Radon Measurement

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Abbreviations

ACD	activated charcoal adsorption detector
ACD-CC	activated charcoal adsorption detector-charcoal-filled container
ACD-LS	activated charcoal adsorption detector-charcoal liquid scintillation device
ATD	alpha-track device
CRM	continuous radon monitor
EIC	electret ion chamber
EID	electronic integrating device
EPA	Environmental Protection Agency
HVAC	heating ventilation and air conditioning
LSC	liquid scintillation counter
MDC	minimum detectable concentration
PAEC	potential alpha energy concentration
RPD	relative percent difference
RPE	relative percent error
QA	quality assurance
QAP	quality assurance plan
QC	quality control
WHO	World Health Organization
WL	working level

Introduction

In the United States, the US Environmental Protection Agency (EPA) provides the general guidance for the measurement of radon gas, radon decay products, and radon in water. In addition, the World Health Organization (WHO) provides detailed guidance for member countries on radon gas and decay product measurement techniques. Both the US EPA and WHO guidance include suggestions for radon measurement protocols and quality assurance (QA) measures related to obtaining valid radon measurements. It is important to note that the radon decay products, mainly polonium-218 and polonium-214, deliver the majority of the radiation dose to the lungs, rather than the radon gas itself. However, because it is easier and less complicated to measure radon gas than it is to measure radon decay products, measurement of the radon gas concentration often serves as a surrogate for the radon decay product concentration.

The technology used in various types of radon detectors is diverse. However, regardless of the technology, radon measurements are often classified as either short term or long term. A short-term radon test, which lasts for a few days to a few weeks, can provide rapid insights into whether or not a particular structure has elevated radon concentrations, especially if the structure is 'closed-up' to maximize radon concentrations within the structure before testing. Alternatively, a long-term radon test, which lasts 3 months or longer, provides a better estimate of the yearly radon concentration to which an individual living within the structure would be exposed. A general guide for the selection of the appropriate radon testing device is presented in Table 1. Detailed information on measurement devices and testing protocols can be found by reviewing the reports and website resources referenced in the Further Readings section.

Radon Gas Measurement Devices

Devices for Measurement of Radon Gas in Air

Devices commonly used for measurement of radon gas are described in this section. Although most of these devices are 'passive' in the sense that they have no moving parts, it is common in the United States to refer to devices that use no electricity during the measurement period (charcoal devices, alpha-track devices (ATDs) and electret ion chambers (EICs)) as 'passive' and those that use electricity (batteries or line power) during the measurement period as 'active.' Unless otherwise noted, all of the devices discussed here are 'passive' in this sense (see also Table 1).

Table 1 Radon gas measurement devices and their characteristics

Detector type (abbreviation)	*Active/ passive*	*Typical sampling period*	*Cost*
Alpha-track detector (ATD)	Passive	1–12 months	Low
Activated charcoal detector (ACD)	Passive	2–7 days	Low
Electret ion chamber (EIC)	Passive	2 days–1 year	Medium
Electronic integrating device (EID)	Active	2 days–year(s)	Medium
Continuous radon monitor (CRM)	Active	2 days–year(s)	High

The minimum detectable concentration (MDC) is the smallest concentration that results in a measurement that is significantly greater than background; in other words, the smallest concentration that can be measured with statistical confidence that radon is actually present in the air. The MDC varies depending on the background of the device or measurement system, the calibration factor or 'sensitivity' of the measurement system, and the duration of the measurement; however, an MDC of 20 Bq m^{-3} (0.5 pCi l^{-1}) is generally achievable for all the devices discussed here.

Table 2 lists the primary methods and devices for measurement of radon gas.

Activated charcoal adsorption detector (ACD)

Activated charcoal detectors are commonly used in the United States for short-term measurements. There are two main types of ACDs: charcoal-filled containers and charcoal liquid scintillation devices.

Charcoal-filled container (ACD-CC)

Charcoal-filled containers, which could be metal or plastic canisters, bags, or trays, contain 15–90 g of activated carbon, depending on the size and design of the device. Canisters that are 'open-faced' are typically used for measurement periods of 2–4 days. Canisters that contain a diffusion barrier to reduce the adsorption of moisture from the air are typically used for periods of 4–7 days. Bags and trays, depending on the specific design, may be used for periods of 2–7 days. Once the device is deployed, radon gas is adsorbed onto the activated charcoal. The quantity of radon adsorbed tends over time to reach an equilibrium condition with the surrounding air; thus, these devices are not truly integrating but may be more accurately considered to be 'equilibrating devices.' The quantity of radon adsorbed at the end of the exposure, for both open-face and diffusion-barrier devices, may be more greatly influenced by the radon concentration in the surrounding air during the last 12–24 h of the measurement period than during the first hours of the period. Therefore, best results are obtained when there are no huge changes in radon concentration during the measurement period. At the end of the measurement, the device should be sealed to prevent further exchange of radon or moisture with the surrounding air. Because the radioactive half-life of radon is only about 3.8 days, the device should be returned to the laboratory for analysis as quickly as possible. The less radon that is in the device when received by the laboratory, the more uncertainty there will be in the result of the analysis. Gamma-ray spectroscopy is used to detect gamma rays emitted from two of the decay products of radon, ^{214}Pb and ^{214}Bi. The adsorption of radon onto the charcoal may be significantly affected by humidity, and if so the devices must be calibrated such that the laboratory can compensate for this effect. Calibration is accomplished by exposing sets of devices in a radon reference chamber under controlled conditions of temperature, relative humidity, and radon concentration. Calibration data should be obtained over the range of temperature, relative humidity, and exposure duration likely to be encountered by the device during field measurements (Figure 1).

