United States
Environmental Protection
Agency

Air And
Radiation
(6604J)

EPA 402-R-92-003
May, 1993

EPA

Protocols For Radon And Radon Decay Product Measurements In Homes

Printed on Recycled Paper

Protocols for Radon and Radon Decay Product Measurements in Homes

Office of Air and Radiation (6609J)
EPA 402-R-93-003, June 1993

Preface

This document, the Protocols for Radon and Radon Decay Product Measurements in Homes (EPA 402-R-92-003, May 1993), is a guidance document. However, one condition of participation in the Agency's National Radon Proficiency Program (RPP) for radon measurement and radon reduction (mitigation) proficiency, is conformance with these protocols. Conformance with its companion document, the Indoor Radon and Radon Decay Product Measurement Device Protocols (EPA 402-R-92-004, July 1992), is also a condition of participation in the Proficiency Program.

Together these protocol documents provide the technical support for the Agency's radon policy and guidance to consumers that is contained in, but not limited to, the Home Buyer's and Seller's Guide to Radon (EPA 402-R-93-003, March 1993), A Citizen's Guide to Radon (EPA 402-K-92-001), and the Consumer's Guide to Radon Reduction (EPA 402-K-92-003, August 1992).

Table of Contents

Section 1: Introduction

This document presents the U.S. Environmental Protection Agency's (EPA) technical guidance for measuring radon concentrations in residences. It contains protocols for measuring radon for the purpose of deciding on the need for remedial action, as presented in the 1992 *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a), and in the *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993).

The guidance for determining the need for mitigation is different in several key aspects from previously issued recommendations, and this document supersedes a previous report (EPA 520/1-86-014-1) published in February, 1987 (U.S. EPA 1987). The technical basis for these policy changes is supplied in the *Technical Support Document for the 1992 Citizen's Guide to Radon* (EPA 400-R-92-011; U.S. EPA 1992g), and the revised policies are described in *Section 2* of this report.

Section 3 of this report describes the Agency's recommended protocols for measuring radon for a real estate transaction. This guidance elaborates on Agency recommendations published in the *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993). The radon testing guidelines in the *Home Buyer's Guide* were developed specifically to deal with the time-sensitive nature of home purchases and sales and the potential for radon device interference. The guidelines are somewhat different from those in other EPA publications, such as the 1992 *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a), which provide radon testing and reduction information for non-real estate situations. Therefore, *Sections 2* and *3* of this document will have different guidance for different situations.

This report is limited to discussions of Agency guidance regarding detector placement, measurement duration, multiple measurements, and the interpretation of measurement results. EPA has also issued a technical report describing measurement techniques, titled *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004) and published in 1992 (U.S. EPA 1992c). That report provides technical information for measuring radon concentrations with continuous radon monitors, alpha track detectors, electret ion chambers, charcoal canisters, unfiltered alpha track detectors, and grab radon techniques; it also provides guidance for measuring radon decay product concentrations with continuous working level monitors, radon progeny integrating sampling units, and grab radon decay product techniques. Copies of the *Indoor Radon and Radon Decay Product Measurements Device Protocols* may be obtained by contacting your State or EPA Regional radon office (Appendix A) A list of EPA documents providing guidance on radon measurements appears in Exhibit 1-1

* The term "radon" refers to radon-222 and its decay products unless otherwise noted.

Title of Document	EPA Document Number
A *Citizens Guide to Radon* (U.S. EPA 1992a)	EPA 402-K-92-001
Consumer's Guide to Radon Reduction (U.S. EPA 1992b)	EPA 402-K-92-003
Indoor Radon and Radon Decay Product Measurements Device Protocols (U.S. EPA 1992c)	EPA 520-402-R-92-004
Interim Radon Mitigation Standards (U.S. EPA 1992d)	Regional Training Centers (see below)
Home Buyer's and Seller's Guide to Radon (U.S. EPA 1993)	EPA 402-R-93-003
Protocols for Radon and Radon Decay Product Measurements in Homes	EPA 402-R-92-003

*****These documents are available from the U.S. Government Printing Office, Superintendent of Document, Mail Stop: SSOP, Washington, D.C. 20402-9328; from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151; or your State or EPA Regional Radon office.

<u>EPA Regional Radon Training Centers:</u>

Eastern Regional Radon Training Center, Rutgers University; (908)-932-2582.

Southern Region Radon Training Center, Auburn University; (205)-844-6271.

Western Regional Radon Training Center, Colorado State University; (303)-491-7742

Northern Regional Radon Training Center, University of Minnesota; (612)-624-6786

This report provides guidelines that are primarily intended to aid State radiation control programs, other organizations conducting indoor radon measurements, and homeowners who want detailed information on radon measurements. The guidelines herein can be adopted as part of a State program or can be provided by States to interested individuals as recommendations. Adherence to these guidelines was a requirement for participation in EPA's former <u>National Radon Proficiency Measurement Proficiency</u> (RMP) Program (EPA 520/1-91-006; U.S. EPA 1991). The method designations that were used in EPA's former RMP listed in Exhibit 1-2. A two-letter code for each method has been adopted, although ATDs (AT), RPISUs (RP), and EICs/ECs (ES or EL) may still be referred to by their traditional acronyms.

EPA recognizes that radon concentrations in buildings may vary over time (Arvela et.al. 1988, Dudney et.al. 1990, Fleischer and Turner 1984, Furrer et.al. 1991, Gesell 1983, Harley 1991, Hess 1985, Martz et.al. 1991, Nyberg and Bernhardt 1983, Perritt et.al. 1990, Ronca-Battista and Magno 1988, Steck

1992, Stranden et.al. 1979, Wilkening and Wicke 1986, Wilson et.al. 1991). Furthermore, concentrations at different locations in the same house often vary by a factor of two or more (Arvela et.al. 1988, Furrer et.al. 1991, George et.al. 1984, Hess 1985, Keller et.al. 1984, Put and deMeijer 1988, Steck 1992). EPA has carefully evaluated these findings, as well as other factors (EPA 400-R-92-011; U.S. EPA 1992g), and has developed policies for ensuring that the most representative and useful information is supplied by the measurement results. These guidelines may be evaluated periodically and refined to reflect the increasing knowledge of, and experience with, indoor radon.

EPA recommends that initial measurements be short-term tests and performed under closed-building conditions. An initial short-term test, which lasts for two to 90 days, ensures that residents are informed quickly should a home contain very high radon levels. Long-term tests, give a better estimate of the year-round average radon level. The closer the long-term test is to 365 days, the more representative it will be of annual average radon levels.

Exhibit 1-2

Radon and Radon Decay Product Measurement Method Abbreviations		
METHOD CATEGORY	**Abbreviations**	
	Common	**Method**
Continuous Radon Monitors	CRM	CR
Alpha Track Detectors	ATD	AT
Electret Ion Chambers Short Term Long Term	EIC/EC	 ES EL
Activated Charcoal Adsorption Devices (formerly called charcoal canisters)	CC	AC
Charcoal Liquid Scintillation	CLS	LS
Three-day Integrating Evacuated Scintillation Cells		SC
Pump/Collapsible Bag Devices (24 hour sample)		PB
Grab Radon Sampling Scintillation Cells Activated Charcoal Pump-Collapsible Bag		 GS GC GB
Unfiltered Track Detectors	UTD	UT
Continuous Working Level Monitors	CWLM	CW
Radon Progeny Integrating Sampling Units	RPISU	RP
Grab Sampling - Working Level		GW

Section 2: Discussion of Guidelines Presented in EPA's "A Citizen's Guide to Radon"

2.1 Introduction and Summary

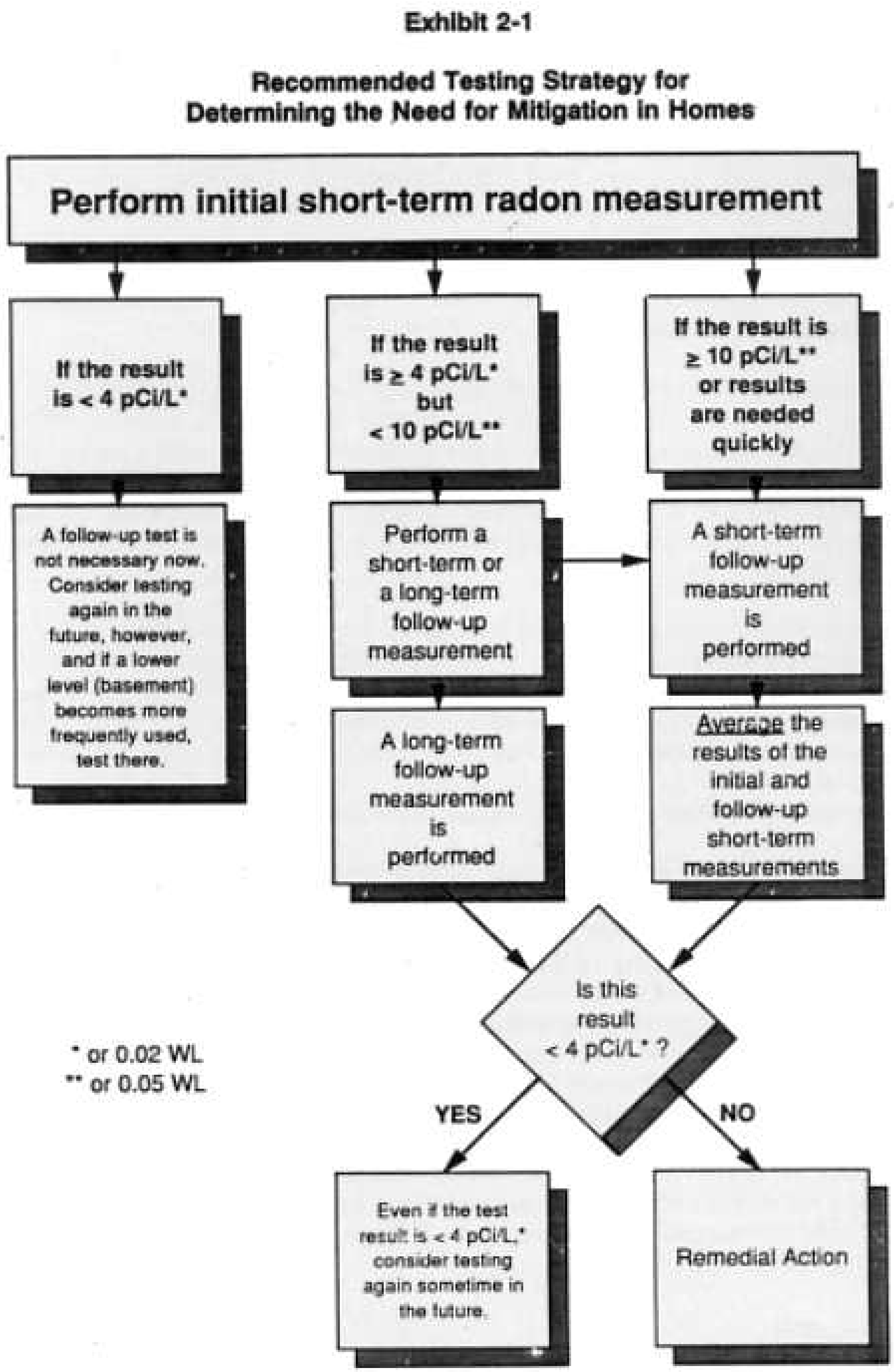
The *Citizen's Guide to Radon* (EPA 402-K-92-001; U.S. EPA 1992a)presents a measurement strategy for assessing radon levels in homes for the purpose of determining the need for remedial action. This measurement strategy is intended to reduce the risk to public health from exposure to radon in air in homes. The strategy begins with an initial measurement made to determine whether a home may contain radon concentrations sufficient to cause high exposures to its occupants.

EPA recommends that initial measurements be short-term tests placed in the lowest lived-in level of the home, and performed under closed-building conditions. An initial short-term test ensures that residents are informed quickly should a home contain very high levels of radon. Short-term tests are conducted for two days to 90 days. Closed-building conditions (*Section 2.3.2*) should be initiated at least 12 hours prior to testing for measurements lasting less than four days, and are recommended prior to tests lasting up to a week.

