radon decay products is the working level month (WLM). One WL is defined as the concentration of radon decay products in air which has a potential alpha energy release of 128,000 MeV per liter. This corresponds to 100 pCi/l of ^{222}Rn in equilibrium with its decay products. One WLM is the occupational exposure to air containing one WL of radon decay products for 170 hours, a working month. For example, continuous indoor exposure to an atmosphere of 0.01 WL for 1 year will result in 0.48 WLM (0.01 x 4 x 12).

Sources of Indoor Radon

There are several common sources of radon in buildings. In order of decreasing radon yield under typical conditions, they are the soil and geological substrate, building materials, the water supply and natural gas.

Radon from Soil and Underlying Geological Substrate

Radon, a noble gas, enters a building by diffusion across the foundation and reaches the indoor environment. A typical soil containing 1 pCi of ^{226}Ra per gram of soil will produce about 0.015 atoms of radon per second per cubic centimeter of soil. This takes into account the density of soil particles, soil porosity and the fraction of radon emanated into the soil pores.[3] At the soil surface the radon flux ranges between 10-500 x 10^{-18} Ci cm^{-2} sec^{-1}. The average value of exhalation rate from soil (world average) was found to be 45 x 10^{-18} Ci cm^{-2} sec^{-1}.[4] During the cold season when the soil freezes the rate of radon exhalation from soil outdoors decreases by as much as a factor of 30.[5] Radon diffusion from the underlying soil through a concrete slab usually is reduced by factors of 5-25. Although concrete walls and concrete floors are good radon barriers, measurements indicate significant radon transport through cracks and openings in the concrete slab and foundation. Changes in barometric pressure cause the greatest impact on radon exhalation. There is usually a doubling of radon exhalation[6] when the barometric pressure falls 1%. The building serves as a collection chamber for radon and its decay products and their concentrations indoors are determined by the amount leaking outside as indoor air is exchanged for outside air.

Radon from Building Materials

All materials with significant amounts of ^{226}Ra are potential contributors of radon. Concrete, stone and brick are the primary sources. Typical building materials contain less than 2 pCi of ^{226}Ra per gram of material. However, there are situations where building materials that incorporated residues from industrial processes such as phosphate slag[7] and Swedish aerated concrete, based on alum shale, may contain ^{226}Ra in excess of 10 pCi/g and may become a significant source of indoor radon.[8]

Radon in Water

Surface waters usually contain very little radon. However, water from wells and particularly from underground aquifers in granite or other ^{226}Ra-bearing rock may contain significant quantities of radon. In New England radon in 136 wells in granitic regions[9] averaged 22,000 pCi/l. Other areas in the United States with drilled wells in granite and pegmatite formations are likely to have higher concentrations of radon in water than those in low-grade metamorphic terrains. Radium-226 is usually relatively immobile in soils but can be dissolved in ground water to about 20 ppb and can migrate far from its source due to its relatively long half-life. Under typical conditions of use in a building, about 50% of radon in water is released into the air.[10] Although radon in water is important in some regions, generally concentration of less than 500 pCi/l can be ignored as important indoor radon source.

Radon in Natural Gas

Combustion of natural gas in buildings with unvented appliances may be a source of radon. The concentration of radon depends on the well head concentration and transmission time from the well to the point of consumption. Concentrations ranging from 1 to 1500 pCi/l have been reported.[11] In the Northeastern States radon from natural gas is not an important source because of considerable radioactive decay occurring from the well-head (Texas and Louisiana) to the distribution point.

Monitoring Needs for Radon and Its Decay Products

Like other indoor air pollutants radon concentrations vary considerably with time and location. The techniques used for monitoring radon and its decay products are sufficiently developed to meet most requirements. Choice of the instrument and method depend on the type of measurement, concentration levels, length of exposure, accuracy required, and consideration of instrument availability and cost. The sampling techniques used today were designed to meet several applications, so one must be selective in satisfying the objectives of a particular task. The different types of measurements required to satisfy different needs are listed below.

Air Concentrations

Measurement of the airborne concentration or radon and its decay products are usually obtained with grab, continuous or integrated sampling methods. It is the most important parameter for assessing the radiation hazard to man.