Table 2 Primary methods and devices for residential radon gas measurements

Method	*Device*
Preliminary test for radon	CRM, EIC, ACD
Assessment of exposure	ATD, EIC, CRM, EID
Remediation testing	CRM, ACD, EIC

Charcoal liquid scintillation device (ACD-LS)

An ACD-LS contains a small amount of activated charcoal, approximately 2.5 g, enclosed in a small container, often a 20 ml liquid scintillation (LS) vial. ACD-LSs function in a manner similar to ACD-CCs in that, when exposed to ambient air, radon is adsorbed onto the charcoal. The exposure period begins when the container is opened. Some combination of (1) a desiccant, (2) a filtered barrier, or (3) a plastic cartridge containing the charcoal is used in most devices. Upon completion of the 2–4 day exposure period, the device is sealed and quickly returned to the laboratory for analysis. Upon receipt at the laboratory, the radon is transferred from the charcoal into approximately 10–15 ml of an organic liquid scintillator in an LS vial. The specific method of this transfer varies depending on the laboratory's procedures. The sample is placed in a LS counter (LSC), and after a delay period of at least 3 h to allow radon decay products to come into secular equilibrium with the radon as well as

Figure 1 Photograph of activated charcoal adsorption-charcoal filled containers (ACD-CCs).

to light adapt the sample, the sample is counted. Weak flashes of light, or scintillations, caused by alpha particles emitted by radon and its decay products ^{218}Po and ^{214}Po, as well as possibly by beta particles emitted by the radon decay products ^{214}Pb and ^{214}Bi, are detected by a photomultiplier tube and converted into electrical pulses. The electronic circuitry of the counter shapes and counts the pulses. The count rate is then converted into radon concentration based on the algorithm and calibration factor used by the laboratory. Similar to ACD-CCs, ACD-LSs should also be calibrated by exposure in a controlled radon reference chamber under varying levels of humidity as well as ranges of exposure durations and temperatures generally encountered under actual field deployment (Figure 2).

Alpha-track device (ATD)

ATDs utilize a specially produced piece of plastic enclosed within a plastic chamber. The chamber has a filtered opening that allows the entry of radon gas, but excludes the entry of radon decay products. The plastic is most commonly composed either of polyallyl diglycol carbonate (PADC or CR-39), polycarbonate (Makrofol) material, or cellulose nitrate (LR-115). Alpha particles, emitted either by the radon gas that entered the chamber or from radon decay products (^{218}Po and ^{214}Po) that are produced by the radon within the chamber, strike the specialty plastic and cause microscopic damage in the plastic. The areas of damage, or latent tracks, are more soluble in a strong caustic solution, such as sodium hydroxide, than is the undamaged portion of the plastic. The tracks can be visualized at $100\times$ magnification after the plastic has undergone chemical or electrochemical etching. The tracks can be counted manually by using a light microscope ($100\times$) or automatically by using a computer to scan the plastic, recognize the tracks, and count them. The track density (in tracks mm^{-2}) is proportional to the integrated radon gas concentration (in Bq h m^{-3}) after subtraction of the background track density determined from etching and counting similar unexposed plastic material (e.g., usually from the same sheet of plastic). The ATD is considered to be an integrating device as the response of net track density is linear with the integrated radon gas concentration. At high track densities, automated counting systems may not be able to distinguish overlapping tracks, and therefore the response of observed track density versus integrated exposure may be nonlinear. In such a case, the device should be used only in the linear portion of the response curve, or the laboratory may employ a correction for overlapping tracks in a manner that is similar to the correction for 'dead time' for other types of nuclear counters. Exposure of ATDs to known values of integrated radon gas concentration in a radon reference chamber provides a calibration factor to convert from tracks per unit area to radon concentration. ATDs are typically used for measurements from 1 month to 1 year in duration. ATDs are not affected by temperature, humidity, or background gamma radiation typically encountered in an indoor environment. As with any device, condensing moisture should be avoided. Other gaseous alpha-emitting radionuclides, such as thoron, can cause interference as they would also produce tracks on the plastic. Some devices are available with thoron barriers; therefore, thoron concentration can also be quantified by exposing devices both with and without a thoron barrier (Figure 3).

Electret ion chamber (EIC)

EICs provide a true integrated measurement of the average radon gas concentration during the exposure period. A positively charged electret is used in conjunction with an ionization chamber made of an electrically conductive plastic. Devices that are designed for short-term measurements use a short-term electret and a

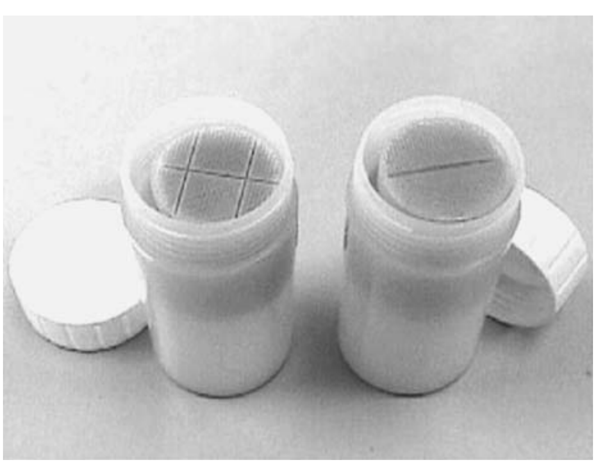

Figure 2 Photograph of activated charcoal adsorption-charcoal liquid scintillation devices (ACD-LSs).

Figure 3 Photograph of two different alpha-track devices (ATDs).

short-term chamber that incorporates a spring-loaded mechanism for exposing the electret to the full volume of the chamber at the time of placement. At the end of the exposure period, this mechanism is closed such that the electret is exposed to a tiny volume of air, thus effectively ‘turning off’ the device. Devices that are designed for long-term measurements use a less-sensitive electret and a smaller chamber. All types of these devices have a filter in the opening of the chamber to preclude the passage of particulate radioactive materials, such as radon decay products, into the chamber. The electret, which is an electrically charged plastic disk, functions both as the source of an electric field and as a sensor in the device. As radon and its decay products undergo radioactive decay within the chamber, the emitted radiation ionizes the air. The positively charged electret collects negative ions that have been produced in the chamber air, resulting in a discharge of the electret that is related to the integrated ionization during the measurement period (**Figure 4**).