If the short-term measurement result is equal to or greater than 4 picoCuries per liter (pCi/L), or 0.02 working levels (WL), a follow-up measurement is recommended. Follow-up measurements are conducted to confirm that radon levels are high enough to warrant mitigation. If the result of the initial measurement is below 4 pCi/L, or 0.02 WL, a follow-up test is not necessary. However, since radon levels change over time, the homeowner may want to test again sometime in the future, especially if living patterns change and a lower level of the house becomes occupied or used regularly.

There are two types of follow-up measurements that may be conducted, and the choice depends, in part, on the results of the initial test. An initial measurement result of 10 pCi/L (or 0.05 WL) or greater should be followed by a second short-term test under closed-building conditions. If the result of the initial measurement is between 4 pCi/L (or 0.02 WL) and 10 pCi/L (or 0.05 WL), the follow-up test may be made with either a short-term or a long-term method. Long-term tests are conducted for longer than 90 days, and give a better estimate of the year-round average radon level. The closer the long-term measurement is to 365 days, the more representative it will be of annual average radon levels. On the other hand, short-term tests yield results more quickly and can be used to make mitigation decisions. If the long-term follow-up test result is 4 pCi/L, or 0.02 WL, or higher, EPA recommends remedial action. If the average of the initial and second short-term results is equal to or greater than 4 pCi/L, or 0.02 WL, radon mitigation is recommended. These recommendations are summarized in Exhibit 2-1.

Exhibit 2-1



In certain instances, such as may occur when measurements are performed in different seasons or under different weather conditions, the initial and follow-up tests may vary by a considerable amount. Radon levels can vary significantly between seasons, so different values are to be expected. The average of the two short-term test results can be used to determine the need for remedial action.

The testing strategy policies presented here allow homeowners to decide on the need for mitigation with a high level of confidence that their decision is correct (EPA 400-R-92-011; U.S. EPA 1992g).

2.2 Measurement Location

Short-term or long-term measurements should be made in the **lowest lived-in level** of the house. The following criteria should be used to select the location of the detectors within a room on this level:

- The measurements should be made in the lowest level which contains a room that is used regularly. Test areas include family rooms, living rooms, dens, playrooms, and bedrooms. A bedroom on the lower level may be a good choice, because most people generally spend more time in their bedrooms than in any other room in the house (Chapin 1974, Moeller and Underhill 1976, Szalai 1972). If there are children in the home, it may be appropriate to measure the radon concentration in their bedrooms or in other areas where they spend a lot of time, such as a playroom, that are situated in the lowest levels of the home.

- In general, measurements should not be made in kitchens, laundry rooms, or bathrooms. The measurements should not be made in a kitchen because of the likelihood that an exhaust fan system and changes in small, airborne particles (caused by cooking) may affect the stability of WL measurements. Measurements should not be made in a bathroom because relatively little time is spent in a bathroom, because high humidities may affect the sensitivity of some detectors, and because of the likelihood that use of a fan may temporarily alter radon or decay product levels.

  Although radon in water may be a contributor to the concentration of airborne radon, radon in air should be measured before any diagnostic radon-in-water measurements are made. (Diagnostic measurements may be made in the bathroom; however, such diagnostic measurements should not be used to determine the need for mitigation.)

- 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 heat, such as on appliances, near fireplaces or in direct sunlight, and areas of high humidity should be avoided.

- Because some detectors are sensitive to increased air motion, fans should not be operated in the test area. Forced air heating or cooling systems should not have the fan operating continuously unless it is a permanent setting.

- The measurement location should not be within 90 centimeters (three feet) of the doors and windows or other potential openings to the outdoors. If there are no doors or windows to the outdoors, the measurement should not be within 30 centimeters (one foot) of the exterior wall of the building.

- The detector should be at least 50 centimeters (20 inches) from the floor, and at least 10 centimeters (four inches) from other objects. For those detectors that may be suspended, an optimal height is in the general breathing zone, such as two to 2.5 meters (about six to eight feet) from the floor.

  Sound judgment is required as to what space actually constitutes a room. Measurements made in closets, cupboards, sumps, crawl spaces, or nooks within the foundation should not be used as a representative measurement.

2.3 Initial Measurements

2.3.1 Rationale

EPA recommends that a homeowner assessing the need for mitigation should first make a short-term test. Short-term measurements can be simple, produce results quickly, and allow the public to make decisions about radon reduction that are cost-effective and protective of human health.

The duration of short-term measurements can range from 48 hours to 90 days, depending upon the method used.

2.3.2 Closed – Building Conditions

Short-term measurements lasting between two and 90 days should be made under closed-building conditions. Closed-building conditions are necessary for short-term measurements in order to stabilize the radon and radon decay product concentrations and increase the reproducibility of the measurement. Windows on all levels and external doors should be kept closed (except during normal entry and exit) during the measurement period. Normal entry and exit include a brief opening and closing of a door, but--to the extent possible--external doors should not be left open for more than a few minutes. In addition, external-internal air exchange systems (other than a furnace) such as high-volume, whole-house and window fans should not be operating. However, attic fans intended to control attic and not whole building temperature or humidity should continue to operate. Combustion or make-up air supplies must not be closed.

In addition to maintaining closed-building conditions during the measurement, closed-building conditions for 12 hours prior to the initiation of the measurement are a required condition for measurements lasting less than four days, and are recommended prior to measurements lasting up to a week in duration. Normal operation of permanently installed energy recovery ventilators (also known as heat recovery ventilators or air-to-air heat exchangers) may also continue during closed-building conditions. In houses where permanent radon mitigation systems have been installed, these systems should be functioning during the measurement period.

Closed-building conditions will generally exist as normal living conditions in northern areas of the country when the average daily temperature is low enough so that windows are kept closed. Depending on the geographical area, this can be the period from late fall to early spring. In some houses, the most stable radon levels occur during late fall and early spring, when windows are kept closed but the house heating system (which causes some ventilation and circulation) is not used. Available information about variations of indoor radon levels in a particular area can be used to choose a measurement time when the radon concentrations are most stable.

It may be necessary, however, to make measurements during mild weather, when closed-building conditions are not the normal living conditions. It will then be necessary to establish some more rigorous means to ensure that closed-building conditions exist prior to and during the measurements.

Those performing measurements in southern areas that do not experience extended periods of cold weather should evaluate seasonal variations in living conditions and identify if there are times of the year when closed-building conditions normally exist. Ideally, measurements should be conducted during those times. The closed-building conditions must be verified and maintained more rigorously when they are not the normal living conditions. Air conditioning systems that recycle interior air can be operated during the closed-building conditions when radon measurements are being made. However, homeowners should be aware that any air circulation system can alter the radon decay product concentration without significantly changing the radon concentration.

Short-term tests lasting just two or three days should not be conducted during unusually severe storms or periods of unusually high winds. Severe weather will affect the measurement results in several ways. First, a high wind will increase the variability of radon concentration because of wind-induced differences in air pressure between the building interior and exterior. Second, rapid changes in barometric pressure increase the chance of a large difference in the interior and exterior air pressures, consequently changing the rate of radon influx. Weather predictions available on local news stations can provide sufficient information to determine if these conditions are likely. While unusual variations between radon measurements may be due to weather or other effects, the measurement system should be checked for possible problems.

During any short-term test, closed-house conditions should be maintiained as much as possible while the test is in progress. In test lasting less than four days (96 hours), closed-house conditions should be maintained for at least 12 hours before conditions should be maintained while the test is in progress; while recommended, the 12 hour closed-house conditions should be maintained as much as possible while the test is in progress.

2.3.3 Interpretation of Initial Measurement Results

If the initial measurement result is less than 4 pCi/L, or 0.02 WL, follow-up measurements are probably not needed. There is a relatively low probability that mitigation is warranted if the result is less than 4 pCi/L or 0.02 WL (EPA 400-R-92-011; U.S. EPA 1992g). Even if the measurement result is less than 4 pCi/L, or 0.02 WL, however, a homeowner may want to test again sometime in the future. **If the occupants' living patterns change or renovations are made to the home and they begin using a lower level (such as a basement) as a living area, a new test should be conducted on that level.**

The average year-round residential indoor radon level is estimated to be about 1.3 pCi/L, and about 0.4 pCi/L of radon is normally found in outside air. The U.S. Congress has set a long-term goal that indoor radon levels be no more than outdoor levels. There is some risk from radon levels below 4 pCi/L, and EPA recommends that the homeowner consider reducing the radon level if the average of the first and second short-term measurements or if a long-term follow-up measurement is between 2 and 4 pCi/L (0.01 and 0.02 WL). While it is not yet technologically achievable for all homes to have their radon levels reduced to outdoor levels, the radon levels in some homes today can be reduced to 2 pCi/L or below.

If the result of the short-term measurement is equal to or greater than 4 pCi/L, or 0.02 WL, the occupant should conduct a follow-up measurement using a short-term or long-term test, as described in *Section 2.4.*

2.4 Follow-Up Measurements

2.4.1 Rationale

The purpose of a follow-up measurement is to provide the homeowner with enough information to make an informed decision on whether to mitigate to reduce radon levels. The follow-up measurement, whether it is short-term or long-term, provides an additional piece of information to confirm that radon levels are high enough to warrant mitigation. There are two major reasons why a second measurement is necessary. First and most important, radon levels fluctuate over time (see *Section 1*), and a second short-term measurement, when averaged with the first test result, will provide a more representative value for the average radon level during the period of the test. If a long-term follow-up measurement is conducted, that result should provide an even more representative value for the long-term average radon concentration. The second reason for making a follow-up measurement prior to mitigation is that there is a small chance of laboratory or technician error in all measurements, including radon measurements, and a second test will serve as a check on the first.

Homes tested using the protocol in this section should not be mitigated on the basis of a single short-term test. A follow-up test is necessary for mitigation decision-making regardless of the initial test result.

2.4.2 Short-Term and Long-Term Follow-Up Testing

Follow-up testing should be conducted in the same location as the first measurement (see *Section 2.2*).

A follow-up test can be conducted with either a short-term or long-term measurement device. Long-term tests (> 90 days) will produce a reading that is more likely to represent the home's year-round average radon level than a short-term test. However, if the initial test result is high (for example, greater than about 10 pCi/L, or 0.05 WL) or if results are needed quickly, EPA recommends a second short-term test. This will allow the homeowners to obtain information necessary to decide quickly on the need for mitigation. If the result of the initial measurement is between 4 pCi/L and 10 pCi/L (or between 0.02 WL and 0.05 WL), then either a short-term or long-term test can be taken.

If the long-term follow-up test result is 4 pCi/L, or 0.02 WL, or higher, then EPA recommends remedial action. Likewise, if the average of the initial and second short-term results is equal to or greater than 4 pCi/L, or 0.02 WL, radon mitigation is recommended. These recommendations are summarized in Exhibit 2-1.

As with the initial short-term test, the second short-term test should be conducted under closed-building conditions (*Section 2.3.2*). These conditions, however, are not necessary for long-term tests (those lasting longer than 90 days).

Section 3: Discussion of Guidelines Presented in The *Home Buyer's and Seller's Guide to Radon*

3.1 Introduction

The unique nature of a real estate transaction, involving multiple parties and financial interests, presents radon measurement issues not encountered in non-real estate testing. EPA's objectives for issuing recommended protocols for radon measurements made for real estate transactions are intended to reduce misunderstanding and protect public health in several ways. First, EPA seeks to provide home buyers, sellers, real estate agents, and testing organizations with a common basis of understanding of the recommended procedures for radon measurements. Second, the widespread implementation of this guidance will produce results that are reliable indicators of the need for mitigation. A significant proportion of radon measurements are conducted as part of real estate transactions, and all aspects of these transactions are carefully scrutinized, so specific guidance from EPA can help to ensure good quality measurements. When the results are interpreted properly and the appropriate remedial action is taken, these protocols will assist the buyer and seller in reducing the risk to the occupants from radon exposure. The availability of a nationally-recognized protocol for measurement and for the interpretation of the measurement results will greatly assist home buyers, sellers, real estate agents, builders, lenders, and radon measurement experts.

