## UNIT THREE

## RADON MEASUREMENT

### I. OBJECTIVES

This unit provides basic information on radon and radon decay product (RDP) measurement. It specifically addresses:

- Measurement techniques, instruments, and methods.
- Measurement method capabilities and limitations.
- Measurement instrument application and selection.
- Conducting measurements and interpretations of results.
- Quality control and assurance.

### II. OVERVIEW

The application of radon and RDP measurement methods depends on several key characteristics, such as relative accuracy, affordability, expertise required for use, and reliability. The most common applications are:

- Short-term measurements to identify quickly buildings with elevated radon concentrations.
- Follow-up measurements to confirm and characterize elevated radon concentrations.
- Diagnostic measurements for determining appropriate remedial solutions.
- Pre- and post-mitigation measurements to determine the effectiveness of remedial actions.

#### A. Units of Measurement

In 1902, French scientists Madame and Pierre Curie were able to isolate 100 mg of almost pure radium chloride from a ton of uranium ore by repeated crystallizations. One gram of radium was found to decay at a rate of 3.7 x 10 to the tenth power nuclear disintegrations per second. It was later decided by international agreement that the amount of any radioactive element that will give 3.7 x 10 to the tenth power disintegrations per second (dps) would be called a **Curie,** (abbreviated Ci).

A radon-222 gas concentration is commonly measured in picoCuries per liter of air (pCi/L). A **picoCurie** equates to one-trillionth of a Curie, or a rate of radioactivity indicating 0.037 decays per second (or 2.22 decays per minute). Therefore, one pCi/L represents the concentration of radon 222 atoms per liter of air that will result in 2.22 alpha emissions per minute.

Because health effects are primarily due to the **radon decay products (RDPs)** and not to the radon-222 gas itself, a unique unit of measure exists for quantifying the amount of RDPs in the air. This unit of measure is the **working level (WL)** and was previously used to measure the occupational exposure of underground miners. The higher the WL, the higher the risk of adverse health effects.

A **working level** is defined as any atmospheric combination of the short-lived radon progeny [polonium-218 (Po-218), lead-214 (Pb-214), bismuth-214 (Bi-214), and polonium-214 (Po-214)] that will deliver 1.3 x 10 to the fifth power million electron volts (MeV) of alpha energy per liter of air.

If the progeny were in perfect **secular equilibrium** with the radon gas, that is, if each of the four short lived RDPs were present in the air at the same activity level as the radon, then 1 working level would be present when there were 100 pCi/L of radon-222 gas (and consequently, 100 pCi/L of each of the progeny). When the **maximum** possible RDP concentration produced by a given radon concentration is present, the **equilibrium ratio (ER)** of radon gas to the RDPs would be 1.

In practice, the RDPs never reach perfect equilibrium with the radon in homes or other buildings. Due to natural infiltration of outdoor air, all radon atoms do not remain in the house long enough (3 to 4 hours) to reach equilibrium with their progeny. In addition, other environmental factors will not allow all of the RDPs created to remain airborne. RDPs are chemically reactive, are solid particles, and have static electric charges, so they easily attach themselves to breathable particulate matter in the air (e.g., dust, smoke and aerosols). Since a percentage of these RDPs will deposit or **plate out** on solid objects such as walls, floors, ceilings, furniture and clothing, their airborne concentrations are reduced.

The degree to which the progeny approach equilibrium in a specific house can vary significantly. For example, increased air movement will blow more RDPs toward solid surfaces where they will plate out. The concentration of airborne RDPs will be reduced, therefore, and the ER (equilibrium ratio) will decrease. Stagnant air containing an abundance of suspended particles will provide more airborne particles to which the RDPs can attach, creating a higher ER. All of these environmental factors can influence the concentration of airborne progeny without affecting the radon-222 gas concentration, making perfect equilibrium unattainable in home atmospheres.

Studies of equilibrium ratios in homes indicate that typically 30% to 70% of the RDPs will be plated out (and therefore not airborne). An ER of 0.50 (or 50%) is commonly assumed to be average. Based on this 0.50 ER assumption, the house with a radon gas concentration of 100 pCi/L would only produce one-half of a working level, meaning it would take approximately 200 pCi/L to generate one full working level. (However, considering the range of 30% to 70%, 1 WL in any given house could, in fact, correspond to anywhere between 150 and 300 pCi/L.) Based on an average 50% equilibrium ratio assumption, the EPA "action level" of 4 pCi/L is equated to 0.02 WL.

## B. Radon vs. Radon Decay Product Measurement

Although the biological effect of radon is due mostly to RDPs, measurements of radon gas, rather than RDPs, are usually taken. There are several reasons for this:

- There are fewer variables in radon gas measurement, facilitating greater certainty in representative results. For instance, unlike RDPs, the gas concentration is not affected by circulation or filtration devices.
- It is generally easier to make time-averaged measurements of radon gas than of RDPs.
- Measuring radon gas also can be a good indicator of RDPs.

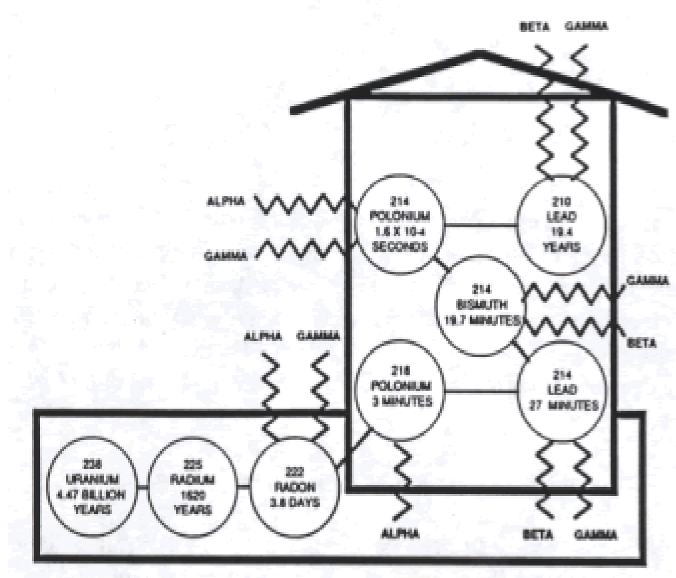
In some cases, however, it is still preferable to measure RDPs. Health effects have traditionally been linked to working level (WL) measurements; measurements made for health-related research, therefore, are usually made using WL monitors. WL monitors are also necessary when making side-by-side measurements to determine the actual equilibrium ratio, or when evaluating an air treatment device designed to reduce RDP concentrations.

## C. Measuring Radon and Its Decay Products: General Considerations

As radioactive nuclei decay, they emit alpha, beta, and gamma radiation in precise quantities. For example, as shown in Figure 3-1, radon, polonium-218, and polonium-214 emit one alpha particle each, for a total of three.

Since, by definition, one picoCurie equates to 2.22 radioactive **disintegrations per minute (dpm)**, one can determine that for each pCi of radon in equilibrium with its short-lived RDPs, there will be a total of 6.66 alpha disintegrations per minute (2.22 dpm/pCi for Rn-222 plus 2.22 dpm each for Po-218 and Po-214).

**Figure 3-1. U-238 Decay**




**Source: NYSEO**

If one could count all the alpha decays occurring within a radon sample of known volume, the concentration (pCi/L) could be derived simply by dividing the total number of alpha **counts per minute (cpm)** by 6.66.

## 1. <u>Counting Efficiency</u>

In reality, radiation detection systems are unable to "see" 100% of all the disintegrations (whether counting alphas, betas or gammas) that would be produced by a given radioactive sample. Different instruments offer varying degrees of **counting efficiency**. Counting efficiency is defined as the fraction of the total radioactive decay events detected and recorded by a radiation detection instrument. It is determined by comparing the number of counts per minute (cpm) a detector is capable of seeing to how many dpm (disintegrations per minute) are actually being emitted from a known activity. For radon/RDP measurements, efficiency may be expressed in cpm per pCi or cpm per dpm.

Once the efficiency is computed, a **calibration factor (CF)** is derived, which is applied to the gross counting rate for converting raw counts per unit time to pCi or WL. Depending on the method, the CF (calibration factor) may vary with the time that has elapsed since the sample was taken.

## 2. <u>Decay Factor</u>

Radon/RDP measurement must account for sample decay rate. Once a sample is collected, and sometimes even while it is being collected, it will begin to decay away at a rate relative to its radioactive half-life. Based on that half-life and elapsed time before analysis, therefore, a **decay factor** must be applied to the measurement calculation. **If the measurement technician improperly records the start/stop date and time of the sampling period, the calculated decay factor will be incorrect and the measurement will be worthless.**

### 3. Background

In addition to determining the gross cpm, counting efficiency, and decay factor, the measurement process almost always includes a correction for **background radiation**. Background activity can be caused by low level ambient radiation, a residue from a previous sample, or even electronic noise within the counter. Background counts must be distinguished from those that are generated only by the sample. To do this, a blank or empty sample is counted and the background cpm are subtracted from the gross cpm of the sample being analyzed, yielding the net cpm attributed to the sample activity.

### 4. Thoron Gas

There is another isotope of radon, radon-220, (sometimes call thoron) which may interfere with some types of radon-222 measurements. The parent isotope for thoron is thorium-232, a primordial element which is widely spread in soils and rocks. Thorium-232 has a half-life of 1.41 x $10^{10}$ years (4.1 billion years) (see Figure 3-2 for the decay chain of thorium-232).