Source Diagnostic Measurements

The radon input rate into the indoor environment is important requiring measurement of radon exhalation from building materials, the underlying soil and radon content of the water supply, and natural gas.

Measurements for Lung Dose Calculations

Measurements of the characteristics of the radon decay products such as particle size distribution and fractional respiratory deposition, particle concentration, their interaction with radon decay products, and plate out require more complex instruments and techniques.

Ventilation Rate (Air Exchange)

The air infiltration rate from the outside and the meteorological parameters and activity patterns that affect it are measured because they have a significant impact on the airborne concentration of both radon and its decay products.

Sampling Strategy for Radon and Radon Decay Products

Studies of indoor radon levels should be undertaken to learn about a) the range and distribution of radon and its decay products inside buildings, and b) their behavior characteristics. The immediate need is to undertake a broad nationally coordinated survey of the concentration levels in buildings of different construction and in various geographical regions. By this procedure a representative number of the building stock can be screened and thus provide an estimate of the exposure of the total population to radon and its decay products. To accomplish this task, one can use detection devices that measure radon or radon decay products or both. The preferred choice is to measure radon only, because it is easier, more convenient and adequate for screening purposes to estimate average exposure. A survey of this type is well under way in Sweden,[12] where already 12,000 dwellings built with aerated concrete based on alum shale have been monitored with radon integrating devices for a minimum exposure of 3 months. A similar national survey program may be instituted in the United States, involving several regional studies that use similar instruments and methods. The success of this broad survey will depend on the utilization of inexpensive radon integrating devices that can be handled through ordinary mail and thus become more accessible to the general public.

For in-depth studies to investigate the behavior of radon and its decay products indoors, more intensive and complex measurements are required. These types of specialized measurements made in a few buildings in different geographical areas of the country can be very important in understanding radon transport, radon decay product particle size distribution and interaction, ventilation-infiltration, as well as for developing control techniques.

Measurement of Air Concentration

Measurement of the airborne concentrations of radon and decay products is the most important step in estimating the indoor exposure levels. Choice of the instrument and method depends on the levels to be measured and the required accuracy. Generally, the measurements are divided into four groups.

1. Grab, or spot or prompt sampling.
2. Continuous sampling.
3. Integrated sampling.
4. A combination of continuous-integrated sampling.

Tables II and III list the most commonly used instruments and methods for radon and radon decay product concentration measurements. Details on each monitoring instruments can be found in the referenced reports.[13-36]

Grab Sampling Method. An air sample is obtained either instantaneously or over a short-sampling period. It involves filling a container (evacuated or flow-through) with an air sample for radon and transferring it to a laboratory for analysis.[13,14] For radon decay products a sample is collected on a filter for a sampling period of 2 to 10 minutes.[25-30] Because of the short half-lives of the radon decay products (mean half-life of about 35 minutes), the analysis must be performed within 60 minutes after sampling, usually at the collection site. Grab sampling is attractive because of its simplicity and low cost. Its main disadvantage is that it does not provide accurate information on the time average air concentration in a building and thus the average exposure of the occupants to radon and its decay products. Also it is not suitable for extended measurement studies.

Continuous Sampling Method. Because of the dynamic behavior of radon in air, it is rarely sufficient to obtain a grab sample. Indoor air quality is subject to spatial and temporal variations and the choice of monitoring technique must take cognizance of these variations. Continuous monitoring is the most convenient technique for sampling and measuring the real-time concentration of radon and its decay products. In addition to average concentrations, peak short-term concentrations can be observed and variations can be correlated with other parameters such as radon source strength and ventilation-infiltration (air exchange). Specially designed monitors meet these requirements although increased instrument size, complexity and cost are necessary to obtain the added convenience. Continuous monitoring requires trained personnel, quality control and periodic maintenance procedures. This type of monitoring is not suitable for large scale surveys due to time and cost considerations. However, the benefits derived from continuous monitoring in a limited number of buildings in selected areas far outweighs the disadvantages.