These protocols are designed for use in residences, as described in the EPA document, *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993). While that document offers general information on radon and testing, this report presents a more technical description of EPA recommendations, including discussion of guidelines for the interpretation of measurement results. As with all of EPA's policies regarding radon measurements, these guidelines have been developed after review and assistance from the radon measurement community and EPA's Science Advisory Board. Technical information on a variety of radon measurement methods is available in the EPA report titled *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; EPA 1992c; these and other EPA publications are available at this web site or from your State or regional EPA office, see *Appendix A*).

The radon testing guidelines in the *Home Buyer's and Seller's Guide to Radon* have been developed specifically to deal with the time-sensitive nature of home purchases and sales. These guidelines are somewhat different from the guidelines in other EPA publications, such as the 1992 *Citizen's Guide to Radon (EPA 402-K-92-001; U.S. EPA 1992a)*, which provide radon testing and reduction information for non-real estate situations.

There are also guidelines in the *Home Buyer's and Seller's Guide to Radon* to deal with the potential for rason test interference. There are approaches that can be used to increase confidence in measurement results by detecting measurements interference. For example, a device that offers a variety of ways to detect tampering may serve to deter as well as detect interference with the device's operation or with proper closed-building measurement conditions. Potential tampering indicators include the ability to a device to record changes in radon levels, temperature, and humidity, or to detect movement of or around the device during the measurements. Refer to section 3.5 for information and recommendations for the interference-resistant testing.

EPA investigated a variety of options for real estate testing. EPA recommends testing in advance of putting the house on the market. A long-term test, which is conducted for longer than 90 days, gives the most representative indication of the annual average radon concentrations in a home. However, for time-sensitive real estate transactions, the *Home Buyer's Guide* offers three short-term testing options. Short-term tests are conducted from two days to 90 days, depending on the measurement device. Based on extensive quantitative analyses to evaluate the frequency with which long-term and short-term testing results lead to the same mitigation decision, EPA and its independent Science Advisory Board concluded that short-term tests can be used to assess whether a home should be remediated.

The reliability of each radon measurement made for a real estate transaction, or for any purpose, is highly dependent upon the existence and documentation of an adequate quality assurance program implemented by both the tester and the analysis laboratory. All the parties involved in the real estate transaction depend upon the testers doing their job. This includes ensuring that the measurements are valid via the performance of quality control measurements and activities, and detecting measurement interference. The protocols outlined in this section were developed by EPA for testers and homeowners adhering to the quality assurance practices summarized in *Section 4.4* of this report, and in EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c).

Three options were determined to be satisfactory and are described here. The availability of three options will allow flexibility on the part of the party purchasing the test. Each of these options will produce results that can be used to determine the need for mitigation.

Both Options 1 and 2 require the use of two measurements made for similar durations. Both measurements should report results in units of pCi/L or both in WL. Similar durations means that the two measurements must be made for a similar time period, with a two-hour grace period. Specific information on measurement methods (listed in Exhibit 3-1) can be found in EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c).

Exhibit 3-1

Radon and Radon Decay Product Measurement Method Categories

A (pCi/L)		**B (WL)**	
AC	Activated Charcoal Adsorption integrating	RP	Radon Progeny Sampling unit
AT	Alpha Track Detection	CW	Continuous Working Level Monitoring
LS	Charcoal Liquid Scintillation		
CR	Continuous Radon Monitoring		
PB	Pump-collapsible Bag		
SC	Evacuated Scintillation Cell (three-day integrating)		
EL	Electret ion Chamber: Long Term		
ES	Electret ion Chamber: Short Term		
UT	Unfiltered Track Detection		

3.2 Options for Real Estate Testing

3.2.1 Option 1: Sequential Testing

Sequential tests should be conducted under conditions that are as similar as possible, in the same location, and using similar devices and durations. Both should produce results in the same units (pCi/L or WL). That is, both methods should be from column A or both from column B of Exhibit 3-1. Any EPA-recognized method may be used. In addition, the results of the first test should not be reported prior to making the second measurement; both measurements should be reported at the same time in order to discourage tampering that may occur if the first test is known to be greater than 4 pCi/L or 0.02 WL. Note that measuring with different methods (e.g., with AC and ES) may increase the potential for differences (e.g., measurement bias) between the results. The results of both measurements should be reported, and the average of the two results should be used to determine the need for mitigation. There will be some variation between the two results, which may be caused by the radon levels fluctuating in response to weather or other factors. If the variation is unusually large, it may be due to weather or other effects, but the measurement system should be checked for possible problems.

3.2.2 Option 2: Simultaneous Testing

This option involves the use of two tests, conducted simultaneously and side-by-side, made for similar durations, and producing results in the same units (i.e., both methods should be from column A or both should be from column B of Exhibit 3-1). Any EPA-recognized method may be used. As with Option 1, using different methods for the two measurements (for example, ES and LS) may increase the potential for differences between the two results. The two test results should be averaged to determine the need for remedial action. The collocated devices should be placed four inches (10 centimeters) apart.

Because radon measurements, like any measurements, usually do not produce exactly the same results, even for simultaneous testing, there will usually be a difference between the two results. EPA offers the following guidance to testers for judging when two simultaneous, side-by-side measurements disagree to such an extent that two additional measurements should be performed.

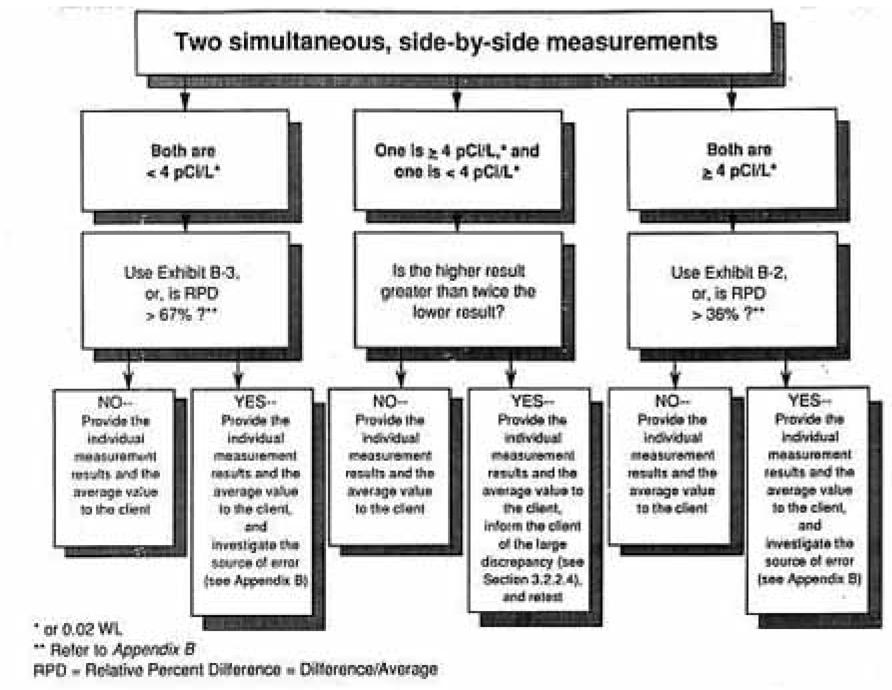
The results of the simultaneous measurements will fall into one of the three categories discussed below and illustrated in Exhibit 3-2.

3.2.2.1 Both Measurement Results Equal To or Greater Than 4 pCi/L (or 0.02 WL)

In this case, the average of the two results will be equal to or greater than 4 pCi/L, or 0.02 WL, and mitigation is recommended. The tester should report both measurement results as well as the average of the two results.

Exhibit 3-2

Deciding on a Retest When Measurements Vary Significantly



3.2.2.2 Both Measurement Results Less Than 4 pCi/L (or 0.02 WL)

In this case, the average of the two measurements will be less than 4 pCi/L, or 0.02 WL, and both measurement results and the average result should be reported to the client.

3.2.2.3 One Measurement Result Greater Than 4 pCi/L (or 0.02 WL), and One Measurement Result Less Than 4 pCi/L (or 0.02 WL)

This is a special situation in which the average of the results is critical. To assist testers in ensuring that the difference between two measurements is small enough so that clients may have confidence in, and understand, the results, EPA offers the following simple guidance.

If the higher result is twice or more the lower result, then the two results are not within a factor of two, and a retest should be conducted. *Section 3.2.2.5* provides language for informing the client that a retest is warranted.

If the higher result is less than twice the lower result, then the two results are within a factor of two, and a retest is not necessary. The results of both measurements and the average of the two results should be reported to the client. (See Section 4 for more detailed information on quality assurance and quality control procedures.)

3.2.2.4 Precision Recommendations

Measurements near the lower limit of detection (LLD) for the measurement system often have large and varying precision errors, and it is difficult to assign any sort of probability level to very low results.

Simultaneous measurement results that are equal to 4 pCi/L, or 0.02 WL, or greater should, however, exhibit some agreement. An example control chart for the precision that may be expected is shown as Exhibit B-2 in *Appendix B*, which was constructed using an average relative percent difference of 14 percent. (Relative percent difference is defined as the difference divided by the average.) Using Exhibit B-2, a relative percent difference greater than 36 percent should be observed less than one percent of the time. Based upon this, EPA recommends that any side-by-side, simultaneous measurements with results greater than or equal to 4 pCi/L, or 0.02 WL, and which exhibit a relative percent difference greater than 36 percent, be cause for informing the client that the two results do not show good agreement. However, since both results are greater than 4 pCi/L, or 0.02 WL, EPA recommends mitigation in this case. Testers should investigate the source of the error (see *Appendix B*).

Results between 2 pCi/L (or 0.01 WL) and 4 pCi/L (or 0.02 WL), should also exhibit some agreement. The level of agreement expected should be based upon the tester's experience with duplicate measurements made with that technique in this range of radon concentrations. An example control chart for the precision that may be expected in this region is shown as Exhibit B-3 in *Appendix B*, which was constructed using an average relative percent difference of 25 percent. Using this chart, a relative percent difference between duplicates greater than 67 percent should be observed less than one percent of the time. Based upon this, EPA recommends that any side-by-side, simultaneous measurements with results less than 4 pCi/L, or 0.02 WL, and which exhibit a relative percent difference greater than 67 percent, be cause for informing the client that the two results do not show good agreement, but that both are less than 4 pCi/L, or 0.02 WL, and therefore mitigation is not recommended. Testers should investigate the source of the error (see *Appendix B*).

3.2.2.5 Recommended Language for Informing the Client that a Retest is Warranted

If a retest is warranted (see *Section 3.2.2.3*), EPA recommends that the tester inform the client that EPA provides guidance for how well two measurements should agree, that the measurements performed fall outside the range, and that a retest should be conducted. A retest should consist of measurements performed according to one of the protocols outlined in *Sections 3.2.1, 3.2.2,* or *3.2.3.*

3.2.3 Option 3: Single Test Option

This option requires an active continuous monitor (method CR or CW) that has the capability to integrate and record a new result at least hourly. Shorter integration periods and more frequent data logging afford greater ability to detect unusual variations in radon or radon decay product concentrations. The minimum measurement period is 48 hours. The first four hours of data from a continuous monitor may be discarded or incorporated into the result using system correction factors (EPA 520-402-R-92-004; EPA 1992c). There must be at least 44 **contiguous** hours of usable data to produce a valid average. (The "backing out" of data [i.e., removal of portions imbedded in the two days] to account for weather or other phenomena will invalidate the measurement.) The periodic results should be averaged to produce a result that is reported to the client.

If the monitor cannot integrate over a period of one hour or less then an additional (secondary) passive or active measurement device must be used. The second measurement, which may be made with a passive or active device, can be used simultaneously or sequentially, as discussed in Option 1 and 2 (Sections 3.2.1 and 3.2.2). If the two measurements are performed simultaneously, their results should be evaluated following the guidance in Section 3.2.2 If these two results will be different. As discussed in Section 3.2.1, the difference between sequential tests may be due to radon levels fluctuating in response to weather or other factors.

In general, confidence in a radon measurement can be increased by performing another measurement with a second measurement device. However, there are other approaches or features that can be used to increase the confidence of a measurement results obtained using active monitor devices. These approaches include the use of device self-diagnostic features and data validation or verification procedures, that could be employed before and/or after the measurement. Example of such approaches are the use of check sources before and after each measurement, and use of spectrum readouts. These capabilities are examples, and different technologies may be able to perform other similar self-diagnostic or quality assurance checks. Other features that increase the confidence of a single active test include (but are not limited to) the ability to check air flow rates and voltage meters before and after each measurement. Measurement companies should incorporate such checks into their routine instrument performance checks as part of their standard operating procedures.