## Figure 3-2. Decay Chain of Thorium

```
Thorium-232
        ↓
Radium-224 (3.62d)
        ↓-----------------→ α
Radon-220 Thoron)(55.6s)
        ↓-----------------→ α
Polonium-216 .15s)
        ↓-----------------→ α
Lead-212 (10.6h)
        ↓-----------------→ β
Bismuth-212 (60.6m)
        ↓-----------------→ β
Polonium-212 (300 ms)
        ↓-----------------→ α
Lead-208 (stable)
```

**Source: BEIRIV**

Usually, about 5% to 10% of the radon in the environment will be the isotope radon-220. This means there is the potential of overestimating the amount of radon-222 in a measurement by inadvertently including the decays from radon-220 (and its decay products) in a radon-222 calculation. Fortunately, the relatively short half-life of radon-220 (55.6 seconds) and the long half-life of lead-212 (10.6 hours) means that radon-220 and its decay products will not interfere in most measurements which sample for radon gas, i.e., grab radon (where counting is delayed for a few minutes, or more, after sampling), continuous radon monitors (where the diffusion time of the radon into the instrument is longer than the half-life of radon-220), and passive integrating devices.

When measuring decay products, however, the long-lived lead-212 in the air being sampled will be collected onto the filter and will subsequently decay into polonium-212, an alpha emitter. Some continuous working level monitors have a built-in correction for subtracting the polonium-216 and polonium-212 contribution, but some do not. For continuous working level devices which do not self-correct and for grab working level devices, a correction can be made by waiting several hours and recounting the filter. The new counts are assumed to be all from the polonium-212, and these counts are used to calculate the radon-220, which is then subtracted from the radon-222 calculated previously (see Ref. 5).

## III. SAMPLING METHODS AND APPLICATIONS

There are three, main, basic methods for radon and RDP sampling:

- Time integrated sampling,
- Grab sampling, and
- Continuous sampling.

### A. Time Integrated Sampling

Due to the time variability of radon and RDP concentrations, it is often desirable to obtain an average concentration over a time period ranging from a few days to a year or more. Devices that sample concentrations over such time periods and average the results are called integrating detectors or instruments. Sample collection may be either passive (no electrical power needed) or active (power needed). Passive integrating devices -- such as charcoal canisters and alpha track detectors (ATDs) -- are particularly useful, because of their simplicity, low cost, and ability to average out short-term variations in concentration. Active integrating devices, such as continuous radon and working level monitors, are able to integrate and track the variation in radon and RDPs.

### B. Grab Sampling

This technique involves collecting a representative air sample from the building over a short period of time, usually only a few minutes. It is essentially an instantaneous measurement: the radon or RDP level found is indicative only of the concentration at the time of sampling. Grab samples are helpful in providing quick feedback during the diagnostic and mitigation processes.

### C. Continuous Sampling

Devices that repeatedly sample over short periods of time, to provide measurement of the variation in radon and RDPs with time, are called continuous monitors. Continuous sampling is used in research and mitigation work, where such feedback on the results of changing certain variables is desirable.

### D. Precautions for All Methods

Given the key role that radon and RDP measurement results play in decisions affecting human health and finances, it is vital to understand the limitations of the measurement process and take every precaution to ensure that measurements are as accurate and reliable as possible.

As described in Unit Two, measurements vary as a result of house conditions. Non-standard procedures used in the measurement process itself (that is, not in keeping with the protocols outlined in Section V and standard precautions) can lead to idiosyncratic results. In addition, there is an inherent lack of precision in the measuring process itself. The limitations of each measurement device must be thoroughly understood by the user and accounted for in interpreting results.

All sampling methods should follow general rules about where and how to sample. These include locating detectors:

- Away from obstructions.
- Away from pets and children.
- Away from heat sources and ventilation ducts.
- In the breathing zone (a minimum of 20 inches from the floor).

## IV. RADON GAS MONITORS AND MONITORING PROCEDURES

### A. Time Integrating (Passive) Devices
B.

#### 1. <u>Charcoal Canisters (Activated Carbon)</u>

Charcoal canisters utilize activated carbon to adsorb radon gas by molecular diffusion into carbon grains, where it decays into the short-lived RDPs (polonium-218 (Po-218), lead-214 (Pb-214), bismuth-214 (Bi-214), and polonium-214 (Po-214)). As shown in Figure 3-1, Bi-214 and Pb-214 are gamma-ray emitters. The radon concentration to which the canisters are exposed, therefore, is determined by counting the gamma-ray emissions of these two RDPs.

All charcoal canisters are initially sealed with a radon proof cover or closure. The measurement is initiated by removing the cover to allow radon-laden air to diffuse into the carbon bed (see Figure 3-3). At the end of the measurement period, the canister is securely resealed and **promptly returned to the laboratory for analysis.** Radioactive decay from the midpoint of the exposure period to the time of analysis is calculated at the laboratory, but if too much time elapses before the can is analyzed, the radon and subsequent RDPs in the carbon bed may decay beyond detection.

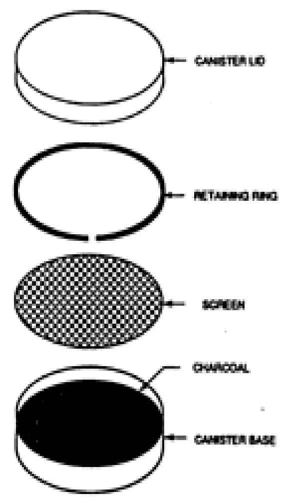
At the laboratory, the sealed canister is analyzed by placing it directly on a gamma spectroscopy system. Such a system usually consists of a sodium iodide detector and photomultiplier tube, shielded by lead to reduce background radiation. The interaction of the gamma-rays produced by the RDPs causes the sodium iodide crystal to emit light pulses. Each light emission is called a scintillation and is sensed by the photomultiplier tube, which produces an electrical pulse whose amplitude is proportional to the gamma-ray energy. The pulse is further amplified by electronics and fed to an analyzer which displays a count rate. The counting efficiency of the gamma spectroscopy system is then determined by counting a calibration standard and dividing the net counts of the detector by the known activity of the calibration standard.

In addition, the laboratory must perform a canister batch calibration to determine the collection efficiency of the canisters themselves. Collection efficiency will vary between canister types and sizes, different batches of charcoal, and the amount of water vapor that can get to the carbon bed. Water vapor in the air will compete with the radon for a place on the carbon grains. The more water adsorbed, the less room there is for radon. Therefore, the higher the relative humidity of the air being sampled, the less sensitive to radon adsorption the charcoal becomes. In some canisters, radon will be adsorbed quickly at first and then more slowly as the moisture takes up more space on the carbon bed. Since the addition of water weight in the carbon changes the rate of radon collection, calibration factors vary depending on the humidity of the air being sampled. To determine these different calibration factors, the laboratory exposes a number of canisters at different humidities and time periods to known radon concentrations in a calibration chamber.

Since the weight gain is indicative of the humidity to which the canister was exposed, measuring the water weight that a canister gains during routine exposures is often necessary to determine which calibration factor must be utilized for calculating the radon concentration.

The 4", open-faced canister, with its charcoal openly exposed, is quite sensitive to radon collection for a two-day exposure. Exposures beyond two days in a high humidity environment rapidly slow the radon adsorption rate, and correction during analysis becomes increasingly more difficult. The optimum exposure period for this style canister is two days. If the canister is placed in areas of extremely high humidity or is exposed longer than the optimum time, so much moisture could be added that the laboratory would be unable to adjust the calibration factor properly. **Do not place charcoal canisters of any type in bathrooms, kitchens, spa rooms, or other areas of high humidity**.

**Figure 3-3. Exploded View of Activated Carbon Canister**




**Source: Burkhart**

Many other canister styles have been designed to make them less sensitive to both humidity and to air velocities across the canister face. Significant air movement across an open-face canister causes it to over respond by increasing the adsorption rate. In 1989, the 4" open-faced canister was modified by inserting a diffusion barrier membrane over the top of the carbon bed. Although the membrane makes this style canister less sensitive to excessive air flows than the open-faced style, **never place any canister near drafts caused by ceiling fans, forced air ducts, etc.**

The diffusion membrane works remarkably well in retarding moisture uptake in the carbon bed, making laboratory adjustments for moisture gain less critical. However, the decreased sensitivity to radon collection caused by the diffusion barrier means this style canister should be exposed for periods of five to seven days in order to collect an adequate sample. For this reason, some laboratories still prefer the open-faced canister, because it works well for a shorter, two-day exposure period.

The passive nature of activated charcoal allows continual adsorption and desorption of radon, while the adsorbed radon undergoes radioactive decay during the exposure period. Charcoal canisters do not truly integrate over time, therefore. Open-faced canisters will be biased to the radon concentration of the last 12 - 24 hours of the exposure period. A diffusion barrier reduces the adsorption/desorption rate of the carbon bed, thus improving integration ability.

**Advantages of Charcoal Canisters**

- Economical.
- Convenient to handle and install.
- Easy to mail.
- Simple to use so skilled operators are not required to place and retrieve the device.
- Measurement periods are short.
- Excellent precision and relatively accurate.

**Disadvantages of Charcoal Canisters**

- Measurements are biased toward the radon concentration of the last 12-24 hours of exposure for the open-faced canister.
- Canisters may be sensitive to temperature, humidity and airflow extremes.
- Sampling periods are limited to a few days.
- Sampling conditions that might adversely affect the measurement may be unknown.