There are four types of continuous radon monitors: the continuous flask, automated two-filter, diffusion electrostatic and diffusion radon only. For radon decay products, there is one type which measures continuously the individual radon decay products approximately every 10 minutes.

Continuous Flask Monitor. This instrument consists of a scintillation flask in contact with a photomultiplier tube counter. Air is drawn continuously through the flask so that the counter records the changes in radon concentration.

Automated Two-Filter Monitor.[15,16] This consists of a two-filter tube with a scintillation phototube detector positioned in front of the exit filter. Air is pumped through the tube continuously. The radon decay products are removed by the front filter and the detector counts the radioactivity accumulating on the exit filter. The exit filter can be fixed or can be advanced by mechanical means at preset time intervals.

Diffusion Electrostatic Monitor.[20] Ambient air enters the sensitive volume of the instrument by molecular diffusion and the resulting radon decay products from the diffusing radon are collected electrostatically and counted by a scintillation detection system.

Diffusion Radon Only Monitor.[23] This latest innovation in monitoring radon continuously, differs from the three just described in that it measures radon alone while the other three types measure radon indirectly by counting the decay products of radon. Air containing radon diffuses into the detector housing where the radon decay products being charged are removed electrostatically away from the detector, and thus pulses from the radioactive decay of radon only are detected.

Continuous Radon Decay Product Monitor.[32] Frequent measurement (essentially continuous) of the individual radon decay products is accomplished with an instrument that samples air automatically through a filter for 2-5 minutes and counts the collected radioactivity with alpha and beta detectors for a pre-fixed counting period of 2-3 minutes. In essence it acquires a concentration datum in approximately every 10 minutes. As an added bonus, it computes the working level, and thus it is known as the instant working level meter (IWLM). The information acquired by this instrument is attained at a high cost and great inconvenience and is thus unsuitable for broad surveys.

Integrated Sampling Method. This type of monitoring yields a single average concentration for an extended time period from a few days to a week or more. In monitoring radon for compliance with regulations or to assess the biological hazard of the occupants of buildings, the average air concentration measured with time-integrating methods is the most important parameter. The sampling period depends on the sensitivity of the particular technique being used to accumulate enough sample for analysis. Collection of a sample can be accomplished either passively (by molecular diffusion) that requires no power or actively (requires power).

Integrating sampling instruments for radon have several advantages: they are simple and less expensive than continuously reading monitors and they can be used to measure concentrations that are too low for continuous and grab sampling methods. Samples can be often analyzed later at a more convenient time and place. An added advantage is that a large number of sites can be monitored with the simple and smaller time-integrating instruments. The main disadvantage of the integrating monitoring devices is that they cannot provide information on short-term variations in concentration. The problem of long-term variations can be partly overcome by taking samples for a week or more in each season with time-integrating devices. This procedure provides a reasonably adequate assessment of the radiation hazard to the occupants of buildings.

The first time-integrating technique developed for radon studies around uranium tailings piles is the plastic bag method.[21] Usually air is sampled over a 2 to 3 day period by pumping air at a slow rate into a bag that is impermeable to radon gas. Analysis for radon concentration is performed later in a laboratory setting by concentrating and transferring the integrated sample to a scintillation flask for alpha counting. Concentrations as low as 0.01 pCi/l can be measured. This method however, is limited for studies in a few selected sites because of time and cost considerations.

An integrating instrument has been developed at Environmental Measurements Laboratory (EML) that integrates for airborne radon by molecular diffusion.[22] The first decay product of radon ^{218}Po is collected in an electrostatic-thermoluminescence detector system that registers the radiation intensity produced by radon

diffusing into the sensitive volume of the monitor. With a sensitivity of about 0.03 pCi/l in a 1 week measurement period this instrument can cover the concentration range of interest.

A more recent undertaking by EML is the development of a monitoring instrument that integrates for radon for a period of up to 4 days.[24] The device, consisting of a small container filled with activated charcoal (150-200 g), is simple, inexpensive and suitable for large scale radon surveys. The amount of radon adsorbed in the container by diffusion is determined by counting the gamma-rays from the decay products of radon. With a lower limit of detection of 0.2 pCi/l for 60 hours of exposure, this monitoring instrument is well suited for determining integrated indoor radon levels.