Additional features that can increase confidence in measurement results are those that detect measurement interference; these features are discussed in *Section 3.5*. For example, a devise that offers a variety of ways to detect tampering may serve to deter, as well as detect, interference with the device's operation or proper closed-building measurement conditions. Potential tampering indicators include the ability of a device to record changes in temperature, humidity, or movement of or around device during the measurement.

Instruments with greater efficiency or sensitivity, or a high signal-to-noise ratio (see *Glossary* for definitions of these terms), can achieve results with a smaller uncertainty than instruments with low efficiency, poor sensitivity, or low signal-to-noise ratio. Greater efficiencies, sensitivities, or a hight signal-to-noise ratio may also facilitate tempering detection by being more sensitive to fluctuations in radon levels. There have been recommendations for setting minimum efficiency standards for active decices at 16 counts per hour per hour per pCi/L. EPA plans to conduct research to establish minimum standards in the future for all categories of devices, passive as well as active detectors. The reliability of any type of equipment, however, needs to be established and documented via a complete quality assurance program. This includes routine instrument performance checks prior to and after each measurement, annual calibrations, semi-annual instrument cross-checks, the performance of duplicate measurements in 10 percent of the measurement locations, and frequent background and spiked measurements.

3.3 Measurement Location

EPA recommends that measurements made for a real estate transaction be performed in the **lowest level of the home which is currently suitable for occupancy**. This means the lowest level that is currently lived-in, or a lower level that is not currently used (such as a basement, which a buyer could use for living space without renovations). Measurements should be made in a room that is used regularly, such as a living room, playroom, den, or bedroom. This includes a basement that can be used as a recreation room, bedroom, or playroom. This provides the buyer with the option of using a lower level of the home as part of the living area, with the knowledge that it has been tested for radon.

3.4 Measurement Checklist

EPA presents the following checklist to help ensure that a radon measurement conducted for a real estate transaction is done properly. The seller, or an EPA-listed or State-listed tester should be able to confirm that all the items in this checklist have been followed. If the tester cannot confirm this, another test should be made.

Before the radon test:

- Notify occupants of the importance of proper testing conditions. Give occupants written instructions or a copy of the EPA *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993), or a State-required alternative, and explain the directions carefully.

- The radon measurement service and device should be listed by EPA's National Radon Measurement Proficiency (RMP) program (EPA 520/1-91-006; U.S. EPA 1991) or listed by your State. Follow the manufacture's instructions that come with the device.

- The radon measurement equipment used should be listed by some proficiency organization or listed by your State. Follow the manufacturer's instructions that come with the device.

- If a testing professional conducts the test, only EPA-listed or State-listed individuals should be hired. Their photo identification should be provided to the client or homeowner at the time of, or before, the test, and the contactor's identification number should be clearly visible on the test report.

- The test should include method(s) to prevent or detect interference with testing conditions or with the testing device itself.

- Conduct the radon test for minimum of 48 hours. Some devices must be exposed for longer than the 48-hour minimum.

- In homes with an active radon reduction system, check that the fan is running at least 24 hours before starting a short-term test lasting less than four days. Air exhaust fans that typically operate for short periods (e.g., bathroom fan) may be used during the test.

- EPA recommends that short-term radon testing, which lasts for no more than a week in length, be done under closed-building conditions. Closed-building conditions means keeping all windows closed, keeping doors closed except for normal entry and exit, and not operating fans or other machines that bring in air from outside. Note that fans that are part of a radon reduction system or small exhaust fans operating for only short periods of time may run during the test.

- When doing short-term testing lasting less than four days, it is important to maintain closed-building conditions for at least 12 hours before the beginning of the test and for the entire test period. Do not operate fans or other machines that bring in air from the outside.

During the radon test:

- Maintain closed-building conditions during the entire time of a short-term test, especially for tests shorter than one week in length.

- Operate the home's heating and cooling systems normally during the test. For tests lasting less than one week, only operate air conditioning units that recirculate interior air.

- Do not disturb the test device at any time during the test.

- If a radon reduction system is in place, make sure the system is working properly and will be in operation during the entire radon test.

After a radon test:

- If a high radon level is confirmed, fix the home. Pages 21 to 23 of EPA's *Home Buyer's and Seller's Guide to Radon* (EPA 402-R-93-003; U.S. EPA 1993) recommends the next steps that should be taken, such as contacting a qualified radon reduction contractor to lower the home's radon level.

- The radon tester or homeowner should be able to verify or provide documentation asserting that testing conditions were not violated during the testing period.

3.5 Interference-Resistant Testing

EPA strongly encourages the use of radon testing devices with interference-resistant features inherent in, or associated with, the device.

Interference with a radon measurement is defined as the altering of test conditions prior to or during the measurement to either change the radon or decay product concentrations or alter the performance of the measurement equipment. The following discussion reviews some of the types of test interferences and methods of detecting and preventing such interferences.

Test interference typically causes measurement results to be different than if all proper test conditions were maintained. False low results have been primarily associated with testing during a real estate transaction, although they also happen when the occupants of the dwelling are not properly informed about the necessary test conditions. Test interference can also inadvertently increase measurement results, although the intent is to lower the results.

The current occupant may have an interest in the test results being as low as possible to avoid hindering the sale of the dwelling or incurring the added expense of having to install a mitigation system. The potential for test interference puts the professional radon tester into the position of verifying that the equipment and the required test conditions have been maintained. A measurement result that is below the action guideline may be suspect if the tester cannot verify that the necessary test conditions were maintained.

If the tester arrives at a property and finds windows or doors open, or suspects that closed-building conditions were not maintained for 12 hours prior to arrival, then the tester should extend the test to account for this condition.

3.5.1 Influencing Test Area Concentration

The primary method of temporarily reducing radon levels is to ventilate the test area with outdoor air. Ventilation will slow down radon entry by both reducing negative pressure in the test area and by diluting the reduced radon concentration. Even small openings of a single window in the test area can have a large effect. Ventilating the floors above the test area has significantly less effect, unless the test area is connected with the ventilated room(s) by an operating central air handling system.

Radon decay product levels are sensitive to air movement. As air movement increases, decay products will plate out on walls and other surfaces, including fans, thereby reducing airborne decay product concentrations. Decay products will be further reduced if the fan also includes a filter. Radon levels are, however, not affected by filtering or air movement.

It is also possible to alter concentrations in a tight room if the heating system is operating in an abnormal fashion. Since this may not be the typical operation of the system, it is, in effect, interfering with normal house conditions.

It is important to recognize that test interference can increase radon or decay product levels, despite intent to lower the results.

3.5.2 Equipment Interference

The primary method of interfering with testing equipment is to move the detector to an area of low radon concentration. Other types of interference vary in their ability to influence different types of detectors. For example, interfering with the air sampling mechanisms can maintain the radon concentration at the time of interference, or cause a large decrease in the reported concentration.

Similarly, covering a decay product or charcoal detector could cause a large drop in the reported values, while other types of radon detectors would only show a reduced response time to changes in the test area level. In addition, charcoal detectors are sensitive to heat. Some active radon monitors and open face charcoal canisters are also sensitive to high humidity. Any detector that yields a single result could be turned off or sealed in its container or lid during most of its exposure period.

3.5.3 Preventing Interference

EPA recommends that a radon measurement conducted for a real estate transaction be performed using tamper-resistant testing techniques. It is more advantageous for the tester to take steps to prevent interference rather than to simply detect it. Preventing interference can best be accomplished by:

- Educating the parties to a real estates transaction about the necessary test conditions.

- Including in standard documentation for each measurement an agreement signed by the parties involved in the real estate transaction listing the necessary test conditions and their agreement not to interfere with the conditions.

  The agreement should also state that the tester in their discretion may nullify the test results were rendered unreliable.

- Informing the client that interference with the test conditions may increase the radon levels.

- Informing the client that the tester is using interference-detecting techniques, and that these allow the detection and documentation of test interference.

3.5.4 Interference-Resistant Detectors

The following is a partial list of common equipment and measures that can serve to prevent and/or detect test interference. There may be other methods available. Equipment that offers a combination of tamper-detecting features also offers a greater chance of detecting interference.

- The ability to integrate and record frequent radon measurements over short intervals (an hour or less) is an important tamper detection feature. Continuous (active) monitors that provide frequent measurements can indicate unusual concentration changes that can be indicators of test interference.

- Measuring other parameters may provide additional indicators of test interference, such as a detector tilt indicator or a continuous recording of pump flow rate.

- A motion indicator can also indicate when the detector was approached or moved.

- A simultaneous, several-day continuous measurement of both radon and decay product concentrations will produce a series of equilibrium ratio values. These values can be inspected for unusual swings or abnormal levels, possibly indicating interference.

- Measurement of CO_2 levels can indicate changes in the test area infiltration rate of outdoor air.

- The performance of a grab radon measurement, a grab decay product measurement, or both, before and after a longer-term measurement can offer useful information. For example, the initial and final concentrations and equilibrium ratios can be compared for consistency. Note: The results of measurements lasting less than 48 hours (e.g., grab samples) should not be used as the basis for deciding to fix a home.

- Frequent temperature readings may help to indicate changes in the test area infiltration rate of outdoor air.

- Humidity (as well as temperature) recordings can be especially helpful in identifying potential unusual changes in test conditions that occur during the test period that might not be detected simply through data logging.

- Instruments that do not allow occupants to view preliminary results (via a visible printer or screen) may reduce occupants' interference.

- Placement indicators can also indicate if a detector has been tampered with or moved. The position of the detector should be noted so that, upon retrieval, any handling of the detector can be indicated by a change in its position. A detector may be hung or placed slightly over the edge of its support to discourage covering it. Passive detectors may be hung or suspended in a radon-permeable bag that uses a unique strap and seal to prevent removing or covering it. Cages can be equipped with a movement indicator to deter handling of the cage or the detector within it.

- Seals can aid in detecting and discouraging test interference, and they are especially important in the absence of other tamper detection. Non-sealable caulks and/or tapes can be used to verify that detectors have not been opened. Seals alone will not prevent excessive ventilation through primary doors.

  Seals should be placed on the lowest operable windows and non-primary exterior doors, as well as between the detector and its support and any other components of the detector that could be tampered with. It may be advisable to attach to the caulk seal something fragile that protrudes out, to indicate any handling or covering of the detector.

A number of different products or combination of products can be used for tamper seals. For a seal to be effective, it needs at least the following unique qualities:

- The seal must adhere readily to a multitude of surfaces, and yet be easily removed without marring the surface.
- It needs to be non-resealable or show evidence of disturbance.
- It must be unique enough to prevent easy duplication.
- It should be visible enough to discourage tampering.

The tamper resistance of the seal can be increased by using a caulk over the seal edges or by slicing a large portion of the center of the seal to ensure the seal is broken in case of tampering. Most paper or plastic tapes and caulks have only some of these qualities. There are, however, a number of seals manufactured specifically for radon testing. It would be advisable to use one of these products and follow the manufacturer's installation recommendations. The best caulking to use as a seal is a removable weatherstripping caulk. This type of caulking adheres readily to most surfaces, yet comes off easily without leaving a mark or being resealable. Upon retrieval of the detector, the tester should carefully inspect the following:

- That all closed-building conditions are still being maintained;
- Any changes in the detector placement;
- The condition of all seals; and
- Any abnormal variations in any of the measurements made.

This information should be recorded, as described in *Section 4.3.5*.

Section 4: General Procedural Recommendations

4.1 Introduction

This section outlines basic procedural recommendations for anyone involved in the measurement of radon in homes for both real estate and non-real estate related measurements.