The electrical potential on the electret is measured before and after the exposure using an electret reader (an electrostatic voltmeter). Some long-term devices are read only by the manufacturers, whereas others can be read by another laboratory or by the end user. EICs that are read by the end user are analyzed by inputting the starting and ending potentials of the electret, the ambient background radiation in $\mu R\, h^{-1}$, the exposure duration in days, and the altitude at which the device was exposed into an algorithm supplied by the manufacturer. This algorithm calculates the calibration factor and the radon concentration based on calibration exposures performed by the manufacturer. The duration of the measurement period depends in part on the type of electret used (short or long term) and the size of the chamber. Short-term electrets and chambers are designed to measure radon for 2 days to 2 weeks. Alternatively, long-term devices can provide an integrated average radon concentration for measurement periods spanning several weeks to a year. EICs are not affected by temperature or humidity in the ranges normally encountered indoors, but condensing moisture should be avoided. The algorithm adjusts for effects due to altitude and ambient background radiation. Best results are obtained when the ambient background is measured or otherwise well known. Sources of gamma radiation in addition to ambient background, such as stone or ceramic ware containing natural radioactivity, can cause the device to give a falsely high reading. The chambers and electrets must be kept clean, because dust or particulates that come in contact with the electret may discharge it. These devices have been used in many countries and have the potential to provide accurate and precise radon gas measurements if standard operating procedures are carefully followed. A very useful function of the short-term device is that it can be opened and

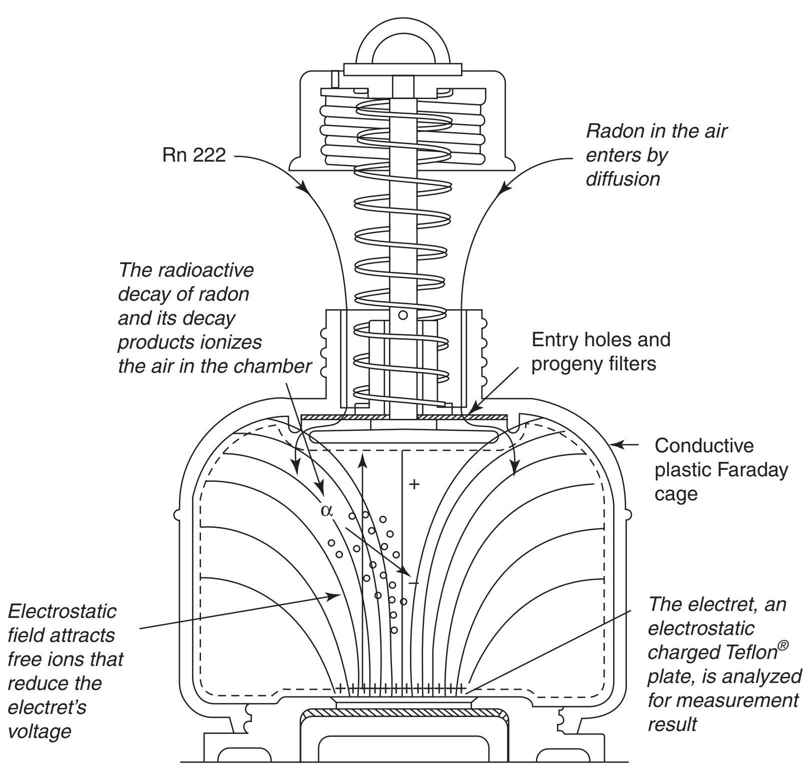

Figure 4 Diagram displaying the functioning of an electret ion chamber (EIC).

closed repeatedly during the exposure period, thus allowing radon measurements for specific periods of the day (e.g., school day hours and work hours) (**Figure 5**).

Continuous radon monitor (CRM)

Continuous radon monitors (CRMs) are electronic instruments that make continuous measurements of radon concentration at least hourly. CRMs are considered to be 'active' devices regardless of whether a pump is used or whether radon enters the detector by passive diffusion. CRMs are typically used for measurements from 2 to 8 days in duration. The hourly measurements and the average over the measurement period are typically stored for printing or transfer to a computer; however, some CRMs provide measurements in real time. There are three types of CRMs that differ depending on the type of detector that is used. One type uses a scintillation cell coupled to a photomultiplier tube. Radon in the ambient air passively diffuses into the cell, or alternatively ambient air containing radon is pumped through the cell. Alpha particles emitted by radon and two of its decay products, ^{218}Po and ^{214}Po, strike the ZnS coating of the interior of the cell and produce weak flashes of light, or scintillations, which are detected by the photomultiplier tube. The electronic circuitry shapes and counts these pulses and converts the count rate into radon concentration. Another type uses a pulse-ion chamber as the detector. Radon in the ambient air passively diffuses into the chamber, or some monitors use a pump to transfer ambient air containing radon into the chamber. The chamber consists of two electrodes with an electrical potential across them. When an alpha particle is emitted by radon or by one of its decay products (^{218}Po and ^{214}Po), the air in the path of the alpha particle is ionized. The ions are collected on the electrodes as an electrical pulse. The electronic circuitry shapes and counts the pulses, and converts the count rate into radon concentration. The third type uses a solid-state detector, usually surrounded by an enclosure, or chamber, that has an electrical potential between the wall of the enclosure and the surface of the detector. Radon passively diffuses into the enclosure. When the radon decays, its decay products are drawn to the surface of the detector. Alpha particles, primarily from the radon decay products ^{218}Po and ^{214}Po, but also possibly alpha particles emitted by radon itself, strike the detector and create electrical pulses. Electronic circuitry shapes and counts the pulses and converts the count rate into radon concentration. Calibration is accomplished by exposing CRMs to controlled conditions of temperature, relative humidity, and radon concentration in a radon reference chamber. The 'sensitivity' or calibration factor of CRMs, in terms of counts per hour (cph) per becquerel per cubic meter (Bq m^{-3}), varies significantly among manufacturers and models (**Figure 6**).

Figure 5 Photograph of electret ion chambers (EICs) opened and closed as well as electret reader.