Another development using a completely passive mode of operation is track-etch detector.[18,19] The monitoring device is small and easily handled in the mail. The principle of detection consists of the damage imparted on the detector material by the alpha particles from radon and radon decay products. The detector is analyzed in a laboratory by observing microscopically the damage (number of tracks). The potential advantage of track etch is simplicity, low cost and the feasibility of use in extensive radon surveys. The main disadvantage is its poor sensitivity for integrated period less than 1 month. In studies of indoor radon, monitoring periods of 3 months or longer are adequate. Measurements made quarterly with track-etch detectors covering each season of the year are practical for the assessment of the average exposure of the occupants of buildings.

Time-integrating monitoring techniques for radon decay products were originally developed and applied to measure their concentration in terms of working level in buildings suspected to be contaminated with uranium tailings. Two techniques developed by Colorado State University[33] and by EML[34,35] use thermoluminescence detectors (TLD) in an active air sampling system. At the end of sampling the TLD is removed and analyzed in the laboratory. A sensitivity of 0.0005 WL in a week-long sample is adequate for numerous field applications. Commercial versions of these instruments have been produced both in the United States and Canada.

A more recent development at EML[36] of an integrating working level monitor offers several advantages over those that use TLD. By replacing the TLD system entirely with a radiation detector, there is substantial improvement in sensitivity. The monitor samples air containing radon decay products continuously which is counted by a surface barrier detector. The integration period can be varied to suit the application. An added feature of this monitoring device is that it can be used as a continuous working-level monitor when studies of the real-time variation of radon decay products is desired. With a lower limit of detection of 0.00004 WL in a 1 week sampling period, this instrument meets most needs adequately.

Radon Source Measurement

For diagnostic purposes, measurements of radon input into the indoor environment are important, necessitating measurements of radon exhalation from building surfaces, and the underlying soil, infiltration through openings in the foundation and radium and radon concentrations in water supplies and natural gas. Table IV lists the most commonly-used techniques for measuring the sources and transport

of radon.[37-44] Of most direct interest for indoor air quality is the actual exhalation rate of radon from surfaces, because the amount of radon entering the indoor spaces depends on the fraction of diffusible radon, diffusion length and other transport mechanisms in the material. Radon flux or areal exhalation rate can be measured by the rapid accumulation or the integrated technique. Rapid measurement of radon flux usually consists of radon accumulation in a flux can, for periods ranging from 1 to 5 hours.[37] Integrated measurements up to 3 days is made with an activated charcoal collector.[38] Measurement of the ^{226}Ra content of soil and building materials can be very useful because radium concentrations are very variable and may account for some of the difference observed in radon concentrations in various buildings. Areas contaminated with uranium mill tailings, phosphate reclaimed land or areas with known uranium mineralization can be identified by measuring the ^{226}Ra content of 100-200 g soil or rock samples using gamma-ray spectrometry. Radon concentration in water can also add significantly to indoor radon when the water source is an underground aquifer. There are several techniques for measuring the radon content of water, of which none is suitable for field analysis. Water samples collected to avoid degassing of the radon are analyzed by various techniques in the laboratory.[43,44] Radon in domestic water supplied from surface waters normally need not be measured.

Special Measurements for Radiation Dose Calculation

Because of its relatively long half-life ($T_{1/2}$ = 3.82 days), radon itself is not a significant source of exposure. It is the short-lived radon decay products that contribute most of the dose to the respiratory tract. Several theoretical dosimetry models have been developed[45-47] resulting in different calculated doses. The reasons for variation in the calculated dose are related in part to the assumptions of the radon decay product characteristics. Therefore, knowledge of the concentration and of the physical characteristics of the radon decay products together with an anatomical model of the respiratory tract and the determination tissue at risk are necessary for accurate dose calculation.

The essential characteristics that need to be measured are:

a) concentration of radon and radon decay products;
b) particle size distribution of the aerosols onto which the radon decay products become attached; and
c) fractional respiratory deposition in the respiratory tract.