4.2 Initial Client Interview

Reasonable efforts should be made to determine whether the home is new and/or occupied, and who will be in charge of the home during the measurement period. Testing organizations should inform the client and other parties to the real estate transaction of:

- The appropriate EPA testing recommendations as outlined in this report, the 1992 *Citizen's Guide to Radon* (EPA 402-k-92-001; U.S. EPA 1992a) , or the *Home Buyer's and Seller's Guide to Radon*;(EPA 402-R-93-003; U.S. EPA 1993); and,

- The types of devices they will be using for that test, and EPA documentation indicating that the testing organization or individual is RMP-listed for that device

4.3 Measurement Recommendations

4.3.1 Selecting a Measurement Approach

The purpose of the measurements, as well as budget and time constraints, dictate the protocol used. Measurements made for the purpose of assessing the need for mitigation of one's own property should be made according to the guidance discussed in *Section 2* of this document; *Section 3* outlines options for protocols for measurements made for real estate transactions. Organizations that provide consultant services, or place or retrieve devices, should review the protocol options and the clients' needs, and inform clients of the buildings and test period conditions necessary for conducting valid measurements. In some areas, companies may offer different types of radon service agreements. Some agreements allow for a one-time fee that covers both testing, and if needed, radon reduction.

The organization or individuals performing the measurement service should use *only those specific devices or methods for which that organization or individuals is listed according to the National RMP Program (EPA 520/ 1-91-006; U.S. EPA 1991).* Adherence to the EPA device protocols, *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c) is a requirement for participation in the RMP program.

4.3.2 <u>Written Measurement Guidance</u>

Measurement organizations should provide clients with written measurement instructions that clearly explain the responsibilities of the client and the other parties to the real estate transactions during the test period. Written and verbal guidance should be in accordance with EPA's *<u>Indoor Radon and Radon Decay Product Measurement Device Protocols</u>* (EPA 520-402-R-92-004; U.S. EPA 1992c).and guidance published in the RMP *Program Handbook* (EPA 520/1-91-006; U.S. EPA 1991).

- A statement of whether the device measures radon or radon decay products and a discussion of the units in which all results will be reported.

  The results of radon decay product measurements should be reported in working levels (WL). If the WL value is converted to a radon concentration and is reported to the homeowner, it should be stated that this approximate conversion is based on a 50 percent equilibrium ratio (unless the actual equilibrium ratio is determined). In addition, the report should indicate that this ratio is an assumed average found in the home environment; any indoor environment may have a different and varying relationships between radon and its decay products.

- A description of closed-building conditions and a stated requirement that these conditions be maintained 12 hours prior to and during all short-term measurements lasting less than four days and preferably for those lasting up to one week.

- Directions that the building's heating, ventilating, and air conditioning (HVAC) system and any existing mitigation system should be normally operated 24 hours prior to and during all measurements.

- A permanent radon reduction system should be fully operational for at least 24 hours prior to testing to determine the mitigation system's effectiveness. The mitigation system is to be operated normally and continuously during the entire measurement

- Specific information on the minimum and maximum duration of exposure for the device.

- If the client will be performing the test, procedures for placing, retrieving, and handling the device.

- A written non-interference agreement (see *<u>Sections 3.5.3</u> and <u>4.3.4</u>*) to be signed and returned by the real estate transaction which confirms that they followed all instructions and did not interfere with the conditions or the measurement device.

4.3.3 <u>Conditions for a Valid Measurement</u>

Measurements should not be conducted if temporary radon reduction measures have been implemented. These included the introduction of unconditioned air into the home or closure or normally accessible areas of the home. In this case, the measurements organization or individual should inform the slient and other parties to the real estate transactions that these conditions have been corrected.

A <u>permanent</u> radon reduction system should be fully operational for at least 24 hours prior to testing to determine the mitigation system's effectiveness. The mitigation system is to be operated normally and continuously during the entire measurements periods.

4.3.4 Non-Interference Controls

The measurement organization should provide parties to a real estate transaction clients with a written statement that discusses the importance of proper measurement conditions and of not interfering with the measurement device or building conditions. The reader should refer to Section 3.5.3 for more information on non-interference agreements.

Organizations that place and retrieve devices should, in addition to providing written guidance, take steps to identify attempts to interfere with the measurement device or building conditions. There is increasing use of non-interference agreements signed by parties involved in real estate transactions to help prevent interference with the radon test and test conditions. The reader should refer to *Section 3.5* for more information on tamper-resistant testing.

The signed non-interference agreement, a description of all non-interference controls employed, and a statement addressing any observed breaches of the non-interference agreement/controls should be made part of the permanent measurement documentation for each measurement.

4.3.5 Measurement Documentation

Measurement organizations should record sufficient information on each measurement in a permanent log to allow for future data comparisons, interpretations, and reporting to clients. EPA recommends that a measurement log be kept with the following information and be maintained for five years. Additional method-specific documentation is outlined in EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c).

- A copy of the final report, including the measurement results, and the statement outlining any recommendations concerning retesting or mitigation provided to the building occupant or agent.
- The address of the building measured, including zip code.
- The exact locations of all measurement devices deployed. It is advisable to diagram the test area, noting the exact location of the detector.
- Exact start and stop dates of the measurement period as required for analysis.
- A description of the device used, including its RMP device identification number and serial number if any.
- A description of the condition of any permanent vents, such as crawl space vents or combustion air supply to combustive appliances.
- The name and PMP identification number (EPA 520/ 1-91-014-3N; U.S. EPA 1992e) of the service or analysis organizations used to analyze devices
- The name and RMP identification number (or State license number) of the individual who conducted the test.
- A description of any variations from or uncertainties about standard measurement procedures, closed-building conditions, or other factors that may affect the measurement result.

- A description of any non-interference controls used and copies of signed non-interference agreements.

- A record of any quality control measures associated with the test, such as results of simultaneous or secondary measurements.

4.4 Quality Assurance in Radon Testing

Anyone providing measurement services using radon or radon decay product measurement devices should establish and maintain a quality assurance program. These programs should include written procedures for attaining quality assurance objectives and a system for recording and monitoring the results of the quality assurance measurements described below. EPA offers general guidance on preparing quality assurance plans (QAMS-005/80; U.S. EPA 1980); a draft standard prepared by a radon industry group is also available (AARST 1991). The quality assurance program should include the maintenance of control charts and related statistical data, as described by Goldin (Goldin 1984), by EPA (EPA 600/9-76-005; U.S. EPA 1984), and in *Appendix B* of this document.

4.4.1 Calibration Measurements

Calibration measurements are measurements made in a known radon environment, such as a calibration chamber. Detectors requiring analysis, such as charcoal canisters, alpha track detectors, electret ion chambers, and radon progeny integrating samplers are exposed in a calibration chamber and then analyzed. Instruments providing immediate results, such as continuous working level and radon monitors, should be operated in a chamber to establish individual instrument calibration factors.

Calibration measurements must be conducted to determine and verify the conversion factors used to derive the concentration results. These factors are determined normally for a range of concentrations and exposure times, and for a range of other exposure and/or analysis conditions pertinent to the particular device. Determination of these calibration factors is a necessary part of the laboratory analysis, and is the responsibility of the analysis laboratory. These calibration measurement procedures, including the frequency of tests and the number of devices to be tested, should be specified in the quality assurance program maintained by manufacturers and analysis laboratories.

4.4.2 Known Exposure Measurements

Known exposure measurements or spiked samples consist of detectors that have been exposed to known concentrations in a radon calibration chamber. These detectors are labeled 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. Suppliers and analysis laboratories should provide for the blind introduction of spiked samples into their measurement processes and the monitoring of the results in their quality assurance programs. All organizations providing measurement services with passive devices should conduct spiked measurements at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month. **Providers of measurements with active devices** are required to recalibrate instruments at least once every 12 months and perform cross-checks with RPP-listed devices at least once every six months. Participation in EPA's National RMP Program will not satisfy the need for annual calibration, as this program is a performance test, not a calibration procedure

4.4.3 Background Measurements

Background measurements are required both for continuous monitors and for passive detectors requiring laboratory analysis. Users of continuous monitors must perform sufficient instrument background measurements to establish a reliable instrument background and to check on instrument operation. For more specific information on how often background measurements should be made, refer to EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-004; U.S. EPA 1992c).

Passive detectors requiring laboratory analysis require one type of background measurement made in the laboratory and another in the field. Suppliers and analysis laboratories should measure routinely the background of a statistically significant number of unexposed detectors from each batch or lot to establish the laboratory background for the batch and the entire measurement system. This laboratory blank value is subtracted routinely (by the laboratory) from the field sample results reported to the user, and should be made available to the users for quality assurance purposes. In addition to these background measurements, the organization performing the measurements should calculate the lower limit of detection (LLD) for its measurement system (Altshuler and Pasternack 1963, ANSI 1989, U.S. DOE 1990). This LLD is based on the detector and analysis system's background and can restrict the ability of some measurement systems to measure low concentrations.

Providers of passive detectors should employ field controls (called 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. These 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 than the LLD is dependent upon the type of detector. More information is available in EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c).

4.4.4 Duplicate Measurements

Duplicate measurements provide a check on the quality of the measurement result, and allow the user to make an estimate of the relative precision. Large precision errors may be caused by detector manufacture, and/or improper data transcription or handling by suppliers, laboratories, or technicians performing placements. Precision error can be an important component of the overall error, so it is important that all users monitor precision.

Duplicate measurements for both active and passive detectors 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 providing measurement services 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 in *Appendix B* of this document. 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.

4.4.5 Routine Instrument Performance Checks

Proper functioning of analysis equipment and operator usage require that the equipment and measurement system be subject to routine checks. Regular monitoring of equipment and operators is vital to ensure consistently accurate results. Performance checks of analysis equipment includes the frequent use of an instrument check source. In addition, important components of the device (such as a pump and pump flow rate, battery, or electronics) should be checked prior to each measurement and the results noted in a log. Each user should develop methods for regularly (daily, or at least prior to each measurement) monitoring their measurement system, and for recording and reviewing results.

4.4.6 Quality Assurance Plans

All organizations should develop, implement, revise periodically, and maintain a detailed quality assurance plan (QAP) appropriate to each device or method used. This was a requirement for participation in EPA's National Radon Measurement Proficiency (RMP) program. Specific guidance on the necessary quality control measures for each measurement method is provided in EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c).

Organizations that do not use continuous monitors or do not analyze detectors also need to write and follow a QAP, and conduct quality control measurements. These include duplicate, blank, and spiked measurements as described in *Section 4.4*. For more information on EPA's RMP Program, please contact:

RMP Program Information Services
Research Triangle Institute
3040 Cornwallis Road-Building 7
P.O. Box 12194
Research Triangle Park, NC 27709-2194
(919-541-7131/FAX -7386)

4.5 Standard Operating Procedures

Organizations performing radon measurements should have a written, device-specific standard operating procedure (SOP) in place for each radon measurement system they use. An SOP must include specific information describing how to operate and/or analyze a particular measurement device. Organizations that analyze devices should develop their own SOP or adapt manufacturer-developed SOPs for their devices. Organizations that receive results from a laboratory should have a device-specific SOP for each brand/model/type of device that they use. All SOPs should be consistent with the appropriate protocol outlined in EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c).

4.6 Providing Information to Consumers

Organizations should provide the customer with the following information:

- Devices that will be placed by the customer must be accompanied by instructions on how to use the device. These instructions should be consistent with EPA's *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA 520-402-R-92-004; U.S. EPA 1992c) and include specific information on the minimum and maximum length of time that the device must be exposed.

- The service organization should inform clients about sources of information on mitigation, such as EPA's *Consumer's Guide to Radon Reduction* (EPA 402-K-92-003; U.S. EPA 1992b), and other information available through their State Radon office. The organizations should also provide any State-required brochures which provide information on mitigation.

- If service organization distribute the *Consumer's Guide* brochure, it should be reproduced in its entirety.

4.7 Reporting Test Results

Organizations should return radon measurement results to clients within a few weeks of retrieving exposed devices or receiving an exposed device which has been delivered for analysis. At a minimum, the client report should contain the following information:

- Measurement results reported in the units that the device measures. Any measurement results based on **radon gas** (pCi/L of air) should be reported to no more than one decimal place, e.g., 4.3 pCi/L. Any measurement result based on **radon decay products** (WL) should be reported to no more than three decimal places, e.g., 0.033 WL. Any conversions from WL to pCi/L or from pCi/L to WL should be presented and explained clearly.