Electronic integrating device (EID)

Electronic integrating devices (EIDs) are similar to CRMs, but are designed for long-term operation, from 2 days to a year, and therefore do not provide hourly measurements. Some models do not display a measurement until at least 2 days of the measurement period have elapsed. EIDs have a significantly less 'sensitivity' than CRMs in terms of cph per Bq m^{-3}. An EID uses a solid-state detector contained within a small enclosure,

Figure 6 Photograph of a continuous radon monitor (CRM).

or chamber, into which radon passively diffuses. Because they have electronic circuitry, EIDs are considered to be 'active' devices. Alpha particles emitted by radon and by its decay products ^{218}Po and ^{214}Po that strike the solid-state detector generate electrical pulses. The electronic circuitry shapes and counts the pulses and converts the count rate into radon concentration. Calibration is accomplished by exposing the devices to controlled conditions of temperature, relative humidity, and radon concentration in a radon reference chamber. EIDs are relatively inexpensive to purchase as compared to CRMs (Figure 7).

Grab radon measurement device

Although grab radon measurements are not used to determine the need for mitigation of a home or building, grab measurements are often used for intercomparisons among laboratories and can be a useful tool for determining the entrance pathway of radon into a building. Grab radon measurements are usually accomplished by filling a scintillation cell, either by pumping air through the cell or by evacuating the cell and then opening a valve to draw air into the cell. The air is filtered to remove any particulate radioactive materials, including radon decay products, and to help keep the interior of the cell clean. After a period of 4 hours to allow radon decay products to come into equilibrium with the radon, the cell is placed on a photomultiplier tube connected to a counting system. Alpha particles emitted by radon and its decay products ^{218}Po and ^{214}Po strike the zinc sulfide (ZnS) coating of the interior of the cell, which causes weak flashes of light, or scintillations. The light flashes are detected and amplified by the photomultiplier tube. The electronic circuitry shapes and counts the pulses. The net count rate is then converted into radon concentration after correction for the decay of radon. Calibration is accomplished by filling the cells in a radon reference chamber or with radon quantitatively transferred from a ^{226}Ra standard source.

Figure 7 Photograph of electronic integrating device (EID).

Radon Decay Product Measurement Device

Continuous or Integrating Radon Decay Product Measurement Device

In situations where an assessment of the radiation exposure is needed (e.g., in occupational situations where the radiation dose to workers must be documented for regulatory purposes), the determination of the radon decay product concentration can be performed in terms of the equilibrium equivalent radon concentration, the total potential alpha energy concentration (PAEC), or the activity concentrations of the individual short-lived decay products. All methods are based on the collection of the radon decay products on a filter and the simultaneous or subsequent measurement of alpha- and/or beta-emitting radionuclides on the filter. Depending on the measurement method and desired flow rate for the sample collection, different filter material is used (e.g., membrane filters are generally used for measurement of alpha particles emitted from material deposited on the surface). Continuous air monitors (CAMs) used in occupational settings typically have a relatively high flow rate, 28–85 $\mathrm{l\,min^{-1}}$ (1–3 cfm). Depending on the monitor, membrane filters, glass fiber filters, or cellulosic filters may be used. Usually a semiconductor diode detector is used, but plastic scintillators or proportional detectors are sometimes used for detection of beta particles. Continuous radon decay product monitors used in homes or occupational settings that are not considered radiation areas typically use lower flow rates (1 $\mathrm{l\,min^{-1}}$ or less) and use a solid-state alpha detector in close proximity to the filter. An integrating radon decay product measuring device uses EICs modified with a filter holder on the side of each chamber. Air is pumped through a glass fiber filter. Alpha and beta particles emitted from activity collected on the filter pass through a thin window into the chamber where they cause ionization to occur. This monitor uses additional EICs to measure simultaneously the radon concentration; therefore, both the concentrations of radon gas and radon decay products are measured and the equilibrium ratio can be determined.

Grab Radon Decay Product Measurement Methods

Grab measurements of radon decay products in air are usually collected by pumping air through a membrane or glass fiber filter and analyzed by gross-alpha counting using a ZnS scintillator and a photomultiplier tube. Several analysis methods are available and vary depending on the number of counts that are made. The Kusnetz method, as originally proposed, allowed for a decay period of 40–90 minutes after the sample was collected so that alpha particles from only ^{214}Po would be present on the filter. The count rate was then measured with an alpha survey meter, and a graph was used to obtain a factor to convert the observed decay rate per volume of air (dpm l^{-1}) to PAEC in working level (WL). This method was modified such that the present Kusnetz method uses gross-alpha counting over a time interval rather than using a rate meter. A typical scheme is to sample for 5 min, delay for 35 min, and count for 10 min. A conversion factor is used to convert to PAEC in WL. The Rolle method uses a much shorter delay time, thus decreasing the amount of time to complete the entire measurement process. All one-count methods provide approximate solutions for the PAEC.

The modified Tsivoglou method uses gross-alpha counting and three counting intervals. The results of the three counts are used in a solution of three equations in three unknowns to solve for the individual radon decay product concentrations in Bq m^{-3} (or pCi l^{-1}). These individual concentrations can then be used to solve for the PAEC in WL. A typical protocol, as published by Thomas, is to sample for 5 min, then count from 2 to 5 min, 6 to 20 min, and 21 to 30 min after the end of the sampling period. This is presently the preferred method for performing intercomparison exercises among reference laboratories that can expose devices in a controlled environment for radon decay product concentration.

Perhaps the best method of analyzing a grab sample for radon decay product concentrations using gross-alpha counting, from a statistical point of view, is based on making multiple counts and solving for the individual concentrations of the radon decay products using nonlinear regression techniques. A method whereby counts were collected each minute and analyzed between data collections using nonlinear regression was used at the radon reference laboratory of the former U.S. Department of Energy Mound Facility. Collecting a series of 1 min counts has the advantage of providing data for the best statistical solution based on nonlinear regression, even in real time as the sample is being counted; therefore, the analysis can be ended when predetermined statistical criteria are met, possibly shortening the analysis time. Further, if the sample is counted long enough, data are available for analysis using all of the methods mentioned here and thus comparisons can be made among the solutions from various methods.