**2. Alpha Track Detectors (AT)**

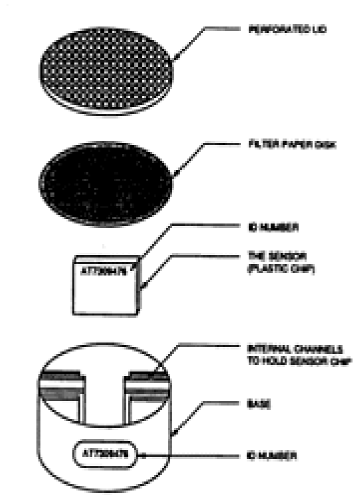
Alpha track detectors consist of a small, alpha-sensitive, plastic chip or cellulose film positioned in a small container (decay chamber) with a membrane filter. The filter allows only radon (not the RDPs) to enter the chamber. However, as radon gas passively diffuses through the filter, radiation damage ("alpha tracks") to the plastic or film results from the subsequent decay of radon and its RDPs (see Figure 3-4).

Alpha track detectors are packaged in an airtight foil bag to prevent exposure during shipping. To collect a sample, the bag is removed to allow air to diffuse through the membrane into the container. After exposure, the detector is resealed and returned to the laboratory for analysis. There, the film is removed from the container and etched by a caustic solution of sodium hydroxide to enhance the damage tracks. The tracks or damage scars can then be counted over predetermined fields, either by a trained technician using a microscope or by a computer image analyzer.

The density (number per area) of tracks is proportional to the radon concentration and is linear over a wide range of exposure durations and concentrations. The average number of tracks per field (unit area) is used to calculate the integrated concentration to which it was exposed. That integrated concentration is expressed in pCi/L-Day and is divided by the total number of exposure days to compute the average radon concentration. Since the number of tracks produced per field per unit of time is proportional to the radon concentration, ATs are true integrating detectors. The lower limit of detection as well as measurement certainty is dependent on the total number of tracks counted. Laboratories will generally analyze enough fields to count at least 100 net tracks. Naturally, the fewer tracks counted, the higher the relative counting error.

The collection efficiency or sensitivity of alpha track detectors is relatively low, requiring exposure for long periods. Typically, such measurements are made for at least 90 days and often up to a year, if the annual average concentration is to be determined. Of course, if the expected radon concentrations are sufficiently high, enough activity may be recorded in shorter periods to provide good counting statistics.

## Figure 3-4. Alpha Track Detector




**Source: Jacobson**

The AT has many of the same advantages as the charcoal canister plus a longer term integrating ability.

**<u>Advantages of Alpha Track Detectors</u>**

- Low cost.
- No need for external power (passive).
- Convenience.
- Unobtrusiveness.
- Easy to mail.
- Simple to use.
- Ability to measure integrated (average) radon concentrations over long periods -- typically 90 days to a year.
- True integration (not biased towards most recent exposure).

**<u>Disadvantages of Alpha Track Detectors</u>**

- Inability to measure for short-time periods unless concentrations are high.
- Relatively large precision error at low concentrations if only a small detector area is counted.
- Sampling conditions during the measurement period that could affect results may be unknown.

The relatively low cost and other advantages of the ATD make it a very popular detector for making both short-term and longer-term measurements.

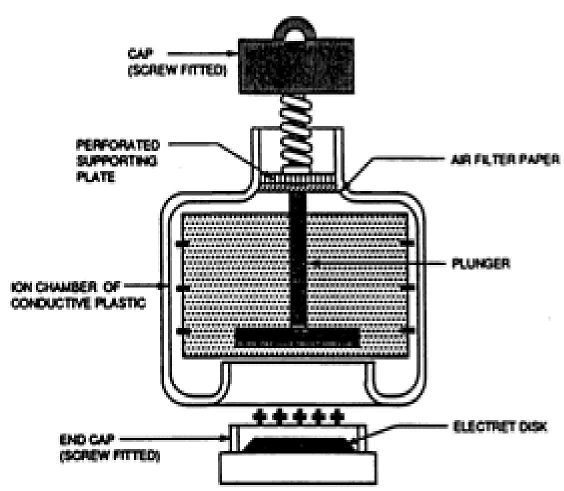
### 3. Electret Ion Chambers (EIC)

Electret Ion Chambers, the most common of which are Electret Passive Environmental Radon Monitors (E-Perms), detect ions produced by the decay of radon as a method of measuring the gas concentration (see Figure 3-5).

Radon in the air is sampled by a small (200 cc), bottle-like collection chamber made of electrically conductive plastic. The chamber is coupled with a charged Teflon disk called an electret to create an electrostatic field. A special voltmeter is used to measure the voltage depletion on the surface of the electret caused by the collection of ions and electrons produced during radon decay. Prior to deployment, the electret is kept covered by a spring-loaded screw cap. Once the cap is released, the disk is exposed to the inside of the collection chamber through several small filtered holes which prohibit the entry of airborne RDPs.

When radon atoms and its RDPs disintegrate, their nuclei emit alpha, beta and gamma particles which pass a short distance through the air. These high energy particles collide with many atoms of oxygen and nitrogen, knocking electrons free from their orbits. A little cloud of free electrons and positively charged oxygen and nitrogen atoms is left in the path of each alpha particle. The charged atoms and electrons (now called positive and negative ions, respectively) are attracted in the electric field established by the electret. Since the face of the electret is positively charged, it attracts the negatively charged free electrons. The shell of the chamber is negative and attracts the positive ions. Every ion that reaches the electret surface depletes the electrical charge of the electret by a small amount.

**Figure 3-5. Basic Features of an EIC Testing Device**




**Source: Jacobson**

The electrostatic charge of the disk is measured both before and after the deployment period. The determination of the specific charge loss for each detector in terms of the radon concentration to which it was exposed is the fundamental calibration factor. **Care must be taken by the technician never to touch the surface of the electret disk itself, to avoid inadvertently depleting its electrostatic charge.**

The electrets can be adversely effected by background gamma radiation at the test site (gamma rays also ionize the air and will penetrate the shell). Average background gamma readings for both lower and higher elevations are available for every state and corresponding correction factors can be subtracted from the measurement calculations. An alternate way to account for this would be actually to take a background gamma reading with a micro-R meter at the test site prior to placement of the EIC.

An electret chamber exposed in a radon environment will typically lose approximately 2 volts of charge per every 1 pCi/L per day of exposure. For example, to calculate the radon for an electret measured at 250 volts prior to placement and remeasured after 2 days at 150 volts:

250 - 150 = 100 volts change

$$\frac{100 \text{ volts}}{2 \text{ volts/pCi/L-day}} = 50 \text{ pCi/L-days}$$

$$\frac{50 \text{ pCi/L-day}}{2 \text{ days}} = \text{average radon } 25 \text{ pCi/L}$$

Two types of electrets are available. The more sensitive short-term disk will be depleted of charge more readily than a less sensitive one which is used for long-term exposures. By utilizing the appropriate electret, EICs can make integrated measurements from 2 days to one year.

**Advantages of EICs**

- They serve as true integrating devices.
- Each electret has the potential for use (depending on the radon concentration to which it was exposed) many times before the voltage is depleted.
- Analysis can be made on-site, using the portable voltage reader and a programmable calculator.

**Disadvantages of EICs**

- The electrets are sensitive to background gamma radiation; a slight error may result if gamma background is not measured and corrected for.
- Excessive humidity can affect the accuracy of the voltmeter.
- A final voltage reading made at much colder or warmer temperatures than the initial voltage reading may result in a slight error when measuring the voltage depletion.

## 4. Charcoal Liquid Scintillation Devices (LS)

Like charcoal canisters, these are passive detectors that utilize activated carbon. A typical device consists of a 20 ml liquid scintillation vial that contains 1 to 3 grams of charcoal. In some cases, the vial contains a diffusion barrier over the charcoal, which improves the uniformity of response to variations of radon concentrations over time. Some LS devices include a few grams of desiccant, which reduces interference from moisture adsorption.

A measurement is initiated by removing the radon-proof closure to allow radon-laden air to diffuse into the charcoal. At the end of deployment, it is resealed and returned to the laboratory, where it is prepared for analysis by radon desorption techniques that transfer a major fraction of the radon adsorbed on the charcoal into a vial of liquid scintillation fluid. The vials of fluid containing the dissolved radon and its RDPs are placed in a liquid scintillation counter and counted for a specified number of minutes.

## B. Radon Grab Samples

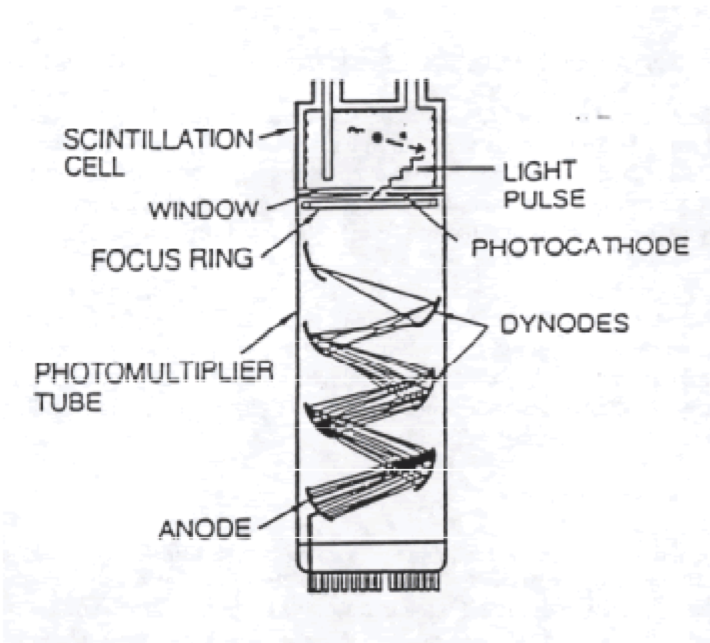
The radon grab sample technique uses an **alpha scintillation cell** (also known as a **Lucas cell**) or flask, ranging in size from about 0.1 to 2.0 liters in volume, with a zinc sulfide phosphor coating on the interior and a counting window on its bottom surface. To prevent RDPs and other background radiation from entering the cell, a filter is attached to the cell's air inlet when filling with a sample of air.