  If the WL value is converted to a radon concentration, it should be stated in the report to the homeowner that this approximate conversion is based on a 50 percent equilibrium ratio (unless the actual equilibrium ratio is determined). In addition, the report should indicate that this ratio is typical of the home environment, but that any indoor environment may have a different and varying relationship between radon and its decay products.

- The dates of the measurement period and address of the building tested.

- A description of the device used, its manufacturer, model or type, and the device identification (serial) numbers.

- The name and any relevant identification numbers of the organization and individual placing and retrieving the device and the organization analyzing the device, if they are different.

- A statement concerning any observed tampering or deviations from the required test conditions.

- Organizations that offer measurement services with grab sampling devices should provide clients with written notification stating that grab sample results can be useful diagnostic tools, but should not be used for deciding whether or not to mitigate.

- Diagnostic measurements should be reported as "for diagnostic purposes only."

4.8 Temporary Risk Reduction Measures

Contractors should refer home's occupants and real estate agents to EPA's *Radon Mitigation Standards* (U.S. EPA 1992d) or the *Consumer's Guide to Radon Reduction* (EPA 402-K-92-003; U.S. EPA 1992b) for information on temporary and permanent risk reduction measures.

If any radon reduction efforts are identified during measurement procedures, testers should inform clients and other parties to the real estate transaction that altered conditions during the measurement will invalidate the results and decline to conduct a measurement until the conditions have been corrected.

4.9 Recommendations for Mitigation

The measurement organization should inform consumers that EPA recommends fixing houses with radon levels equal to or greater than 4 pCi/L, and that EPA recommends in its "Consumer's Guide to Radon Reduction" the use of EPA Radon Contractor Proficiency (RCP)-listed and/or State-listed mitigation contractors to perform the work.

Organizations should refer customers to their State radon office for copies of EPA's "Consumer's Guide to Radon Reduction" (EPA 402-K-92-003; U.S. EPA 1992b) and a list of EPA RCP-proficient and State-listed mitigators.

Homes should also be tested again after they are fixed to be sure that radon levels have been reduced. If the occupants' living patterns changes and they begin occupying a lower level of their home (such as a basement), the home should be retested on that level. In addition, it is a good idea for homes to be retested sometime in the future to be sure radon levels remain low.

4.10 Worker Safety

Individuals and organizations should comply with all applicable Occupational Safety and Health Administration (OSHA) standards and guidelines relating to occupational worker exposure, health, and safety. Information on worker health and safety contained in EPA or State publications is not considered a substitute for any provisions of the *Occupational Safety and Health Act of 1970* or for any standards issued by OSHA.

Appendix A - State and EPA Regional Radon Offices

A.1/A.2 State and EPA Region Radon Offices - www.epa.gov/iaq/whereyoulive.html

Appendix B - Interpretation of the Results of Side-by-Side Measurements

B.1 Assessment of Precision

Radon and working level measurements, like all measurements, usually do not produce exactly the same results, even for collocated measurements. It is therefore critical to understand, document, and monitor the variability, or precision, of the measurements. This knowledge and proper will allow you to characterize precision error to clients. Further more the continual minitoring of precision provides a check on every aspect of the measurement system.

The objective of performing simultaneous or duplicate measurements is to assess the precision error of the measurement method, or how well two side-by-side measurements agree. This precision error is the "random" component of error (as opposed to the calibration error, which is systematic). The precision error, or the degree of disagreement between duplicates, can be composed of many factors. These include the error caused by the random nature of counting radioactive decay, slight differences between detector construction (for example, small differences in the amount of carbon in activated carbon detectors), and differences in handling of detectors (for example, differences in accuracy of the weighing process, and variations of analysis among detectors).

There is a variety of ways to quantitatively assess the precision error based on duplicate measurements. It is first necessary to understand that precision is characterized by a distribution; that is, your side-by-side measurements will exhibit a range of differences. There is some chance that any level of disagreement will be encountered, due merely to the statistical fluctuations of counting radioactive decays. The probability of encountering a very large difference between duplicates is smaller than the chance of observing a small difference similar to those that are routinely observed. It is important to recognize that a few high precision errors do not necessarily mean that the measurement system is flawed.

Ideally, the results of duplicates should be assessed in a way that allows for the determination of what level of chance is associated with a particular difference between duplicates. This will allow for the pre-determination of limits for the allowable differences between duplicates before an investigation into the cause of the large differences is made. For example, the ***warning level***, or the level of discrepancy between duplicates which triggers an investigation, may be set at a five percent probability. This level is a difference between duplicates that is so large that, when compared with previous precision errors, should only be observed five percent of the time. A ***control limit***, where further measurements should cease until the problem is corrected, may be set at one percent probability.

A control chart for duplicates is not as simple as a control chart used to monitor instrument performance, as for a check source. This is because the instrument's response to a check source should be fairly constant with time. Duplicates are performed at various radon concentrations, however, and the total difference between two measurements is expected to increase as radon levels increase.

Use of statistics such as the *relative percent difference* (RPD; difference divided by the mean) or the *coefficient of variation* (COV; standard deviation divided by the mean) can be used in a control chart for duplicate measurements at radon concentrations where the expected precision error is fairly constant in proportion to the mean, e.g., at levels greater than around 4 pCi/L or 0.02 WL. At lower concentrations, for example, between 2 pCi/L (or 0.01 WL) and 4 pCi/L (or 0.02 WL), a control chart may be developed by plotting these same statistics; however, the proportion of the precision error to the mean will be greater than that proportion at levels above 4 pCi/L or 0.02 WL. At concentrations less than about 2 pCi/L, or 0.01 WL, the lower limit of detection may be approached, and the precision error may be so large as to render a control chart not useful.

Example control charts, using three different statistics, are described in the following sections.

B.2 Example Control Charts for Precision

Before a control chart can be developed, it is necessary to know, from a history of making good quality measurements with the exact measurement system (detectors, analysis equipment, and procedures), the level of precision that is routinely encountered when the system is operating well or "in control." It is that "in control" precision error that forms the basis of the control chart, and upon which all the subsequent duplicate measurements will be judged. There are two ways of initially determining this "in control" level. The first, and preferable, way is to perform at least 20 duplicate pairs of measurements at each range of radon concentrations for which a control chart is to be prepared. For example, if you will only assess precision at concentrations greater than 4 pCi/L, or 0.02 WL, you will need at least 20 pairs of measurements at concentrations greater than 4 pCi/L, or 0.02 WL, to assess the "in control" level. The average precision error (RPD or COV) should be the "in control" level.

The second way to initially set the "in control" precision error level is to use a level that has been used by others, and that is recognized by industry and EPA as a goal for precision, for example, a 10 percent COV (corresponding to a 14 percent RPD). After at least 20 pairs of measurements are plotted, it will become apparent whether the 10 percent COV (or 14 percent RPD) is appropriate for your system. If itis not, a new control chart (using the guidelines below) should be prepared so that the warning and control limits are set at the correct probability limits for your system.

B.2.1 Sequential Control Chart Based on Coefficient of Variation

It can be shown (Iglewicz and Myers 1970, EPA 600/9-76-005; U.S. EPA 1984) that when the expected precision is a constant function of the mean, control limits can be expressed in terms of the COV ($COV=S/X_m$; where S is the variance or the square of the standard deviation, and X_m is the mean or average of the two measurements). One method for obtaining percentiles for the distribution of the COV is to apply a chi-squared (X^2) test:

$X^2_{n-1} \approx B[(n-1)COV_n^2/(n+(n-1)COV_n^2)]$ (Equation 1)

where: $B = n[1 + (1/COV^2)]$;

COV_n = the observed COV of the n^{th} pair (the pair that is to be evaluated); and

COV = the "in control" COV (e.g., 10 percent at levels greater than 4 pCi/L).

For duplicates, where n=2, Equation 1 becomes

$X^2 = [2 + (2/COV^2)][COV_n^2/(2 + COV_n^2)]$ (Equation 2)

For a value of 0.10 for COV, it further reduces to

$X^2 = 202[COV_n^2/(2 + COV_n^2)]$ (Equation 3)

Referring to a X^2 chart, you learn that the probability of exceeding a X^2 of 3.84 is only five percent. Inserting this value of 3.84 for X^2 and solving for COV_n, produces a COV_n of 0.20. This level of probability forms the *warning level* shown in Exhibit B-1. The *control limit* corresponds to a X^2 of 6.63 and a COV_n of 0.26, where the probability of exceeding those values is only one percent.

This sequential control chart should be used by plotting results from each pair on the y-axis, and noting the date and measurement numbers on the x-axis.

B.2.2 <u>Sequential Control Chart Based on Relative Percent Difference</u>

The RPD (or percent difference) is another expression of precision error, and is given by

RPD = $[100|x_1-x_2|]/[(x_1+x_2)/2]$ (Equation 4)

For n=2,

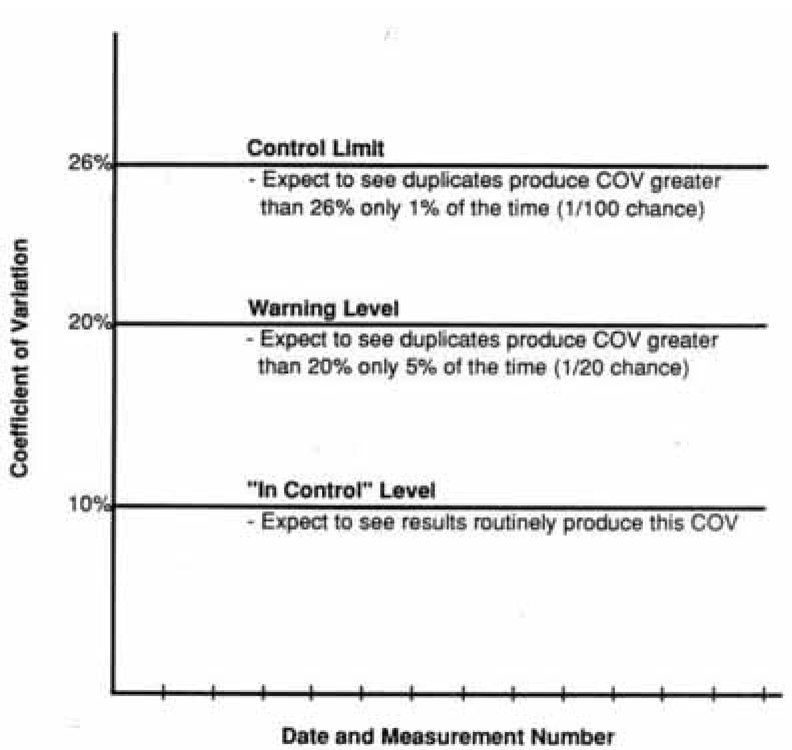
RPD = COV SQRT 2 (Equation 5)

The control limits for RPD can be obtained simply by multiplying the control limits for COV by the square root of two, or 1.41. These limits are shown in Exhibit B-2. This sequential control chart for RPD should be used in the same way as the control chart for COV, that is, with the vertical scale in units of RPD and the horizontal scale in units of date and measurement numbers.

A control chart using the statistic RPD based on an "in control" level of 25 percent RPD is shown in Exhibit B-3. The *warning level* and *control limit* are set at 50 percent and 67 percent, respectively. Use of these limits may be appropriate for measured radon concentrations less than 4 pCi/L.