Grab radon decay product samples also may be analyzed using a solid-state detector system and alpha spectroscopy. In this case, counts from alpha particles of differing energies can be quantified. This is a particularly useful tool for identifying and quantifying mixtures of decay products of ^{222}Rn (radon), ^{220}Rn (thoron), and ^{219}Rn (actinon).

Measurement of Waterborne Radon

Measurement of waterborne radon samples by use of an LSC is a widely used technique to quantify the radon content of water. The LSC method for analysis of waterborne radon exhibits excellent accuracy and precision. The method also has a low level of detection and measurement preparation is fairly simple. An important consideration for measuring radon in water is ensuring that radon is not lost during the water sampling procedure. The US EPA has adopted recommended collection methods for sampling for radon in water, including the use of special sampling vials generally used for sampling of volatile organic compounds. Because radon has a fairly high solubility in organic liquids, water containing radon can be directly injected under approximately 10 ml of a scintillation fluid (e.g., mineral oil) that was premeasured into a liquid scintillation vial. Similar to radon moving from the charcoal to the fluid for the ACD-LS method, radon is lipophilic and moves from the water phase to the scintillation fluid. After a 3-h wait period to allow equilibration between radon and its decay products as well as to light adapt the sample, the scintillation flashes of light in the fluid caused by the radioactive decay of radon and decay products are counted in an LS detector. The LSC technique quantifies the activity of radon, as well as the decay products, by measuring the rate of photons emitted from the LS fluid. Limitations of the LSC method include the significant cost to purchase the LSC and the need to perform the analyses in a laboratory. In addition, depending on the clarity of the water sample, correction for quenching may also need to be performed to ensure that the appropriate spectrum of energies from radon and its decay products are recorded correctly. Other established methods for measuring waterborne radon include de-emanation, direct gamma counting, and an EIC method.

Measurement Protocols

The protocols used for radon measurements reflect the diversity of information required, assessment types, and situations where radon exposure is a potential concern. Given the fundamental variability of indoor radon concentrations and the powerful desire to have a rapid, inexpensive assessment of the exposure, measurement protocols usually make compromises that lead to substantial uncertainty in the long-term exposure estimates. These uncertainties should be taken into account in any program of action decisions based on the measurements. Often the uncertainties reflect regional patterns of climate and building practices. A number of national radiation protection institutions have published detailed guidelines for measuring radon in various situations and making action decisions. This section gives only a general picture of the important similarities and differences among the various guidelines applied to a few major radon risk assessment tasks. For example, most European measurement protocols seek to minimize uncertainty associated with temporal radon variations on the seasonal level by employing long-term measurements under typical living conditions. In the United States, the US EPA believes that most people will not take the time to make long-term measurements. The US EPA guidelines emphasize short-term measurements in the lowest floors under closed-house conditions with the hope that the assumed 'worst-case' measurements estimate will lead to a proper remedial action decision. With this approach it is important to recognize the measurement uncertainties when comparing the results to reference or action levels particularly in regions where the median house may have concentrations near the action level.

The following sections provide general discussion of some typical radon measurement applications including personal exposure in private homes and large buildings, exposure assessment for epidemiologic studies, radon source assessment, and measurements for mitigation decisions. The best approach for each situation should consider the measurement variability and the predictive value of the results, given the uncertainties that arise from spatial, temporal, and instrument variation.

Measurements in homes

In private homes, one should make radon measurements in a manner that cost-effectively attempts to provide reliable estimates of an individual's exposure. For current residents in existing homes, the high temporal variation of indoor radon in many regions makes short-term measurements unreliable for long-term radon exposure assessment, except in cases where extremely high-radon concentrations are expected. Seasonal adjustments allow for measurements shorter than a year to provide adequate surrogates in the countries where the 'typical' seasonal variation is well known. In highly variable regions, year-long measurements typically are within 25% of the very long-term average if the structure remains unmodified. Spatial variation within a house can also be a significant source of exposure uncertainty. A single measurement in one room where the radon is expected to be highest is sometimes used to estimate the 'whole house' radon concentration but houses with strongly variable radon sources or poor air circulation can have significant variation, particularly from floor to floor. So radon measurements should be made in a frequently occupied room on levels with ground contact in regions where soil gas radon is the main radon source or in frequently occupied space with the least airflow if building material is the main source of radon. The measurement protocol should minimize the potential for technical failure of those detectors whose results may be affected by drafts, moisture, temperature, strong light, gamma rays, or thoron.

Radon measurements are part of a home safety assessment during a sale in some countries. Time constraint pressures place special stress on the measurement protocol to assure a valid remediation decision is made during the transaction. In regions where radon testing during real-estate transactions is a common practice (e.g., the United States), side-by-side (collocated) short-term measurements at a single location are the diagnostic tests for radon concentrations exceeding the action level. These diagnostic tests frequently fail in radon-prone areas with strong seasonal radon variation. Current short-term radon measurement technologies are unable to consistently produce accurate estimates of annual-average radon concentrations in regions where elevated radon concentrations are common. Temporally sequential short-term measurements are more effective in reaching a reliable mitigation decision when used with a wide confidence interval about the action level. One possible solution to this problem is a simultaneous deployment of short-term and long-term detectors, which would allow the transaction to proceed while an accurate assessment takes place. Additional detailed recommendations about deployment of the detectors are given in some countries; for example, placement at breathing height, at some distance from doors, windows, heating, and walls and not in bath/washing rooms.