Measurement techniques for the concentration levels have been discussed and are shown in Tables II and III. Measurement of the particle size distribution adds a degree of complexity to instrument requirements. In recent years, EML developed three different types of diffusion batteries[48] suitable for measuring the size distribution of radon decay products in uranium mines and in indoor and outdoor environments. Because of the complexity of these instruments and the time involved in obtaining real-time measurements of particle size, their use should be limited to a few buildings representative of the U.S. housing stock. Fortunately, measurements of particle size made by EML[2] indicate a range between 0.10 μm and 0.15 μm in diameter, a somewhat narrow range. Therefore, an extensive measurement program appears unnecessary.

Respiratory deposition of radon decay products depends on the particle size distribution, the breathing rate and tidal volume. Deposition data are too sparse to permit generalizations, due in part to the difficulty in conducting measurements on human subjects. From the existing data of respiratory deposition and particle size distribution, it appears that measurements in a few buildings will be sufficient to determine the site of deposition of radon decay products in the respiratory tract.

The annual mean absorbed dose to the basal cells of the bronchial epithelium (the site of lung cancer in uranium miners) can be approximated by the expression:

$$\text{Annual dose (millirads)} = 42\ C_{Rn} + 25{,}000\ WL$$

where

C_{Rn} = the annual mean concentration of radon in pCi/l, and

WL = the annual mean concentration of radon decay products in terms of working level.

The expression assumes that 93% of the radon decay products are attached to particles of 0.10 μm in diameter and 7% are unattached (about 10-20 Angstroms in diameter), and that the occupant of the building breaths about 18 m^3 of air per day. The above calculation is only accurate if conditions in all buildings are similar. Therefore, generalities from this simple calculation should be avoided until more data from different geographical areas are accumulated.

Ventilation Measurements

Indoor radon levels are quite variable throughout the year as the degree of ventilation changes. During mild weather when windows may be open, indoor radon levels are lower than during the colder season and the summer when the building is likely to be closed up for heating and air conditioning, respectively. The air exchange rate is an important parameter due to its influence on the airborne concentration of radon and its decay products. Increased ventilation is probably the simplest means by which airborne radon concentration can be reduced to acceptable levels, though there may be significant costs attached due to less efficient energy use.

By far the most commonly used method for measuring air exchange is the tracer gas technique.[49] One approach is to inject the tracer gas (helium or sulfur hexafluoride) into the building space at one or more points and then monitor the reduction of concentration with time. An alternate method, is to inject the gas at a low flow rate until a steady-state concentration is achieved.[50] From this and the injection rate, the infiltration rate can be calculated. As is the case with the measurement of radon sources, ventilation measurements at present are not feasible in a broad survey, but can be very useful in diagnostic studies in selected buildings.

Typical Measurement Results in U.S. Buildings

Although the average level of the U.S. population exposure to indoor radon has not been well established, several studies have been conducted on selected localities associated with uranium mill tailings, uranium processing wastes, phosphate mining and uranium mineralized lands. Most recently attention has been directed to studies of energy efficient and ordinary buildings in uncontaminated areas. The available data were obtained to meet different needs and are not systematic. Both grab sampling and integrated week-long or year round sampling were used. Since good determination of the average exposure depends on long-term measurements, Table V summarizes some of the available integrated concentrations of radon and radon-decay products in terms of working level. The data indicate that indoor levels vary by at least a factor of 20 in different geographical areas. Such a large range is not surprising because the studies included various types of buildings, constructed over various underlying geological substrates and with different ventilation rates.

The health effects from radon-decay products have been reasonably well established from studies of uranium miners, where high concentrations of radon decay products resulted in hundreds of excess cases of lung cancer. The lifetime cancer risk to occupants of buildings from lower concentrations of radon decay products, estimated on the basis of a linear, no-threshold dose-effect relationship, are generally lower by a factor of 100 - 10,000 than that of U.S. uranium miners.