Scintillation cells can be either a single-valve type or a double-valve flow-through type. In preparing them for use, single-valve cells are evacuated with a pump and purged with nitrogen or low radioactivity air several times to reduce background radiation within the cell. Double-valve cells are flushed with nitrogen or low radioactivity air (typically outdoor air). The turbulence from high flow, extended duration flushing appears to enhance cell recovery by removing attached RDPs from cell walls.

To collect a sample with a single-valve cell, a vacuum is created in a low-background cell, then the valve is simply opened to admit air from the sample location. For the double-valve flow-through cell, both valves are opened and an air volume equal to at least 10 cell volumes is pumped through the cell. Both valves are then closed to hold the sample.

For greatest accuracy, the radon sample is allowed to reach secular equilibrium with its RDPs; this requires about a four-hour wait after collection. The cell's clear window is then placed in contact with a photomultiplier tube, in order to count light pulses from the interaction of the alpha particles (emitted from radon and its RDPs) with the zinc sulfide coating. Figure 3-6 shows a schematic of a scintillation cell and photomultiplier tube. A counting system consisting of a scaler/timer, high voltage power supply, and photomultiplier tube is calibrated so that the counting rate is proportional to the radon gas concentration in the cell. Appropriate corrections are made for the time elapsed after the sample was taken and for the actual counting duration. Figure 3-7 depicts a technique for executing count conversions for radon grab samples, while Table 3-1 shows the associated radon decay factors.

**Figure 3-6. Scintillation Cell and Photomultiplier Tube**
**Source: NYSEO**




**Advantages of Radon Grab Samples**

- Quick results are possible.
- Portable or laboratory analysis is possible.
- Radon and RDPs may be sampled simultaneously.
- Several samples can be completed per day.
- House conditions are known to the sampler at the time of measurement.

**COUNT CONVERSIONS FOR RADON GRAB SAMPLE**

This technique uses a calibration factor computed by the following steps:

1. Take a background count. (Measure scintillation cell before sampling.)
2. Take a grab sample of air to be measured.
3. After waiting 4 hours measure the counts of the cell while timing the measurement period. (Generally ten minute or longer to obtain at least 1000 counts in order to reduce inaccuracies.)

Radon is calculated by the following formula:

$$pCi/L = \frac{cpm\ (s) - cpm\ (bkg)}{E} \times \frac{C}{A} \times \frac{1}{V}$$

where:

cpm (s) = the counts per minute measured from the sample or total counts divided by the sample time.

cpm (bkg) = counts per minute of the cell measured when no radon was present

E = Efficiency of cell which is determined by previously calibrating the cell in a known radon environment. This term is expressed in terms of cpm per pCi/L.

A = Correction for the amount of radon decay that has occurred within the sample from the time it was taken to the time it was measured. This can be obtained from radon correction factor tables or mathematically as follows:

$$A = e^{-\lambda t}$$

where: e = natural logarithm
$\lambda$ = radon decay constant = 0.0001258
t = time in minutes between sampling and measurement

C = Correction factor for radon decay that occurs during measurement period. This can be obtained from Table 3-1.

V = Volume of sampling cell

## Figure 3-7. Count Conversions for Radon Grab

Example:
CPM (bkg) = 10 counts measured over 10 minutes or 1 cpm

CPM (s) = 1200 counts over 120 minutes taken 4 hours after sample collection

From previous calibration the system efficiency of detecting available counts in an environment of known radon was 4.62 cpm/pCi/L

Volume of cell from manufacturer is 0.170 liters

From the table, one finds that:

$A = 0.97026$ or $A = e^{-.0001358 \text{ x } 4 \text{ hr x } 60 \text{ min}} = 0.97026$

$C = 1.00757$ (for measuring time of 2 hours)

CPM (bkg) = 10/10 = 1 cpm

CPM(s) = 1200/120 = 10 cpm

Therefore:

$$\text{Radon} = \frac{10 - 1}{4.62} \text{ x } \frac{1.00757}{0.97026} \text{ x } \frac{1}{.170} = 11.9$$

## Figure 3-7 (Continued)

**Disadvantages of Radon Grab Samples**

- Correlation of a short-term grab sample with a long-term average is unknown.
- Skilled samplers and counting system operators are needed.
- House conditions must be controlled for 12 hours before measurement are taken (e.g., doors and windows closed except for normal use).
- System cost is high.

**Source: EPA**

**Table 3-1. Radon Decay Factors**

A = Correction for radon decay from time of collection to start of counting
C = Correction for radon decay during counting

| | A | | | C |
|---|---|---|---|---|
| Time | Minutes | Hours | Days | Hours |
| 0 | 1.00000 | 1.00000 | 1.00000 | 1.00000 |
| 1 | 0.99987 | 0.99248 | 0.83431 | 1.00378 |
| 2 | 0.99975 | 0.98502 | 0.69607 | 1.00757 |
| 3 | 0.99962 | 0.97761 | 0.58074 | 1.01136 |
| 4 | 0.99950 | 0.97026 | 0.48451 | 1.01517 |
| 5 | 0.99937 | 0.96296 | 0.40423 | 1.01899 |
| 6 | 0.99925 | 0.95572 | 0.33726 | 1.02281 |
| 7 | 0.99912 | 0.94864 | 0.26138 | 1.02665 |
| 8 | 0.99899 | 0.94140 | 0.23475 | 1.03050 |
| 9 | 0.99887 | 0.93432 | 0.19586 | 1.03435 |
| 10 | 0.99874 | 0.92730 | 0.16341 | 1.03821 |
| 11 | 0.99862 | 0.92033 | 0.13633 | 1.04209 |
| 12 | 0.99849 | 0.91340 | 0.11374 | 1.04597 |
| 13 | 0.99837 | 0.90654 | 0.09490 | 1.04986 |
| 14 | 0.99824 | 0.89972 | 0.07917 | 1.05377 |
| 15 | 0.99811 | 0.89295 | 0.06605 | 1.05768 |
| 16 | 0.99799 | 0.88624 | 0.05511 | 1.06160 |
| 17 | 0.99786 | 0.87958 | 0.04598 | 1.06553 |
| 18 | 0.99774 | 0.87296 | 0.03836 | 1.06947 |
| 19 | 0.99761 | 0.86640 | 0.03200 | 1.07342 |
| 20 | 0.99749 | 0.85988 | 0.02670 | 1.07738 |
| 21 | 0.99736 | 0.85342 | 0.02228 | 1.08135 |
| 22 | 0.99724 | 0.84700 | 0.01859 | 1.08532 |
| 23 | 0.99711 | 0.84063 | 0.01551 | 1.08931 |
| 24 | 0.99699 | 0.83431 | 0.01294 | 1.09331 |
| 25 | 0.99686 | 0.82803 | 0.01079 | 1.09732 |
| 26 | 0.99673 | 0.82181 | 0.00901 | 1.10133 |
| 27 | 0.99661 | 0.81563 | 0.00751 | 1.10536 |
| 28 | 0.99648 | 0.80950 | 0.00627 | 1.10939 |
| 29 | 0.99636 | 0.80341 | 0.00523 | 1.11344 |
| 30 | 0.99623 | 0.79737 | 0.00436 | 1.11749 |
| 31 | 0.99611 | 0.79137 | 0.00364 | 1.12155 |

| | | | | |
|---|---|---|---|---|
| 32 | 0.99598 | 0.78542 | 0.00304 | 1.12562 |
| 33 | 0.99586 | 0.77951 | 0.00253 | 1.12971 |
| 34 | 0.99573 | 0.77365 | 0.00211 | 1.13380 |
| 35 | 0.99561 | 0.76784 | 0.00176 | 1.13790 |

**Table 3-1 (Continued)**

| | A | | | C |
|---|---|---|---|---|
| Time | Minutes | Hours | Days | Hours |
| 36 | 0.99548 | 0.76206 | 0.00147 | 1.14201 |
| 37 | 0.99536 | 0.75633 | 0.00123 | 1.14613 |
| 38 | 0.99523 | 0.75064 | 0.00102 | 1.15026 |
| 39 | 0.99511 | 0.74500 | 0.00085 | 1.15440 |
| 40 | 0.99498 | 0.73940 | 0.00071 | 1.15854 |
| 41 | 0.99486 | 0.73384 | 0.00059 | 1.16270 |
| 42 | 0.99473 | 0.72832 | 0.00050 | 1.16687 |
| 43 | 0.99461 | 0.72284 | 0.00041 | 1.17105 |
| 44 | 0.99448 | 0.71741 | 0.00035 | 1.17523 |
| 45 | 0.99435 | 0.71201 | 0.00029 | 1.17943 |
| 46 | 0.99423 | 0.70666 | 0.00024 | 1.18363 |
| 47 | 0.99410 | 0.70134 | 0.00020 | 1.18784 |
| 48 | 0.99398 | 0.69607 | 0.00017 | 1.19207 |
| 48 | 0.99385 | 0.69084 | 0.00014 | 1.19630 |
| 50 | 0.99373 | 0.68564 | 0.00012 | 1.20054 |
| 51 | 0.99360 | 0.68049 | 0.00010 | 1.20479 |
| 52 | 0.99348 | 0.67537 | 0.00008 | 1.20905 |
| 53 | 0.99336 | 0.67029 | 0.00007 | 1.21332 |
| 54 | 0.99323 | 0.66525 | 0.00006 | 1.21760 |
| 55 | 0.99310 | 0.66025 | 0.00005 | 1.22189 |
| 56 | 0.99298 | 0.65528 | 0.00004 | 1.22619 |
| 57 | 0.99286 | 0.65036 | 0.00003 | 1.23060 |
| 58 | 0.99273 | 0.64547 | 0.00003 | 1.23481 |
| 59 | 0.99261 | 0.64061 | 0.00002 | 1.23914 |
| 60 | 0.99248 | 0.64579 | 0.00002 | 1.24347 |

**In fact, EPA protocols do not recommend the use of grab samples for follow-up measurements or for pre- or post-mitigation testing.** They are most useful for diagnostic and investigatory measurements.