Measurements in Large Buildings

In large buildings including schools, commercial buildings, and multiunit residential structures, radon exposure patterns may differ from private houses due to differences in building structure, heating ventilation and air conditioning (HVAC) operation, and occupancy. These patterns suggest that measurement protocols should reflect these differences by having multiple sampling locations in highly occupied locations for buildings with large floor areas, multiple floors, and multiple compartments with separate HVAC systems. If soil is suspected as the radon source, floors with ground contact should be sampled at a higher rate. If building materials are the main radon source, enhanced sampling (e.g., additional systematic selection of additional sampling locations) may be required on higher floors since ventilation rates of individual rooms might then be the main variable. Significant room-to-room radon variations in some buildings suggest that a higher fraction of rooms need to be measured in most buildings. Buildings which show strong diurnal radon variation and are occupied during only part of the day may need to be measured during occupied periods to determine if there are significant differences in radon concentrations, and perhaps radon progeny concentrations, when the occupants are present.

Measurements for Epidemiologic Studies

Epidemiologic studies require accurate retrospective radon exposure assessment for the study participants. Several factors can cause significant uncertainty including intrinsic radon detector measurement error, failure to account for temporal and spatial radon variations within a home, missing measurement data from previously occupied homes, failure to link radon concentrations with an individual's mobility, measuring radon gas as a surrogate for radon decay product exposure, and potential cross sensitivity to thoron. Year-long radon gas measurements using ATDs with linkage to the individual's mobility pattern is recognized as the best available methodology. To minimize missing data due to the inability to measure radon in previously occupied homes, inclusion criteria for cases and controls can include the requirement for long residencies in the current home. Inclusion of glass-based retrospective radon detectors that measure the implanted radon progeny improve the past radon exposure information particularly in homes that have been modified.

Measurements for Mitigation

An accurate assessment of the long-term average radon concentrations in frequently occupied spaces is needed to decide if a building should be mitigated. If short-term screening tests indicated a very low radon concentration compared to the reference level, then a long-term measurement should be done to confirm that the radon is truly low when averaged over many seasons. If a short-term screening test showed a very high-radon concentration compared to the reference level, then confirmatory long-term tests may not be necessary. Post-mitigation tests should be done a few days after a mitigation system is first installed and repeated every few years to ensure sustained effectiveness of the mitigation system. Short-term tests appear to be adequate for this task.

In some cases, it may be necessary to identify the primary source of radon to design an effective mitigation system. Radon flux, or exhalation, from building materials or soil can be measured either in the laboratory or field setting. If a sample of the material is easily obtainable, the radon exhalation rate can be determined by placing the sample in a closed chamber called an accumulator. The ingrowth of radon in the accumulator or its equilibrium concentration can be used to determine the radon emanation rate. In the field, a selected area of the material can be covered with an accumulator and various radon concentration measurements will yield radon flux values. Preliminary evaluation of a material's potential for radon generation can be done by measuring the radon progeny content of sealed and unsealed samples using high-resolution gamma-ray spectrometry.

Quality Assurance of Radon Measurements

A program of QA includes a number of items that help to ensure the quality of measurements. Many of the concepts are addressed in US EPA documents, WHO Guidance, and guidance from other national and governmental organizations. Some important aspects of QA discussed here are common to all types of radon measuring devices; however, some quality control (QC) measurements that are specific to certain devices are discussed separately.

Quality Assurance Plan (QAP)

Any person (individual, business, agency, etc.) performing radon measurements should follow a quality assurance program. A quality assurance plan (QAP) should be written and maintained describing the details of the QA program. These should include standard operating procedures, QA objectives, and a means for recording and assessing the results of QC measurements. Guidance on the content of QAPs is available from several sources.

Minimum Detectable Concentration (MDC)

The MDC is the smallest concentration that results in a measurement that is significantly greater than background; in other words, the smallest concentration that can be measured with statistical confidence that radon is actually present in the air. The MDC varies depending on the background of the device or measurement system, the calibration factor or 'sensitivity' of the measurement system and the duration of the measurement. Anyone performing radon measurements should state the MDC for its measurements, and how it was derived, in the QAP and report it with all radon measurement results. Discussions regarding the detection limit and MDC are available elsewhere (see Further Readings section).

Reference Laboratories and Intercomparison Exercises

A laboratory that maintains a radon test atmosphere, usually in some type of controlled chamber, and provides services such as calibration of radon measuring devices, spiking or performance testing is a 'radon reference laboratory.' It is essential that the measurements of every radon reference laboratory trace back to a primary national reference standard by some method of intercomparison. This can be done by intercomparing directly with the laboratory that serves as the national reference or with another reference laboratory that does so. Intercomparison exercises among several reference laboratories are an important way to determine the extent of agreement among those laboratories. One method of performing such an exercise is to send a 'transfer standard,' usually a CRM, to several reference laboratories. Each operator of a radon reference laboratory then places the transfer standard monitor in a test atmosphere and compares its readings with the laboratory measurement system that monitors the test atmosphere. A 'hosting' entity that coordinated the sending of the transfer standard then compiles the results of how the various laboratories compared with the common instrument (Figure 8).

Another way of conducting an interlaboratory comparison is that one radon reference laboratory hosts the exercise. Personnel from other reference laboratories or other radon measurement practitioners, such as manufacturers, radon testing laboratories, universities, and government agencies, send or take devices to the host laboratory for side-by-side exposures in a radon test chamber. The radon concentration to which the various devices were subjected is not disclosed until all of the participants report their results to the host laboratory. A report is then issued comparing the results of all of the participants with the value(s) from the host laboratory. Results of several interlaboratory comparisons have been published elsewhere (see Further Readings section).

Performance Tests and Blind Spikes

Persons or companies that are licensed or certified by states or radon proficiency programs may be required to participate in a performance, or proficiency test. The participant contracts with a recognized reference facility with a controlled radon reference atmosphere (radon chamber) to expose one or more devices to conditions typically found in an indoor environment. The devices are returned to the participant without disclosing the average concentration in the chamber (i.e., the 'target value'). The participant reports the measurement results to the reference facility personnel, who compare them to the target value and issue a report to the participant. A radon measurement firm may wish to test itself unofficially, for its internal QA program, by having devices exposed without prior knowledge of the target value. This is called a 'blind spike.' In this case, no licensing or certifying agency is informed of the results.

Figure 8 Photograph of detectors in an exposure chamber undergoing controlled radon exposure at a reference laboratory.