Exhibit B-1

Control Chart* for Coefficient of Variation (COV)
Based on an "In Control" Level of 10%
(For duplicates where average ≥4 pCi/L or 0.02 WL)



COV=standard deviation of two measurements divided by their average

Example: Detector A=5 pCi/L, B=6 pCi/L, COV=13%

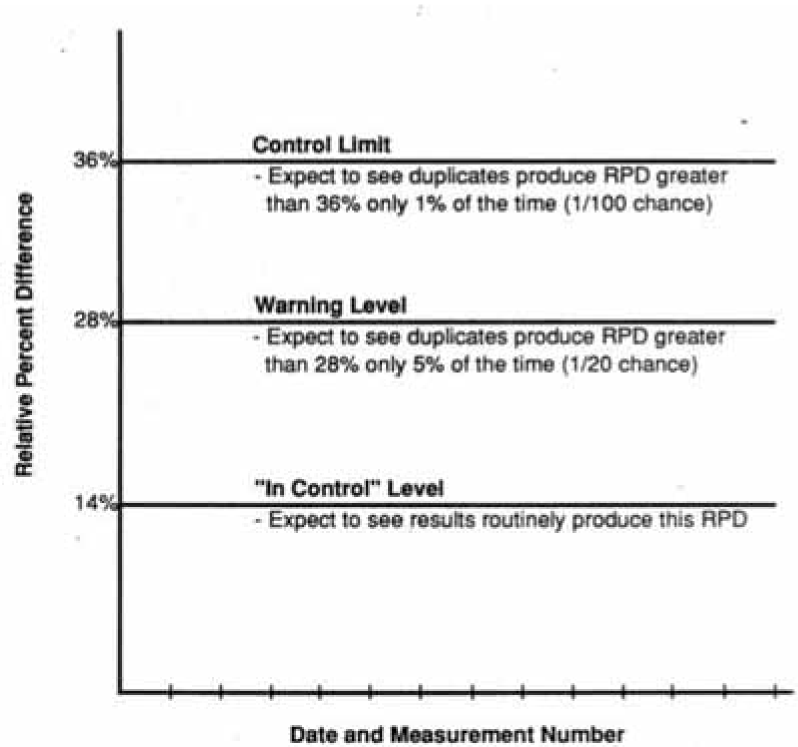
If COV exceeds the control limit--cease measurements until the problem is identified and corrected.

If COV exceeds the warning level--follow guidance in *Section B.3* and see Exhibit B-5.

*As calculated from guidance provided in "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume I" (EPA 600/9-76-005; U.S. EPA 1984)

Exhibit B-2

Control Chart* for Relative Percent Difference (RPD)
Based on an "In Control" Level of 14% (=COV of 10%)
(For duplicates where average >4 pCi/L or 0.02 WL)



RPD=difference between two measurements divided by their average

Example: Detector A=5 pCi/L, B=6 pCi/L, RPD=18%

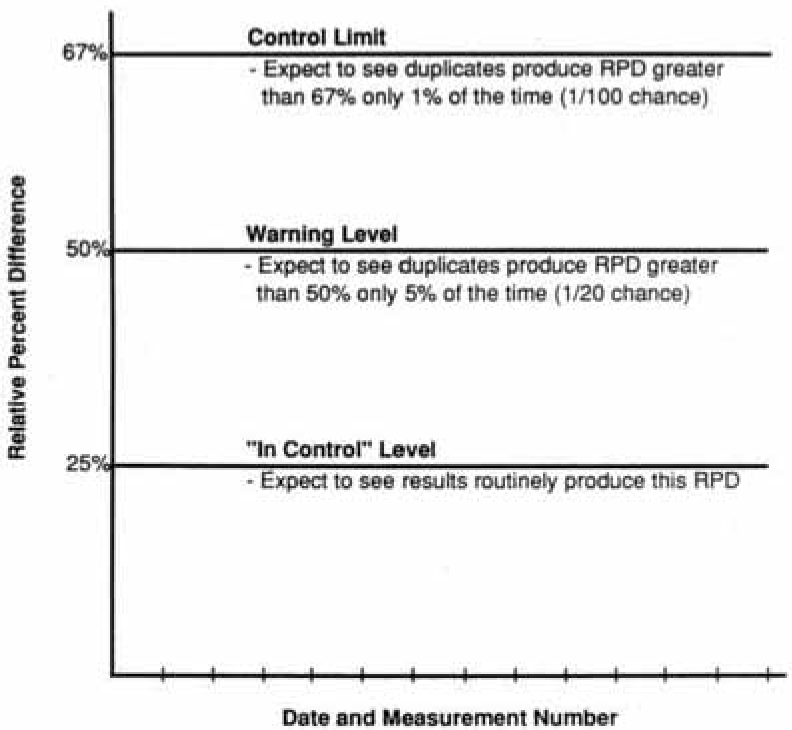
If RPD exceeds the control limit--cease measurements until the problem is identified and corrected.

If RPD exceeds the warning level--follow guidance in *Section B.3* and see Exhibit B-5.

*As calculated from guidance provided in "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume I" (EPA 600/9-76-005; U.S. EPA 1984)

Exhibit B-3

Control Chart* for Relative Percent Difference (RPD)
Based on an "In Control" Level of 25% (=COV of 18%)
(For duplicates where average <4 pCi/L or 0.02 WL)



RPD=difference between two measurements divided by their average

Example: Detector A=2 pCi/L, B=3 pCi/L, RPD=40%

If RPD exceeds the control limit--cease measurements until the problem is identified and corrected.

If RPD exceeds the warning level--follow guidance in *Section B.3* and see Exhibit B-5.

*As calculated from guidance provided in "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume I" (EPA 600/9-76-005; U.S. EPA 1984)

B.2.3. Range Control Chart

A range control chart (Goldin 1984) can be constructed to evaluate precision, using the statistics of the range (difference between two measurements) plotted against the average of the two measurements. The control limits are again based on the variability of the measurements, as decided upon from previous results or using an industry standard (e.g., 10 percent).

In this type of control chart, the limits are expressed in terms of the mean range (R_m), where, for n=2,

$R_m = 1.128\ s(x)$ (Equation 6)

where s(x) is the standard deviation of a single measurement, which reflects counting and other precision errors. Goldin shows that the limits can be expressed as follows:

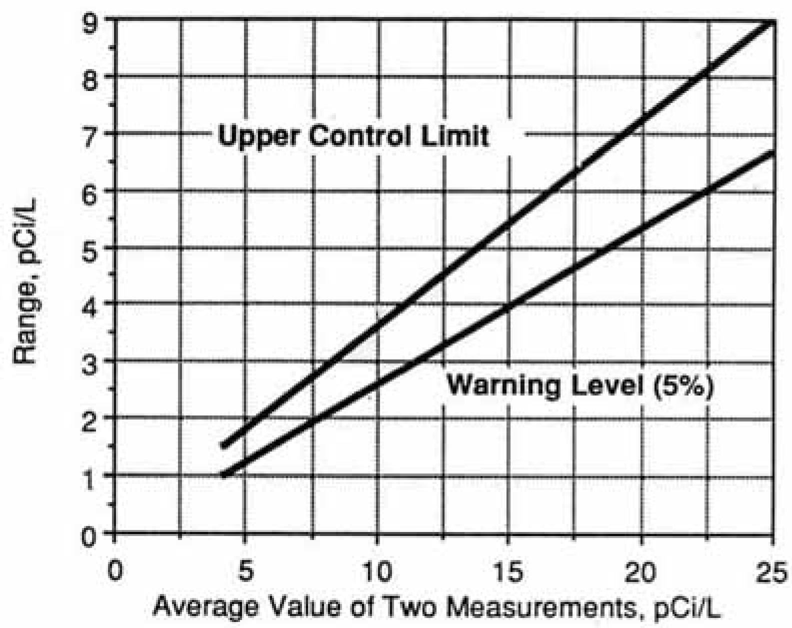
Control limit = 3.69 s(x) (Equation 7)

Warning level = 2.53 s(x) (Equation 8)

An example range control chart, using an assumed s(x) equal to 10 percent of the mean concentration, is shown in Exhibit B-4. The chart is used by plotting the range versus average concentration as duplicate measurements are analyzed.

Exhibit B-4

Range Control Chart to Evaluate Precision
(Limits Based on $s(x)=0.1x_m$)



If results exceed the control limit--cease measurements until the problem is identified and corrected.

If results exceed the warning level--follow guidance in *Section B.3* and see Exhibit B-5.

B.3 Interpretation of Precision Control Charts

The control chart should be examined carefully every time a new duplicate result is plotted. If a duplicate result falls outside the control limit, repeat the analyses if possible. If the repeated analyses also fall outside the control limit, stop making measurements and identify and correct the problem.

If any measurements fall outside the *warning level*, use the table in Exhibit B-5. Refer to the row showing the number of duplicate results outside the *warning level*. If the total number of duplicate results accumulated in the control chart is contained in column A, investigate the cause of the high level of precision error but continue making measurements. If the total number of duplicate results on the chart is contained in column B, stop making measurements until the cause for the high precision error is found, and it is determined that subsequent measurements will not suffer the same high level of precision error.

Note that the example control charts shown here are simplifications of actual conditions, because they are premised on the assumption that the precision error is a constant fraction of the mean concentration. In fact, the total precision error may best be represented by a different function of the mean concentration, for example, the square root of the concentration. The most accurate control chart can be rendered by a range control chart using the measurement uncertainty expressed as the standard deviation, s(x), expected at the concentrations where measurements are made. If the precision error is not a constant fraction of the mean, the control limits will not appear as straight lines, but may exhibit changing slope. However, methods discussed here present a conservative way to monitor, record, and evaluate precision error and are very useful for comparing observed precision errors with an industry standard.

Exhibit B-5

Criteria for Taking Action for Measurements Outside the Warning Level*

Number of Duplicate Results Outside the Warning Level	Total Number of Duplicates	
	Investigate, But Continue Operations **A**	Stop Operations Until Problem is Corrected **B**
2	8-19	2-7
3	17-34	8-16
4	29-51	17-28
5	41-67	29-40
6	54-84	41-53
7	67-100	54-66
*Modified from Goldin (Goldin 1984) and based upon cumulative probability tables of the binomial distribution.		

Glossary

Accuracy: The degree of agreement of a measurement (X) with an accepted reference or true value (T); usually expressed as the difference (or bias) between the two values (X – T), or the difference as a percentage of the reference or true value (100[X – T]/T), and sometimes expressed as a ratio (X/T).

Active radon/radon decay product measurement device: A radon or radon decay product measurement system which uses a sampling device, detector, and analysis system integrated as a complete unit or as separate, but portable, components. Active devices include continuous radon monitors, continuous working level monitors, and grab radon gas and grab working level measurement systems, but does not include devices such as electret ion chamber devices, activated carbon or other adsorbent systems, or alpha track devices.

Alpha particle: Two neutrons and two protons bound as a single particle that is emitted from the nucleus of certain radioactive isotopes in the process of decay.

Background instrument (analysis system, or laboratory) count rate: The nuclear counting rate obtained on a given instrument with a background counting sample. Typical instrument background measurements are:

- Unexposed carbon: for activated carbon measurement systems.
- Scintillaton vial containing scintillant and sample known to contain no radioactivity: for scintillation counters.
- Background measurements made with continuous radon monitors exposed <u>only</u> to radon-free air (aged air or nitrogen).

Background fields measurements (blanks): Measurements made by analyzing unexposed (closed) detectors that accompanied exposed detectors to the field. The purpose of field background measurements is to assess any exposure to the detector caused by radon exposure <u>other than</u> from the concentration in the environment to be measured. Results of background field measurements are subtracted from the actual field measurements before calculating the reported concentration. Background levels may be due to electronic noise of the analysis system, leakage of radon into the detector, detector response to gamma radiation, or other causes.

Background radiation: Radiation arising form radioactivity material, the sun, and parts of the universe, other than that under consideration. Background radiation may also be due to the presence of radioactive substances in building materials.

Becquerel (Bq): The International System of Units (SI) definition of Activity. 1 Bq = 1 disintegration per second.

Calibrate: To determine the response or reading of an instrument relative to a series of known values over the range of the instrument; results are used to develop correction or calibration factors.

Check source: A radioactive source, not necessarily calibrated, which is used to confirm the continuing consistent and satisfactory operation of an instrument.

Client: The individual or parties who hire(s) the radon tester.

Closed House Conditions: During any short-term test, closed-house-conditions should be maintained as much as possible while the test is in progress. In tests of less than 4 days duration, closed-house-conditions should be maintained for at least 12-hours before starting the test and for the duration of the test. While closed-house-conditions are not required before the start of tests that are between 4 and 90-days, closed-house-conditions should be maintained as much as possible.

Coefficient of variation (COV), relative standard deviation (RSD): A measure of precision, calculated as the standard deviation (s or s) of a set of values divided by the average (X_{ave} or μ), and usually multiplied by 100 to be expressed as a percentage.

COV = RSD = (s/ X_{ave}) x 100 for a sample,

COV ' = RSD ' = (σ/μ) x 100 for a population

See **Relative percent difference**.