## C. Continuous Radon Monitors (CRM)

### 1. <u>Alpha Scintillation CRMs</u>

Most CRMs consist of an alpha scintillation cell and photomultiplier tube counting system with timing circuitry and a control system. The CRM sums the number of counts for a predetermined time period, stores the count in memory, then begins a new count for the next time period. (The microcomputer in some models will automatically convert the counts to pCi/L.) This results in a series of short-term averages, reflecting the variations in radon concentration over time. Radon in the air can be sampled either by passive diffusion through a filter to remove RDPs in the cell or by continuously pumping filtered air through the cell. The sensitivity of these instruments typically ranges from 1 count per minute per picoCurie per liter (1 cpm/pCi/L) to as high as 15 cpm/pCi/L, depending on the design.

The CRM runs continuously, recording the integrated radon concentration usually at hourly or half-hourly intervals. A CRM takes several hours to stabilize, so initial data points are normally discarded. This stabilization time is necessary because of:

- The time it takes the air in the chamber to be replaced with the room air.
- The inherent delay in the RDP decay process.
- The equilibration time between the instrument and the temperature and humidity of the room.

As with scintillation cells, the device must be calibrated in a radon chamber, usually semi-annually, and the background count rate should be checked regularly. In addition, pump flow rates must be calibrated to ensure that the volume of air sampled during the measurement period is known.

### 2. Pulsed Ionization Chamber CRMs

Another type of commonly used CRM consists of a pulsed ionization chamber in conjunction with an electrometer and data logger. Ambient air samples are delivered to the internal detector either by passive diffusion or active pumping. RDPs are electrostatically removed and prevented from entering the internal pulsed ion sensing area. (As the initial Po-218 RDPs are created in air as positively charged ions, they are swept away from the sensing volume and collected on the negatively charged cabinet wall. This prevents them and subsequent RDPs from contributing to the counts resulting from Radon-222 decay within the sensing volume.)

As radon gas atoms decay within the sensing volume of the chamber, a burst of ions is produced and converted to electrical pulses. The pulses are counted, stored, displayed by the electrometer and the computerized data logger, and then converted to pCi/L using a calibration factor. The data logger is programmed to subtract a fixed background, which is determined by performing periodic measurements of aged air. The sensitivity of this type of CRM is around 0.3 cpm/pCi/L.

### 3. Solid State Silicon CRMs

A third type of CRM relies on diffusion sampling, using a solid state silicon detector to sense alpha decays. These units output continuous data to a printer and will display the current radon concentration. While not as sensitive as other CRMs (1 to 3 counts per hour/pCi/L), they are gaining acceptance because of their simple operation and comparatively low cost. Care should be taken, however, to allow for exposure periods of sufficient length to obtain adequate counting statistics.

### Advantages of CRMs

- Portability of most types.
- On-site availability of results.
- Relative precision of the data produced.
- Ability to track real time variations of radon concentrations.

- Flexibility of measurement intervals.

**Disadvantages of CRMs**

- Higher cost than other methods.
- Bulk and weight of some models.
- The necessity of regular calibration.
- Requires a skilled operator.
- Pulsed ionization chamber CRMs are somewhat sensitive to humidity.

## V. RADON DECAY PRODUCT MONITORS AND MONITORING PROCEDURES

### A. Time Integrating (Active) Devices

There are no passive RDP integrating monitors similar to the ATD and the AC. While several types of monitors using thermoluminescence detectors (TLDs) were developed in the 1970s to integrate RDPs in houses contaminated with uranium tailings, the fairly recent development of a surface barrier integrating WL monitor has significant advantages.

The surface barrier WL monitor uses an air pump and filter to continuously sample air. The silicon detector measures the alpha decays from the RDPs and provides the RDP concentration in WL based on a calibration factor. The integrating period may be chosen by the user depending upon the application. For short integration periods of 30-60 minutes, the monitor behaves similarly to a continuous WL detector.

**Advantages of the Surface Barrier WL Monitor**

- Provides an integrated RDP measurement.
- Provides high sensitivity.
- Provides on-site measurements.
- Portability.

**Disadvantages of the Surface Barrier WL Monitor**

- Cost.
- Requires trained personnel for operation.
- Requires regular calibration.
- Sampling conditions during measurement period that could affect results may be unknown.

### B. Grab Sampling

RDP grab samples use an air pump to collect RDPs on a filter. The air pump must be calibrated to obtain accurate airflow over the sampling time interval (normally around 5 minutes).

There are several methods used to obtain the RDP concentration in WL, the most common of which is the Kusnetz method. In this method, a sample is taken by a scintillation counting system for about 10 minutes, after which total alpha activity is measured between 40 and 90 minutes. The counting system is quite similar to that used for radon grab samples. The sample collection filter is placed on a tray against a zinc sulfide phosphor disc. The tray is then placed in the counting chamber against the photomultiplier tube counting surface. The photomultiplier tube counts light pulses occurring from the interaction of the alpha decays and the zinc sulfide phosphor.

A calibration-based conversion factor allows the counts collected over the analysis time interval to be converted directly to WL. Depending on the type of detector used, this calibration requires the use of either a standard alpha-emitting source or an RDP sample traceable to a National Institute of Standards and Technology (NIST) standard.

**Advantages of the WL Grab Sample**

- Quick results.
- Portable or laboratory analysis possible.
- Radon and RDP may be sampled simultaneously.
- Conditions are known to the sampler.

**Disadvantages of the WL Grab Sample**

- Limited to short sampling duration.
- Skilled operator needed.
- System cost is relatively high.
- Frequent calibration.

### C. Continuous RDP or WL Monitors

The continuous WL monitor (CWLM) is similar to the integrating WL monitor described above. The RDPs are collected on a filter using an air pump, and the subsequent alpha decays are counted with a silicon surface barrier detector or by alpha scintillation. The measured number of alpha counts in a preselected energy window (2-8 MeV) over a specified time interval are converted directly into WL by means of a calibration factor. The data are stored and/or printed on a regular basis (typically hourly).

**Advantages of the CWLM**

- Relatively quick results.
- Results are obtained on-site.
- Ability to track real-time variation.
- Portability.

**Disadvantages of the CWLM**

- Filter loading (filter surface becomes clogged over time).
- Requires calibration and maintenance.
- Relatively high cost.
- Requires trained operator.
- Sampling conditions during the measurement period which may affect results.

## VI. CONDUCTING MEASUREMENTS

### A. EPA Protocols Overview

The Environmental Protection Agency (EPA) has developed a set of radon/RDP measurement protocols outlining consistent procedures for making reproducible and accurate measurements. These protocols include guidance regarding house conditions, location of equipment or detectors, sampling times, and operating procedures for different types of measuring instruments. Although these are summarized below, persons actually conducting measurements should refer to:

- The specific instrument protocols, which are found in "Indoor Radon and Radon Decay Product Measurement Device Protocols;"
- The measurement strategies, as found in "A Citizens Guide to Radon," Second Edition; and
- The 2 documents "Protocols for Radon and Radon Decay Product Measurements in Homes (U.S. EPA1992c) and "Radon Measurements in Schools."

### B. Categories of Measurements

There are 4 categories of measurements:

- Short-term tests.
- Long-term tests.
- Pre- and post-mitigation tests.
- Diagnostic tests.

#### 1. **Short-Term Tests**

Short-term tests are from 2 to 90 days in duration and are normally used as the initial test of a house, business, or school to determine quickly if the radon levels are sufficiently high to warrant further action. Short-term tests may also be used as a second or confirmatory test, especially if the confirmatory tests results are needed quickly (as in a real estate transaction). The EPA protocols for short-term tests are very specific and must be followed.

#### 2. **Long-Term Tests**

Long-term tests last longer than 90 days and are normally used (1) as a confirmation of an initial short-term test that reported a radon concentration of 4 pCi/L or higher (0.2 WL or higher) and (2) to determine the annual average radon concentration. EPA protocols must be adhered to in administering these tests.

### 3. Pre and Post-Mitigation Tests

Pre-mitigation tests are conducted to establish a baseline radon concentration (and to verify that mitigation is indeed necessary). Post-mitigation testing is done to determine if the mitigation was successful. When the results of the measurements are given to a homeowner to determine the need for further measurements or remedial action, all EPA protocols must be followed. When the results are used only by the mitigator or researcher within the context of their project (for example, in-progress diagnostic measurements), some EPA protocols can be set aside. One example would be the 48 hour minimum sampling time. Shorter sampling times may be used by contractors during in-progress diagnostic measurements.