Blind Tests

Devices that are marketed to the public or to professional testing companies but are analyzed in a laboratory can be purchased, exposed in a chamber, and returned to the laboratory for analysis as if the devices were used for field measurements. This is called a 'blind test.' As long as fictitious location information is given to the laboratory and the samples are returned from a location other than a radon reference laboratory, the analyzing laboratory has no way of knowing that it is being tested. In the case of charcoal devices, however, it is essential that the actual dates of times of the exposure in the chamber are given to the laboratory so that the proper correction for decay of the radon can be made. Blind testing for devices such as continuous monitors is more difficult and costly. Anyone performing blind tests must realize that all measurements of radioactivity are random processes, and therefore results based on a small sampling may be misleading if not confirmed by further testing.

Continuous Device Methods

Calibration

The manufacturer of a continuous monitor provides the initial calibration of each individual device. Subsequent calibrations are performed by the manufacturer or by a separate radon reference laboratory whose personnel have been trained and authorized by the manufacturer to calibrate its monitors. US EPA protocols specify that continuous monitors must be calibrated at least annually, and after any modification has been made to the monitor. Calibration means some combination of the following processes as appropriate to the specific monitor: (1) checks of recharging circuitry and batteries, replacing as needed, (2) checks of voltages, current or wave patterns at critical points of the circuitry with adjustments as necessary, (3) determination of proper discriminator and high voltage settings for a monitor using a photomultiplier tube, (4) determination of the background count rate, or equivalent radon concentration, by exposure to a radon-free environment of nitrogen or aged air and adjusting the internal background setting if possible, and (5) determination of the calibration factor by exposure to a reference atmosphere in a radon chamber, taking into account the background count rate or equivalent radon concentration, and adjusting the internal calibration factor setting, as appropriate. For continuous monitors that use scintillation cells, a cell and photomultiplier tube should be considered to be a 'matched pair.' If more than one scintillation cell is to be used with a single photomultiplier tube, then a background count rate and calibration factor must be determined for each combination of photomultiplier tube and scintillation cell.

For each monitor, a statement, or certificate, of calibration should be issued, which includes the following information, as appropriate: (1) the 'as received' condition of the monitor including any physical damage and settings of discriminator, high voltage, background and calibration factor, (2) the conditions (temperature, relative humidity, and radon concentration) to which the monitor was subjected and the duration of the exposure, (3) the results of measurement of background and response to the reference atmosphere in terms of radon concentration or relative percent error (RPE), (4) the 'as calibrated' settings of the discriminator, high voltage, background and calibration factor, (5) the date the calibration was performed, and (6) the signature of a responsible person. Calibration personnel should affix a calibration sticker onto the monitor displaying the following information: (1) the name of the calibration facility, (2) the initials of the responsible person, (3) the calibration date, (4) the expiration date of the calibration, (5) the background count rate, or equivalent radon concentration, (6) the calibration factor (or a 'correction factor,' if appropriate), and (7) an identification of the monitor, such as its serial number.

Background

It is essential that the background count rate of a continuous monitor be measured and taken into account in the calibration process and in the determination of every measurement. In the case of most monitors, the long-lived decay products of radon build up on the detector and cause the background to slowly increase over time. US EPA protocols indicate that 'an inherent element in the calibration process is a thorough determination of the background count rate using clean, aged air or nitrogen. Subsequent recalibrations and background checks should be done at least once every 12 months …'

It may be necessary to measure the background of a scintillation cell more often than annually depending on the frequency of use and the concentration of radon to which it is subjected. Current US EPA protocols state that "after every 1000 hours of operation of scintillation cell-type continuous monitors (about every 20th 48 h measurement), and whenever any type of continuous monitor is calibrated, the background should be checked…" Experience may show, however, that the background of this type of monitor can be checked less frequently if it is not subjected to high concentrations of radon. The background should be measured for each combination of scintillation cell and photomultiplier tube.

Internal Checks

Some continuous monitors provide ways of checking their operation each time they are used; for example, a check of batteries, a radioactive standard source for checking the operation of the detector, or an electronic check of the detector. If such internal checks are provided, they should be used before every measurement. Some types of monitors automatically perform some of these checks before each measurement is started.

Duplicates

Current US EPA protocols specify that duplicate measurements should be "made in at least 10 percent of the total number of measurement locations, or 50 each month, whichever is smaller." For continuous monitors, this should be done by collocating two monitors of the same type and performing the measurement with both monitors. The relative percent difference (RPD) of the two measurements should then be calculated as a measure of precision of that specific type of monitor. The measurements of RPD should be tabulated and plotted on a control chart. If values of RPD indicate that the duplicates are not 'in control,' this could indicate a problem with one or both of the monitors and should prompt further investigation.

Informal Intercomparisons

If two monitors of the same type are not available for a duplicate measurement, a different type of device, such as a charcoal or EIC device, can be collocated with a monitor. Such measurements are not duplicates but rather are called 'informal intercomparisons,' as they do not provide an estimate of precision for either type of device. However, such measurements can be useful. The RPD should be calculated and plotted on a control chart in the same manner as duplicate measurements. Values of RPD that are not 'in control' can be an indication of a problem with one or both types of devices.

Cross Checks

US EPA protocols indicate that a monitor should be cross checked 'to a recently calibrated monitor at least semi-annually.' This means that approximately midway between annual calibrations, a monitor should be collocated with another monitor of the same type that has been recently calibrated, and a measurement made with both monitors. It is assumed that the recently calibrated monitor provides a better measurement of the radon concentration; therefore, the RPE (not RPD) should be calculated with the assumption that this monitor provides the conventionally true value. Such values of relative error from cross checks should be tabulated and plotted on a control chart.