Conclusions

Indoor airborne levels of radon in some buildings may account for some of the lung cancers in the United States. The health effects from indoor radon levels are compounded by the implementation of energy conservation measures and the introduction of new building technology and materials that may have an adverse effect on the indoor air quality. Indoor radon levels were found to vary over a wide range in different geographical areas, and human exposure may be high in a substantial number of buildings. The extent of the exposure and the exposure-response relationship is uncertain and thus estimation of the health effects on humans cannot be made accurately. Only by a combination of data on the average concentration of radon in buildings and human, animal and cellular studies on radiation effects will it be possible to estimate with some confidence the risk for indoor radon exposures. There is certainly a need to conduct a broad national survey throughout the United States with the proper monitoring instruments for the characterization of radon in the indoor environment. Because of the temporal and spatial variations of radon concentration, measurements should be averaged over as long a period as possible to eliminate short-term perturbations and should include as many measurements as are reasonably possible. To accomplish this, it is advantageous to use integrating monitoring instruments that provide direct estimates of the average exposure. Continuous measurement methods repeated often may be adequate. Grab sampling study programs would have to be quite extensive to provide comparable information.

For diagnostic measurements, information on the sources of radon and on how it is transported is needed for the development of techniques to prevent it from entering the living or working environment.

Measurement of ventilation-infiltration rate is very important because of its impact on the airborne concentration of both radon and its decay products.

For calculation of the radiation dose to occupants of buildings, studies of the respiratory deposition, particle interaction and size distribution in a laboratory setting, and in a few buildings should be carried out.

Knowledge of the magnitude of the radon exposure indoors and the factors that influence it will help in the development of measures that can be applied to control it. The techniques for controlling indoor concentrations of radon and its decay products consist of measures that decrease radon sources and transport by removal and by dilution of the inside air with outside air. In future constructions, the use of materials with a low content of ^{226}Ra will reduce the source strength of radon. Unusually high ^{226}Ra content of soils and rocks on the construction site may be indicative of future high indoor radon levels.

Radon transport into the building space can be reduced by sealing cracks and holes and by isolating crawl space through which air with radon is transported. Partial removal of the radon decay products can be accomplished by filtration or by electrostatic means. However, both these techniques have no effect on radon gas, and tend to alter the size distribution of the particlates.

Because of the small number of systematic studies conducted in the United States, generalities about the present exposure of the general public to radon and its decay products should be avoided.

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Table I. Characteristics of radium decay series

Isotope	Alpha ray energy MeV	Half-life	Number of atoms/pCi	Ultimate alpha ray energy/ atom	Total alpha ray energy MeV/pCi
^{222}Rn	5.49	3.82 days	17,700	Insignificant	None
^{218}Po	6.00	3.05 min	10	6.00 + 7.68	137
^{214}Pb	0	26.8 min	86	7.68	660
^{214}Bi	0	19.7 min	63	7.68	484
^{214}Po	7.68	10^{-6} min	8×10^{-6}	7.68	0.00006
^{206}Pb(Stable)				TOTAL =	1,281[a]

[a]The value of 1281 MeV/pCi = 0.01 WL, which is the quantity of alpha energy delivered from a mixture of 1 pCi each of ^{218}Pb, ^{214}Pb, ^{214}Bi and ^{214}Po in 1 liter of air.

Table II. Instruments and methods for measuring radon in air

Instrument and method	Application	Principle of operation	Sensitivity	Reference
Scintillation flask	Grab or continuous sampling	Scintillation alpha count	<.01 - 1.0 pCi/l	13, 14
Two filter	Grab or continuous sampling	Decay of radon and collection of progeny products on second filter; alpha count	0.01 - 5 pCi/l	15, 16
Pulse ionization	Grab (laboratory only)	Sample transferred into ion chamber; pulse ion count	< 0.05 pCi/l	17
Track etch	Time integrating	Alpha sensitive films register tracks when etched in NaOH	0.2 - 1.0 pCi-month/l	18, 19
Passive monitor	Continuous	Radon diffusion into sensitive volume ^{218}Po collected on scintillation counter electrostatically	0.5 pCi/l	20
Plastic bag	Time integrating	Collection of ambient air in bag. Transfer in scintillation flask; alpha count	< 0.1 pCi/l	21
Passive monitor	Time integrating	Radon diffusion into sensitive volume ^{218}Po collection on TLD electrostatically	0.03-0.3 pCi/l	22
Passive monitor	Continuous	Radon diffusion into sensitive volume. Removal of radon daughters by electret. Count alpha particles from radon only	0.1 pCi/l	23
Passive monitor	Time integrating	Radon adsorption on activated charcoal. Gamma count on NaI(Tl) analyzer for ^{214}Pb and ^{214}Bi	0.2 pCi/l in 60 hours	24