### 4. Diagnostic Tests

Diagnostic tests are conducted by contractors and/or measurers to help define radon entry points and sources. There are no specific EPA Protocols for diagnostic testing but the instruments must be operated properly.

## C. House Conditions

Any short-term test (tests which are from 2 days to 90 days in duration) must be performed under closed-building conditions. Long-term tests (longer than 90 days) may be done under normal living conditions. Short-term pre- and post-mitigation measurements should follow short-term test protocols, whereas long-term pre- and post-mitigation measurements should follow long-term test protocols. The house conditions for diagnostic measurements are not specific, although common sense would dictate that the house not be ventilated during diagnostic testing and that the house be closed for 12 hours prior to testing for the most representative results.

Closed-building conditions are:

- Windows and outside doors are closed during the test and, if the test is only 2 or 3 days long, for 12 hours before the beginning of the test.
- Short-term tests lasting just 2 or 3 days should not be conducted during unusually severe storms or periods of unusually high winds.
- Internal-external air exchange systems (other than a furnace), such as high- volume attic and window fans, should not be operating during the test and, for tests only 2 or 3 days long, at least 12 hours before measurements are initiated.
- Air conditioning systems that recycle interior air may be operating. Normal operation of permanently installed air-to-air heat exchanges may also continue during closed-house conditions.
- Permanent radon mitigation systems already installed should be functioning during the measurement period.

## D. Measurement Device Location

### 1. Placement Within the House

Both short-term and long-term test devices should be placed in the lowest lived-in level of the home (the basement if it is frequently used, otherwise the first floor). It should be put in a room that is used regularly (like a living room, playroom, den, or bedroom) but not the kitchen or bathroom. The occupants should be notified that if their living patterns change, and they begin occupying a lower level of the house, they should retest the home at that level.

People who are selling their homes should be made aware that a buyer might want the home tested in areas that the seller might not otherwise test (like a basement which they plan to finish).

### 2. <u>Placement Within the Room</u>

The following list may be applied to each of the measurement methods described earlier in section IV. However, there may be method-specific location criteria that are mentioned in the applicable instrument protocol.

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

- The measurement should not be made near drafts caused by heating, ventilating, and air conditioning vents, doors, fans and windows.

- Locations near excessive heat, such as fireplaces, in direct sunlight, and areas of high humidity should be avoided.

- The measurement should not be within 12 inches (30 cm) of the exterior walls of the building but, in no case, closer than 3 feet (90 cm) to windows or other potential openings in the exterior wall.

- The measurement should be at least 20 inches (30 cm) from the floor, 4 inches (10 cm) from other objects, and 12 inches (30 cm) from the ceiling.

## E. Measurement Strategies

There are two general ways to test for radon. The first strategy begins with a short-term test, with this test being placed in the lowest lived-in area of the building and the building closed up. Since radon levels tend to vary from day to day and season to season, a short-term test is less likely than a long-term test to tell you the year-round average. Because a short-term test is done with the building closed up, however, a low reading on a short-term test (done properly) probably means that the annual average will also be low. Consequently, if the initial short-term test is below 4 pCi/L, the EPA's recommendation is only that "the homeowner may want to test again in the future." If, however, the initial short-term test is several times above the action level (for example, 10 pCi/L or higher), the homeowner should take a second short-term test immediately. This follow-up, short-term test should be done under closed-building conditions, with the test placed in the same location as the initial test.

The final step of the first strategy is that the home should be fixed if the average of the two short-term tests are 4 pCi/L or higher. This first strategy is also recommended for real estate transactions, as it allows for a relatively quick determination of whether or not a house should be mitigated.

The second strategy also begins with an initial short-term test placed in the lowest lived-in area (with the building closed-up). If the result of the initial short-term test is at or above 4.0 pCi/L but below 10 pCi/L, a follow-up test is also performed. For this strategy, however, the follow-up test is a long-term test. The long-term test is performed under normal living conditions and the test device is put in the same location as the initial short-term test. The long-term test gives the homeowner a better understanding of the year-round average radon level. If the result of the long-term test is 4.0 pCi/L or more, the home should be mitigated.

# VII. QUALITY CONTROL AND ASSURANCE

There are several causes of uncertainty or variability in radon/RDP measurements:

- The house conditions under which tests are conducted.

- The procedures used to make the measurements.
- The limitations of the measurement process.
- Errors attributable to either monitor limitations or user mistakes.

The measurement technician must understand and recognize these variables and follow quality control standards and operating procedures to define and limit uncertainties as much as possible.

## A. Accuracy and Precision

The quality control procedures and the means for documenting performance should be defined in a written quality assurance plan, aimed at ensuring that measurement data is scientifically sound and of known accuracy and precision.

The accuracy of any one measurement is the difference between the result of the measurement and the actual or true radon concentration. It can also be expressed as a percentage error, by dividing this difference by the actual radon concentration:

True radon = 4.0 pCi/L

Measured radon = 4.1 pCi/L

Accuracy is .1 pCi/L , or .1/4 = 2.5% at 4.0 pCi/L

In its Radon Measurement Proficiency Program (RMP), the EPA requires that all individual measurements of any device be within 25% of the target value in order for the laboratory to be listed for that device. The EPA calculates this accuracy by simply dividing the measured value by the true value (which they call the "Target" value). The resultant quotient is called the performance ratio. Example:

Measured radon = 4.1 pCi/L

Target value = 4.0 pCi/L

$$\text{Performance ratio} = \frac{4.1}{4.0} = 1.025$$

The ±25% accuracy required by the EPA for each reported measurement translates to a performance ratio that must be between .750 (-25%) and 1.250 (+25%) for each individual measurement.[1]

The systematic errors (i.e. the bias) are those errors which are inserted methodically into the measuring process and show up consistently in every reported measurement. For example, if there are ATs improperly stored and already recording enough alpha tracks for a reading of 1 pCi/L (without even being exposed) then, later, when the ATs are used in a house, they will all read 1 pCi/L high. Usually, of course, the bias is not so simply calculated and has to be found by subtracting the average of all the readings from the target value. For example, 5 simultaneous readings are taken of a radon environment:

1) 11.1
2) 11.2
3) 11.3
4) 11.4
5) 11.5

The systematic error, or bias, is the average of these 5 values subtracted by the target value, which is 10.0 pCi/L. First, the average is found:

$$\text{average} = (11.1 + 11.2 + 11.3 + 11.4 + 11.5)/5$$
$$= 11.3,$$

Then, this average is subtracted by the target value:

$$11.3 - 10.0 = 1.3.$$

The bias is 1.3 pCi/L.

[1]Although the EPA only uses the accuracy of each individual measurement in determining whether a device passes or fails the RMP, another meaning of the word "accuracy" is in common usage. In this sense, the accuracy of a series of measurements (for example, 5 simultaneous measurements) of an unknown target value can be calculated by separately calculating the systematic errors (also called bias) and the radon errors. These errors can be combined to give the overall error, a measure of the accuracy, thus;

$$\text{Overall error} = \_(\text{systematic error})^2 + (\text{random error})^2$$

Until this systematic error is located and corrected, it should be assumed that all measurements with this device are 1.3 pCi/L high.[2]

Random (precision) errors are inherent in the limited precision of the measuring device, the operator, and the statistical nature of radiation counting. Sometimes, laboratories will predict that part of the precision which is due to the counting errors, but it should be understood that reporting this part of the precision error does not actually tell the customer the total precision error, nor does it tell any additional bias.

Technically, the precision of a series of measurements is the standard deviation of those measurements. The standard deviation is a statistical measure of the spread of the measurements from their own average. Often, one can estimate the precision of a series of measurements by simply looking at how close the measurements are grouped together. For example, if one were to compare the 2 groups of measurements,

| **Group 1** | **Group 2** |
|---|---|
| 10.1 | 9.1 |
| 10.2 | 10.1 |
| 10.2 | 11.2 |
| 10.3 | 12.3 |
| 10.3 | 13.0 |

One could tell at a glance that group 1 was the more precise, regardless of what the target value may be. The other common usages for precision have evolved and are found in the literature:

1) Precision of a group of measurements can be calculated by finding the coefficient of variation (COV) where:

$$COV = \frac{\text{standard deviation of the measurements}}{\text{mean if the measurements}}$$

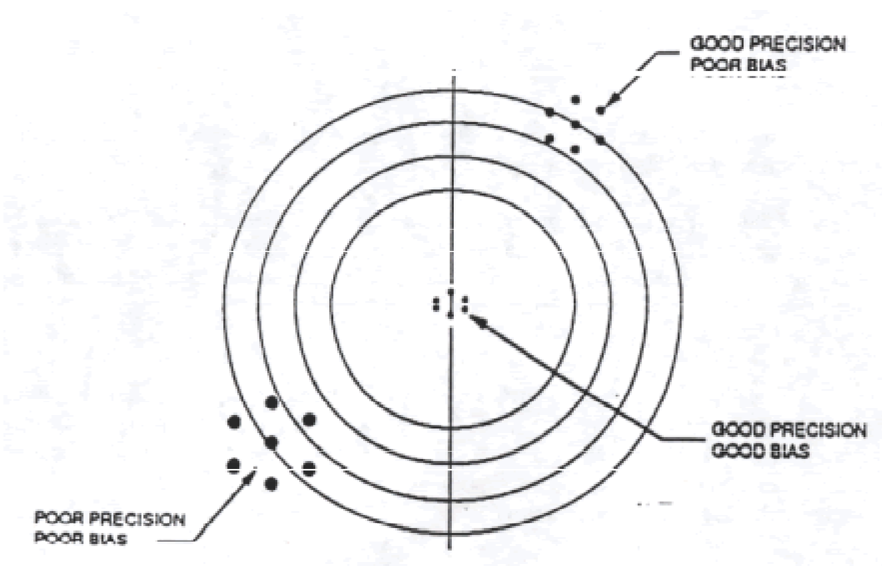
2) For 2 measurements, precision can be calculated from the percent difference, where:

$$\text{Percent difference} = \frac{\text{reading \#1 - reading \#2}}{\text{average of reading \#1 and reading \#2}}$$

[2]Some books will have the bias changed to a percentage by dividing the bias by the target value. This new number is called the relative bias.