Integrating and Equilibrating Device Methods

Calibration

Integrating and equilibrating devices (EICs, ATDs, and charcoal devices) are calibrated in batches rather than individually as continuous monitors are. Devices similar to those that are used in the field are subjected to exposures in a radon reference chamber under varying conditions of radon concentration, duration of exposure, relative humidity, and temperature. The manufacturer, or the laboratory that analyzes the device, uses the data from the exposures performed in the reference chamber to develop sets of calibration curves or algorithms. Descriptions of procedures for calibrating charcoal canister devices are available elsewhere (see Further Readings section). The curves or algorithms provide values of the device's calibration factor as a function of such operational factors as duration of exposure and electrical potential on electrets and of such environmental factors as ambient gamma background, relative humidity, temperature, and altitude. Periodically, devices that have been exposed in a radon reference chamber ('spiked' samples) are used by the manufacturer or laboratory to assess the accuracy of the measurements. The RPE of the measurement of each device relative to the conventionally true value (the chamber value) should be tabulated and plotted on a control chart. Current US EPA protocols require that spiking be done at a rate of at least 3%, with a minimum of three spiked samples per year and a maximum of six per month. Such a program of spikes, and the consequent plots of RPE on a control chart, can be used to demonstrate that the calibration of the device continues to produce results that are 'in control.' The device must be recalibrated any time that the QC data indicate that the system is no longer 'in control,' or whenever there is a physical change made to the device or the analysis system. This includes changing the supplier or even the 'lot' of charcoal for those devices that contain charcoal.

Duplicates or Collocated Measurements

Collocated, or side-by-side, measurements provide an estimate of the precision of the measurements. US EPA protocols specify that duplicate measurements should be made at a rate of 10% with a maximum of 50 per month. Performing duplicate measurements at a specific interval (e.g., such as every tenth measurement) helps to ensure that estimates of precision are made over the range of radon concentration encountered in the field. If two collocated measurements (duplicates) are consistently made then the RPD statistic should be calculated, tabulated, and plotted on a control chart. If more than two devices are collocated, then the coefficient of variation must be calculated rather than the RPD.

Performance goals for precision should be specified in the QAP. Ranges of RPD values for duplicate measurements that may be considered 'in control,' and values for 'warning levels' and 'control limits,' for two ranges of radon concentration, can be found in the US EPA protocols (see Further Readings section). The protocols also provide guidance on when corrective actions should be taken. Discussions regarding control charts, setting limits, and determining when corrective action should be taken are available elsewhere (see Further Readings section).

Laboratory Background Measurements

Analysis systems, such as those used to analyze charcoal canisters and alpha-track detectors, have an inherent background that must be measured and subtracted from the response of detectors used in the field. This type of background can be established by measuring laboratory 'blank' devices; in other words, devices that have not left the laboratory and have not been exposed to radon. Such measurements of laboratory background are necessary for establishing the detection limit and MDC of the analysis system. The procedure for measuring the laboratory background, including the minimum number of devices from each batch that require testing, or the frequency of measurement of a laboratory blank device, should be stated in the QAP of the analysis laboratory.

Field Background Control Measurements

A portion of the devices that are purchased for use in the field should be returned to the laboratory unused. These devices are considered to be 'field blanks.' The purpose of field blanks is to identify problems with shipping, handling, and storage that may affect the results of devices that are deployed in the field. US EPA protocols specify that field blanks should be analyzed at a rate of 5% with a maximum of 25 per month. Blank devices should be handled in the same manner as those used for field measurements. When field devices are deployed, the blank devices should be stored in a low-radon environment, such as sealed in a box containing activated charcoal. The blank detectors should be shipped to the laboratory, along with field detectors, with fictitious location information so that the blanks do not receive special handling or processing. Results from field blanks that are greater than the MDC established by the laboratory may indicate a problem that should be discussed with the analysis laboratory. Instructions for action to be taken if a reported measurement for a blank exceeds the laboratory's MDC should be included in the QAP. As a minimum, the analysis laboratory should be alerted. The source of the problem not only could be with the user's handling or storage, but also could be with the device itself or with the procedures of the analysis laboratory. Use of the blank measurement value, such as subtracting it from the measurement of field samples, should only be done at the direction of the analysis laboratory.

Spikes

A portion of the devices that are purchased for use in the field should be sent to a radon reference laboratory where they are exposed to a known radon concentration for a specified period of time and under controlled environmental conditions in a radon reference chamber. These are called 'spiked samples' or just 'spikes.' Spikes provide an estimate of the bias of the device and laboratory process. US EPA protocols specify that spikes should be performed at the rate of 3%, with a minimum of three per year and a maximum of six per month. The RPE for each individual measurement should be calculated assuming the value provided by a radon reference laboratory is the conventionally true value. The values of RPE should be tabulated and plotted on a control chart. Performance goals for bias should be specified in the QAP. Ranges of RPE values for spikes that may be considered 'in control,' and values for 'warning levels' and 'control limits,' can be found in US EPA documents on QA. Discussions regarding control charts, setting limits, and determining when corrective action should be taken are available elsewhere (see Further Readings section).

See also: Assessing Human Exposure to Environmental Toxicants, Assessment of Human Exposure to Air Pollution, Cellular Stress Responses to DNA Damage: An Intracellular Balance between Life, Senescence, and Death, Children's Environmental Health: General Overview, Cigarette Smoke, DNA Damage Repair, and Human Health, Clinical Consequences of Radiation Exposure, Environmental Carcinogens and Regulation, Environmental Lung Cancer Epidemiology, Exposure Guidelines and Radon Policy, Exposure Reconstruction Using Space-Time Information Technology, Exposure Science: Contaminant Mixtures, Exposure Science: Ingestion, Exposure Science: Inhalation, Exposure Science: Monitoring Environmental Contaminants, Exposure Science: Pharmacokinetic Modeling, Fate and Transport: Geostatistics and Environmental Contaminants, Frequency and Timing of Environmental Exposure, Genome Effects and Mutational Risk of Radiation, Indoor Radon Prevention and Mitigation, Long-Term Effects of Particulate Air Pollution on Human Health, Measurement of Air Pollutants, Mineral and Fuel Extraction: Health Consequences, Models of Human Exposure to Environmental Contaminants, Perceptions and Physiological Responses to Indoor Air Quality, PM2.5 Sources and Their Effects on Human Health in China: Case Report, Productivity and Health Effects of High

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