Table III. Instruments and methods for measuring radon decay products in air

Instrument and method	Application	Principle of operation	Sensitivity	References
Kusnetz and Rolle	Grab sample for working level only	Collect sample on filter; alpha count	0.0005 WL	25, 26
Tsivoglou and modifications	Grab sample for individual radon decay products and working level	Collect sample on filter; alpha count	0.1 pCi/l each of RaA, RaB and RaC-0.0005 WL	27, 28, 29
Alpha Spectrometry	Grab sample for individual radon decay products and working level	Collect sample on filter; count in alpha spectrometer	0.5 pCi/l each of RaA, RaB and RaC-0.002 WL	30, 31
Instant working level monitor	Grab sample for individual radon decay products and working level	Automatic sample collection, alpha or alpha and beta count	0.01-1.0 pCi/l each of RaA, RaB and RaC-0.001-0.01 WL	32
WL Monitor	Time integrating radon decay product concentration	Collect sample on filter (1-2 weeks). Detect with thermoluminescent material	0.0005 WL in a week	33, 34, 35
WL Monitor	Time integrating or continuous radon decay product concentration	Collect sample on filter continuously. Detect alpha radioactivity with silicon surface barrier detector	0.00004 WL in a week	36

Table IV. Radon sources and transport

Type of measurement	Instrument and method	Principle of operation	References
In situ			
Radon exhalation rates from materials	Charcoal canister	Radon adsorption on activated charcoal; count in NaI (Tl) analyser for ^{214}Bi and ^{214}Pb	37
	Accumulation chamber	Transfer radon to scintillation flask; alpha count	38
Radium-226 content	Gamma-ray spectrometry	Measure primary gamma ray flux from ^{214}Bi and ^{214}Pb with high resolution Ge(Li) detector	39
Laboratory			
Emanation power	Emanation chamber	Seal material in chamber; gamma count. Open chamber, aerate sample and recount	40, 41
Radon in soil gas	Tube in ground	Transfer soil gas sample into scintillation flask; alpha count	6
	Passive CARD	Radon progeny plate out on both sides of alpha CARD; count both sides in two solid state silicon detectors	42
Radon in water	Liquid scintillation vial	Water sample mixed with scintillation fluid; count in liquid scintillation counter	43
	Modified Marinelli beaker	Count sample in NaI (Tl) analyser for ^{214}Bi and ^{214}Pb	44

Table V. Sources and air concentrations of radon and radon decay products in U.S. buildings

Location of building	Number of buildings	Type of measurement	Location in building	Radon pCi/l	WL	^{226}Ra in soil pCi/g	Radon flux from cellar aCi cm^{-2} sec^{-1}	Radon in water pCi/l
NJ - NY Metropolitan Area EML Study[2]	21	Integrated, weekly over a 2 year period	Cellar first floor	2.0 1.0	.01 .0046	1.0	6.4	330
Energy efficient buildings, in NH, CT, NJ, NY & NM EML Study[51]	11	Integrated over 1 week in winter	first floor	1.5	.01	.08 - 2.1	5.6	10-9,000 (1700)
All-Electric homes Eastern Pennsylvania EML Study[52]	6[a]	Integrated over 1 week in May	Cellar first floor	35 20	.20 .07	1.25	24	800
Central Florida Background homes near phosphate region EPA Study[53]	28	Integrated, weekly over a 1 year period	First floor	0.5	.0033			
Grand Junction, CO, Background buildings Colorado Dept. of Health Study[54]	29	Integrated, weekly over a 1 year period	First floor	1.1	.007			
Butte, Montana mineralized region EPA Study[55]	56	Integrated, weekly over a 1 year period	First floor	3.3	.02			

[a]Average measured ventilation rate in four homes was 0.27 air changes per hour.