Although mathematically imprecise, a useful picture for helping to understand the relationship between precision, accuracy, and bias is found in the following target diagram (Figure 3-8).

**Figure 3-8. Accuracy = Precision + Bias**




**Source: J. Burkhart**

In this analogy, if a person aims a rifle at the "bullseye" on a target and consistently hits the outermost ring at the 2 o'clock position, the precision is excellent, but the accuracy is poor because of the large bias. When the rifle bullets are within the bullseye every time, the rifle is both precise and unbiased, hence there is good accuracy. Finally, the scattered holes at the 7 o'clock position have both a poor bias and a poor precision, resulting in a very poor accuracy.

The precision, bias, and overall accuracy must be controlled. All manufacturers, suppliers, radon analysis laboratories, and commercial users of radon and RDP measurement devices should establish and implement a quality assurance program to do that. Five important elements of any QA plan are described below:

- **Calibration Measurements:** These are samples collected or measurements made in a known radon environment, such as a calibration chamber, and must be conducted to determine the conversion factors used to derive the concentration results. Calibration measurement procedures,including the frequency of such tests and the number of devices to be tested, should be specified in the QA plan.

- **Spiked (Known) Samples**: These apply mostly to passive detectors and consist of known exposures in a radon calibration chamber that are labelled and submitted to the laboratory in the same manner as ordinary samples to preclude special processing. The results of these measurements are used to monitor the **accuracy** of the entire measurement system including the routine performance of personnel. Both laboratory suppliers and secondary placement companies should arrange for the regular introduction of spiked samples for routine analysis as part of their QA plan. Providers of passive measurement devices should conduct spiked measurements at a rate of three per 100 measurements, with a minimum of three per year and a maximum of six per month.

- **Duplicate Measurements:** These are made by exposing two or more detectors side by side to the same conditions and seeing how much they differ. Replicate measurements provide a way to estimate the reproducibility of measurement techniques and determine **precision**. The following table lists acceptable precision errors between duplicate (side by side) measurements for different devices:

  Duplicate measurements should be side-by-side measurements made in at least 10 percent of the total number of measurement locations, or 50 each month, whichever is smaller. The locations selected for duplication should be distributed systematically throughout the entire population of samples. Groups selling measurements to homeowners can do this by providing two measurements, instead of one, to a random selection of purchasers, with the measurements made side-by-side. As with spiked samples introduced into the system as blind measurements, the precision of duplicate measurements should be monitored and recorded in the quality assurance records. The analysis of data from duplicates should follow the methodology described by Goldin in section 5.3 of his report and plotted on range control charts. If the precision estimated by the user is not within the precision expected of the measurement method, the problem should be reported to the analysis laboratory and the cause investigated.

| **Measurement Device** | **Precision Estimate** |
|---|---|
| Charcoal canisters........... | less than 10% |
| Continuous radon monitor..... | less than 10% |
| Electret ion chambers........ | less than 10% |
| Continuous WL monitor........ | less than 10% |
| Alpha track detectors..... | less than 20%, but dependent on the total area of the detector analyzed |
| Grab samples......... | less than 30% |

- **Background Measurements:** Background measurements are made with instruments exposed to very low radon concentration environments (such as outdoor air), or they can be blanks (unexposed passive detectors). Background measurements are of 2 types:

-- Laboratory control blanks are used to establish background levels which are then subtracted from samples before calculating sample concentrations.

-- Field control blanks, are used to uncover problems of shipping and storage. If a constantly high reading above the lower limit of detection (LLD) is found by the field control blanks, this high background must be considered a **bias** and be subtracted from the individual values reported for the other devices in the exposure group. Blank passive detectors should be labelled and submitted as normal samples to verify the quality control of the laboratory.

Providers of passive detectors should employ field blanks equal to approximately five percent of the detectors that are deployed, or 25 each month, whichever is smaller. These controls should be set aside from each detector shipment, kept sealed and in a low radon environment, labeled in the same manner as the field samples to preclude special processing, and returned to the analysis laboratory along with each shipment. The field blanks measure the background exposure that may accumulate during shipment and storage, and the results should be monitored and recorded. The recommended action to be taken if the concentrations measured by one or more of the field blanks is significantly greater that the LLD is dependent upon the type of detector.

- **Sensitivity Checks:** Sensitivity checks are made to determine the LLD for a particular measurement system. Background radiation and inherent instrument design often limit the ability to measure very low concentrations of radon.

Measurement and mitigation firms should maintain a quality assurance plan for all types of measurements and devices used. Mitigators using detectors and analysis provided by an outside vendor should submit spiked, duplicate, and blank samples to their laboratory on a routine basis to verify their accuracy and precision.

## B. Recordkeeping

While protocols certainly go a long way toward standardizing the measurement process, quality control is a larger issue, and one that must be addressed by everyone involved in measurements. Due to differences in equipment operation, manufacturer's instructions should be followed carefully at all times. In addition, a journal or log should be kept which provides detailed, permanent information on both the measuring instrument type and the particular instrument used. Pertinent log information might include:

- Type of instrument used.
- Serial number or identification number of detector.
- Date of last calibration.
- Calibration factor.
- Results of background measurement checks.
- Flow rate calibration.
- Times and dates of measurement beginning and end.
- Exact detector location.
- Observance of standardized building conditions.

- Any house or lifestyle variables that may affect the measurement, such as type of house, type of substructure (basement, crawl space, slab), occupants use of appliances (humidifiers, air filtration units, air conditioners, furnace), etc.

- Any other conditions (such as weather or climate conditions) that may affect the measurement process.

## C. Causes of Uncertainty in Measurements

### 1. <u>Fluctuation in House Radon Levels</u>

As discussed in Unit Two, the levels of radon entering houses can be affected by house conditions. The most important of these include whether:

- The house is closed (doors and windows shut).
- Ventilation fans are off.
- The furnace is on or off.

Even with constant indoor conditions, it is possible for outside weather conditions to affect radon levels. For example, high winds, large barometric pressure changes accompanying storms, and different moisture levels in the soil may temporarily affect radon concentrations in homes. All of these factors affect radon entry. Also, if radon in the water supply is contributing to the radon in the inside air, radon gas concentrations will vary depending on the amount and type of water use.

### 2. <u>Non-Standard Measurement Procedures</u>

House radon levels require time to stabilize after closed house conditions are met. Non-representative measurements may be obtained if this stabilization has not occurred.

Next, the exact location of a given measuring device within a house is important in assuring reproducibility of results. For example, the lower levels in a home usually have higher radon concentrations than do upper levels. Readings taken in bathrooms and kitchens may be affected by turbulence from ventilation and by high humidity.

Elevated concentrations of radon can be found next to exterior walls due to potential high entry rate from floor-to-wall joints. Location of device closer than 12 inches (30 cm) from the outside wall may result in an artificially high reading.

Instruments also need to be calibrated carefully and operated in a consistent and reproducible manner to ensure valid results.

### 3. <u>Imprecision in the Measurement Process</u>

Even if standard measurement procedures are followed, there is an inherent lack of precision in the measurement process itself. For example, statistical accuracy depends on the number of counts taken. When radon levels are low and counting times are short, large uncertainties are the result. In addition, there is background radiation which can be picked up in the measurement process and which may limit a measurement's accuracy. These errors that would occur even with absolutely precise instruments are called sampling errors.

### 4. <u>Operator Error</u>

Common operator errors include misreading the instrument, copying down a wrong number or date, or inadequately accounting for background. It is vital that all measurements be done as carefully as possible following the equipment manufacturer's instruction, and that all pertinent information be written down in a permanent log. In addition to the radon or RDP concentration, separately record background counts, total counts, flow rates, and counting times so data can be reconstructed if an error is made. Only constant vigilance in following protocols and procedures can reduce this type of error.

As the data on radon and RDP variability show, many factors influence measurement in unpredictable ways. To minimize these errors, measurement conditions must be controlled and the inherent capabilities and limitations of the measuring device being used must be understood. Thus, closed-building conditions, bad weather conditions, detector location, and house and lifestyle variables must all be controlled to the extent possible (and recorded) to enhance the accuracy, reproducibility, and interpretation of the measurement process and results.

## VIII. THE RADON MEASUREMENT PROFICIENCY PROGRAM

In February 1986, the EPA established the Radon Measurement Proficiency (RMP) Program to assist the public in identifying organizations capable of providing reliable radon measurement services. Presently, the RMP Program measures the proficiency of organizations and lists them according to their measurement service capabilities. Organizations listed in this report are called Listed RMP Program Participants. A company may offer primary, secondary, or both types of measurement services.

### A. Primary Services

Organizations that offer radon measurement services that include the capability to analyze or read radon measurement devices are defined as "primary" for that device. Radon measurement tests are required for a primary participant to become listed. The test allows participants to demonstrate their ability to analyze accurately the level of radon to which their device(s) was exposed and to report the correct result. Successful participants are listed as proficient for an individual radon measurement device. Participants also will be tested periodically thereafter to maintain their primary listing with a given device.

### B. Secondary Services

Organizations that offer radon measurement services, but rely on another party (a primary) for analysis or reading of the measurement device, are defined as "secondary" for that method. This type of service may include consulting with the consumer, placing and retrieving the measurement device, or providing consumers with measurement results. It does not include over-the-counter retailers of measurement devices. Secondaries are listed by the measurement method they use rather than by device. An EPA measurement method may include a number of specific types of measurement devices.

### C. The Measurement Examination

The Measurement Examination adds to the RMP Program by evaluating the knowledge of individual radon measurement service providers. The addition of this component is necessary, since the quality and reliability of radon measurement services depend on the ability of individual measurement contractors. The examination also evaluates the ability of measurement contractors to provide informed answers to radon questions the public may ask.

The application booklet for the RMP Measurement Examination provides information on EPA's RMP Measurement Examination and how to apply to take it. Applicants should also read and be familiar with the contents of the RMP Handbook (EPA 520/1-91-006, February 1991). The *Application Booklet* is available from RIS at (919) 541-7131.

The examination is administered by EPA Regional Radon Training Centers and State Radon Offices. Most examination offerings are scheduled on a national date once a month. Radon Contractor Proficiency (RCP) Program examinations are often also scheduled at the same location and on the same date, but at a different time.

The Measurement Examination focuses on knowledge of residential radon measurement in six major areas:

- Problem Evaluation.
- Performance of Tests.
- Analysis of Measurements.
- Interpretation of Results.
- Report of Findings.
- Professional Standards of Conduct and Ethics.

Applicants are allowed three and one-half hours to complete the examination, which consists of 150 multiple choice questions. Applicants should have a thorough understanding of all the subject areas in the study guide. If applicants fail the examination, they can retake it the next offered date that is convenient. Applicants are strongly recommended to take a measurement training course before attempting to retake the examination. They may continue to retake the examination until they pass, but they must pay a new fee each time.

EPA strongly recommends, but does not require, that participants take a radon measurement training course before taking the Measurement Examination. The examination is rigorous and may be challenging for those not familiar with multiple-choice examinations. A two-day introductory course on radon measurement is offered by EPA's Regional Radon Training Centers (RRTCs). Other training providers may also offer suitable measurement courses.

EPA recommends, but does not require, that applicants also take eight hours of continuing education per year. Continuing education includes courses and other professional activities that keep participants knowledge about changes in the radon field. Recommended topics include:

- Quality Assurance/Quality Control
- Risk Communication, and
- EPA's Measurement Guidance for Real Estate Transactions.

**D. Proficiency Listings**

There are three types of reports in the RMP Program:

- The State Proficiency Report, which contains information on RMP-listed organizations that provide measurement services to residents of a given State.
- The National Proficiency Report, which contains information on RMP- listed organizations nationwide.
- The Individual Proficiency Report, which contains information on individuals who have passed the RMP Measurement Exam and met other EPA requirements for proficiency in residential radon measurement.

If an applicant chooses to appear in the Individual Proficiency Report, the applicant's name will appear along with company affiliation. The individual is not listed by measurement device or method. These designations are made for the listing of RMP organizations. This report is issued to States, EPA Regional Offices, and RRTCs.

Applicants demonstrate individual proficiency in radon measurement by meeting all of the following requirements:

- Passing the Measurement Examination.

- Passing a biennial (every 2 years) re-examination.

- Meeting existing RMP Organization Level requirements and being affiliated with an organization that has listed status. These requirements include, but are not limited to the following:

  -- Adhering to Measurement Protocols.

  -- Providing services according to Standard Operating Procedures (SOPs) and Quality Assurance Plans (QAPs) of the applicant's listed organization (defined in sections 2.3 and 2.4 of the RMP Handbook).

  -- If offering secondary services, using analytical service from a listed primary organization.

  -- Following RMP Guidelines for reporting measurement results (section 2.8 of RMP Handbook).

- Individuals must maintain their affiliation with an RMP listed organization to retain their proficiency status. They must notify EPA's contractor (ICF Inc.) in writing within 30 days of any change in such affiliation. If the RMP-listed organization with which individuals are affiliated loses its proficiency status, individuals may not use their ID cards or represent themselves as having listed status in the RMP Program until such time as they become affiliated with another RMP listed organization, or their current affiliated organization resumes its listed status.

Upon completing the requirements, participants will be listed and, if they choose, will appear in the Proficiency Reports. At the time of listing, participants will be issued a photo identification card valid for two years. Listed individuals may use this card to represent their EPA-listed status to consumers.

Notice: Some States may have different requirements than those of the RMP Program for radon measurement service providers. Contact your State radon office for additional information on radon and measurement and mitigation services.

## ACTIVITY:

## SELECTING AND PLACING MONITORS FOR SCREENING AND FOLLOW-UP MEASUREMENTS

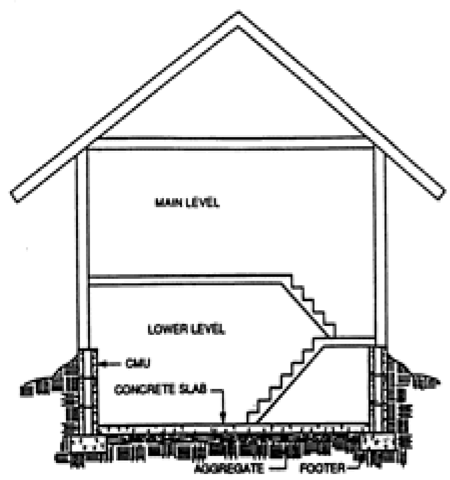
**Directions:** You are hired to conduct short-term and follow-up measurements in the houses pictured on the following pages (see Figures 3-9, 3-10, 3-11, and 3-12). Assume that you own the following equipment: activated carbon, alpha track detector, scintillation cell and photomultiplier.

**1.** What equipment would you use for short-term and follow-up measurements, and why?

**2.** Explain where you would put the monitor and for how long in conducting short-term and follow-up measurements.

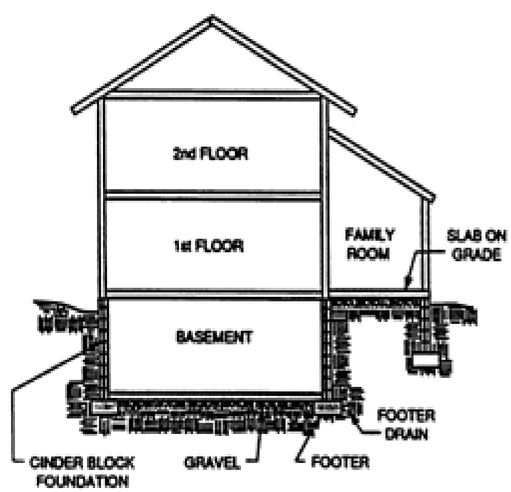
**3.** Cite any precautions you would take to ensure an accurate reading.

**Figure 3-9. Bi-Level House**



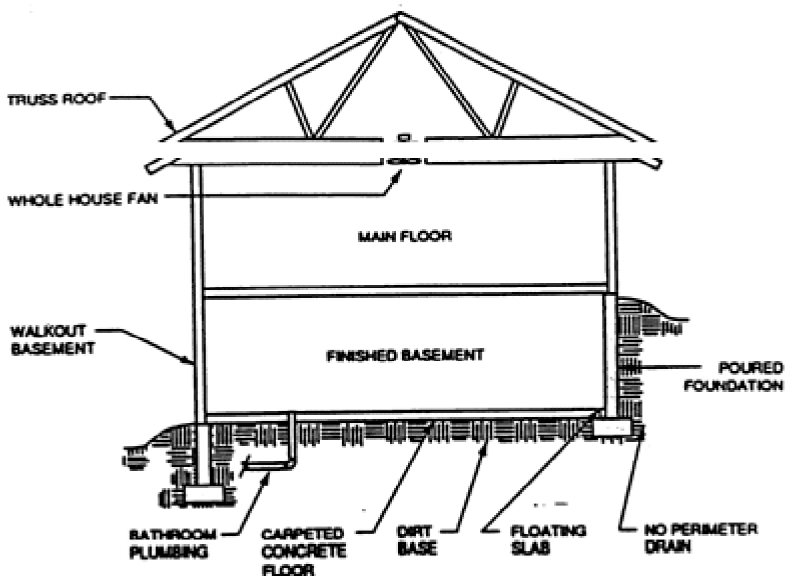

**Source: NYSEO**

**Figure 3-10. 2-Story Colonial**



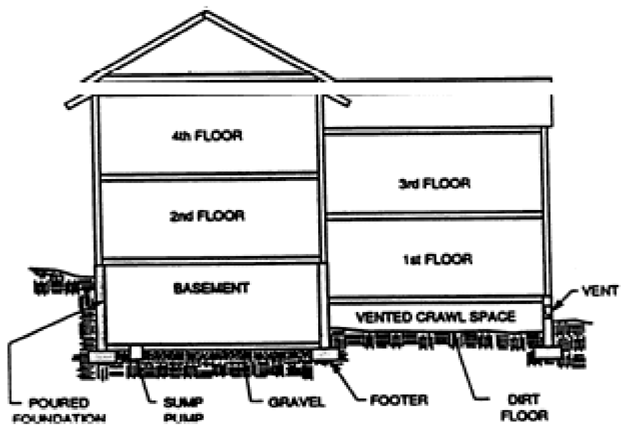

**Source: NYSEO**

**Figure 3-11. Ranch House/Finished Basement**




**Source: NYSEO**

**Figure 3-12. Split Level**




**Source: NYSEO**

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