Curie (Ci): A commonly used measurements unit for radioactivity, specifically the rate of decay for a gram of radium – 37 billion decays per second. A unit of radioactivity equal to 3.7 x 10^{10} disintegrations per second.

Duplicate measurements: Two measurements made concurrently and in the same location, or side-by-side. Use to evaluate the precision of the measurement method.

Efficiency, Intrinsic detector: The relationship between the number of events recorded (counts, voltage lost, tracks) and the number of radioactive particles incident upon the sensitive element of the detector per unit time. Efficiencies for radon detectors are commonly expressed in terms of the calibration factor, which is the number of events (counts) per time (hour or minute) per radon concentration (pCi/L). Methods with high efficiencies will exhibit more counts (signal) per time in response to a given radon level than will a method with a low efficiency.

Equilibrium ration, radon: Equilibrium ratio = [WL(100)]/(pCi/L). At complete equilibrium (i.e., at an equilibrium ratio of 1.0), 1 WL of RDPs would be present when the radon concentration was 100 pCi/L. The ratio is never 1.0 in a house. Due to ventilation and plate-out, the RPDs never reach equilibrium in a residential environment. A commonly assumed equilibrium ratio is 0.5 (i.e., the decay products are halfway toward equilibrium), in which case 1 WL would correspond to 200 pCi/L. However, equilibrium ratios vary with time and location, and ratios of 0.3 to 0.7 are commonly observed.

Equilibrium equivalent concentration (EEC): The radon concentration in equilibrium with its short-lived progeny, that has the same potential alpha energy per volume as exists in the environment being measured (see working level).

Exposure time: The length of time a specific mail-in device must be in contact with radon or radon decay products to get an accurate radon measurement. Also called exposure period, exposure parameters, or duration of exposure.

Gamma radiation: Short-wavelength electromagnetic radiation of nuclear origin, with a wide range of energies.

Integrating device: A device that measures a single average concentration value over a period of time. Also called a time integrating device.

Lower limit of detection (LLD): The smallest amount of sample activity which will yield a net count for which there is confidence at a predetermined level that activity is present. For a five percent probability of concluding falsely that activity is present, the LLD is approximately equal to 4.65 times the standard deviation of the background counts (assuming large numbers of counts where Gaussian statistics can be used [ANSI 1989, Pasternack and Harley 1971, U.S. DOE 1990]).

Lowest Level suitable for occupancy: The lowest level currently lived in or a lower level not currently used, such as a basement, which a prospective buyer could use for living space without renovations. This includes a basement that could be used regularly, as for example a recreation room, bedroom, den, or playroom.

Lowest lived-in level: The lowest level or floor of a home that is used regularly, including areas such as family rooms, living rooms, dens, playrooms, and bedrooms.

Passive radon measurement device: A radon measurement system in which the sampling device, detector, and measurement system do not function as a complete, integrated unit. Passive devices include electret ion chamber devices, activated carbon or other adsorbent systems, or alpha track devices, but do not include continuous radon/radon decay product monitors, or grab radon/ radon decay product measurement system

PicoCurie (pCi): One pCi is one trillionth (10^-12) of a Curie, 0.037 disintegrations per second, or 2.22 disintegrations per minute.

PicoCurie per liter (pCi/L): A unit of radioactivity corresponding to an average of one decay every 27 seconds in a volume of one liter, or 0.037 decays per second a liter of air or water. 1 pCi/L = 37 Becquerels per cubic meter (Bq/m3).

Precision: A measure of mutual agreement among individual measurement made under similar conditions. Can be expressed in terms of the variance, pooled estimate of variance, range standard deviation at a particular concentration, relative percent difference, coefficient of variation or other statistic.

Quality assurance: A complete program designed to produce results which are valid, scientifically defensible, and of known precision, bias, and accuracy. Includes planning, documentation, and quality control activities.

Quality control: The system of activities to ensure a quality product, including measurements made to ensure and monitor data quality. Includes calibrations, duplicate, blank, and spiked measurements, inter-laboratory comparisons, and audits.

Radon (Rn): A colorless, odorless, naturally occurring, radioactive, inert, gaseous element formed by radioactive decay of radium (Ra) atoms. The atomic number is 86. Although other isotopes of radon occur in nature, radon in indoor air is primarily Rn-222.

Radon chamber: An airtight enclosure in which operators can induce and control different levels of radon gas and radon decay products. Volume is such that samples can be taken without affecting the levels of either radon or its decay products within the chamber.

Relative percent difference (RPD): A measure of precision, calculated by:

$$RPD = [(|X1 - X2|)/ X_{ave}] \times 100$$

where:

X_1 = concentration observed with the first detector or equipment;

X_2 = concentration observed with the second detector, equipment, or absolute value;

|X1 - X2| = absolute value of the difference between X1 and X2; and

X_{ave} = average concentration = ((X1 + X2) / 2)

The relative percent difference (RPD) and coefficient of variation (COV) provide a measure of precision, but they are not equal. Below are example duplicate radon results and the corresponding values of relative percent difference and coefficient of variation:

Rn1 (pCi/L)	Rn2 (pCi/L)	RPD (%)	COV (%)
8	9	12	8
13	15	14	10
17	20	16	11
26	30	14	10
7.5	10	29	20

Note that the RPD divided by the square root of 2 = COV

See **Coefficient of variation** (COV).

Relative standard deviation: See **Coefficient of variation**.

Sensitivity: The ability of a radon or WL measurement method to produce reliable measurements at low concentrations. This ability is dependent upon the variability of the background signal (counts not due to radon or WL exposure) which the method records, as well as its efficiency. Methods with stable background rates and high efficiencies will be able to produce reliable measurements at lower concentrations than methods with variable background rates and low efficiencies. Sensitivity can be expressed in terms of the lower limit of detection or minimum detectable activity.

Signal-to-noise ratio: For radon and WL detectors, this term expresses the proportion of the number of counts due to exposure to radon or WP (signal) to the number of counts due to background (noise). Measurement methods with high signal-to-noise ratios will produce more counts due to radon or WL exposure (signal) in proportion to the background counts (noise) than will methods with low signal-to-noise ratios. A method with a high signal-to-noise ratio is more likely to exhibit good sensitivity, i.e., be able to produce reliable measurements at low concentrations.

Spiked measurements, or known exposure measurements: Quality control measurements in which the detector or instrument is exposed to a know concentration in a calibration facility and submitted for analysis. Used to evaluate accuracy.

Standard deviation (s): A measure of the scatter of several sample values around their average. For a sample, the standard deviation (s) is the positive square root of the sample variance:

$$s = \frac{\sqrt{\sum_{i=1}^{n} (X_i - X_{ave})^2}}{\sqrt{n - 1}}$$

For a finite population, the standard deviation (σ) is:

$$\sigma = \frac{\sqrt{\sum_{i=1}^{N} (X_i - \mu)^2}}{\sqrt{N}}$$

where μ is the true arithmetic mean of the population and N is the number of values in the population. The property of the standard deviation that makes it most practically meaningful is that it is in the same units as the observed variable X. For example, the upper 95% probability limit on differences between two values is 2.77 times the sample standard deviation.

Standard operating procedure: A written document which details an operation, analysis, or action whose mechanisms are prescribed thoroughly and which is commonly accepted as the method for performing certain routine or repetitive tasks.

Statistical control chart, (Shewhart control chart): A graphical chart with statistical control limits and plotted values (for some applications in chronological order) of some measured parameter for a series of samples. Use of the charts provides a visual display of the pattern of the data, enabling the early detection of time trends and shifts in level. For maximum usefulness in control, such charts should be plotted in a timely manner (i.e., as soon as the data are available).

Statistical control chart limits: The limits on control charts that have been derived by statistical analysis and are used as criteria for action, or for judging whether a set of data does or does not indicate lack of control. On a means control chart, the warning level may be two standard deviations above and below the mean, and the control limit may be three standard deviations above and below the mean.

Systeme Internationale (SI): The International System of Units as defined by the Conference of Weights and Measures in 1960.

Test Interference: The altering of test conditions prior to or during the measurement in order to change the radon or radon decay product concentrations or the altering of the performance of the measurement equipment.

Time Integrated measurement: A measurement conducted over a specific time period (e.g., from two days to a year or more) producing results representative of the average value for that period.

Uncertainty: The estimated bounds of the deviation from the mean value, expressed generally as a percentage of the mean value. Taken ordinarily as the sum of (1) the random errors (errors of precision) at the 95% confidence level, and (2) the estimated upper bound of the systematic error (errors of accuracy).

Working level (WL): Any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy. This number was chosen because it is approximately the alpha energy released from the decay products in equilibrium with 100 pCi of Ra-222. Exposures are measured in working level months (WLM).

Working level months (WLM): (working level x hours or exposure)/(170 hours/working month). In SI units, 1 WLM = 6×10^5 Bq-h/M^3 (EEC).

References

Altshuler, B. and Pasternack, B., 1963, *Statistical Measures of the Lower Limit of Detection of a Radioactivity Counter*, Health Physics, Vol. 9, pp. 293-298.

American Association of Radon Scientists and Technologists (AARST), 1991, *Draft Standard: Radon/Radon Decay Product Instrumentation Test and Calibration*, AARST, Park Ridge, New Jersey.

American National Standards Institute (ANSI), 1989, *Performance Specifications for Health Physics Instrumentation-Occupational Airborne Radioactivity Monitoring Instrumentation*, ANSI N42.17B-1989, The Institute of Electrical and Electronics Engineers, Inc., New York, New York.

Arvela, H., Voutilainen, A., Makelainen, I., Castren, O., and Winqvist, K., 1988, *Comparison of Predicted and Measured Variations of Indoor Radon Concentration*, Radiat. Prot. Dosim., Vol. 24, No. 1/4, pp. 231-235.

Chapin, Jr., F.S., 1974, *Human Activity Patterns in the City: Things People Do in Time and Space*, John Wiley and Sons, New York, NY.

Dudney, C.S., Hawthorne, A.R., Wallace, R.G., and Reed, R.P., 1990, *Radon-222, Rn-222 Progeny and Rn-222 Progeny Levels in 70 Houses*, Health Physics, Vol. 58, No. 3, pp. 297-311.

Fleischer, R.L. and Turner, L.G., 1984, *Indoor Radon Measurements in the New York Capital District*, Health Physics, Vol. 46, pp. 999-1011.

Furrer, D., Crameri, R., and Burkart, W., 1991, *Dynamics of Rn Transport From the Cellar to the Living Area in an Unheated House*, Health Physics, Vol. 60, No. 3, pp. 393-398.

Gesell, T.F., 1983, *Background Atmospheric Rn-222 Concentrations Outdoors and Indoors: A Review*, Health Physics, Vol. 45, pp. 289-302.

George, A.C., Duncan, M., and Franklin, H., 1984, *Measurements of Radon in Residential Buildings in Maryland and Pennsylvania*, Radiat. Prot. Dosim., Vol. 7, pp. 291-294.

Goldin, A.S., 1984, *Evaluation of Internal Quality Control Measurements and Radioassay*, Health Physics, Vol. 47, No. 3, pp. 361-364.

Harley, N.H., 1991, *Radon Levels in a High-Rise Apartment*, Health Physics, Vol. 61, No. 2, pp. 263-265.

Hess, C.T., 1985, *Field and Laboratory Tests of Etched Track Detectors for Rn-222: Summer – vs – Winter Variations and Tightness Effects in Maine Houses*, Health Physics, Vol. 49, pp. 65-79.

Iglewicz, B. and Myers, R.H., February 1970, *Comparison of Approximations to the Percentage Points of the Sample Coefficients of Variation*, Technometrics, Vol. 12, No. 1, pp. 166-170.

Keller, G., Folkerts, K.H., and Muth, H., 1984, *Special Aspects of the Rn-222 and Daughter Product Concentrations in Dwellings and the Open Air*, Radiat. Prot. Dosim., Vol. 7, pp. 151-154.

Martz, D.E., Rood, A.S., George, J.L., Pearson, M.D., and Langner, Jr., G.H., 1991, *Year-to-Year Variations in Annual Average Indoor Rn-222 Concentrations*, Health Physics, Vol. 61, No. 3, pp. 409-413.

Moeller, D.W. and Underhill, D.W., December 1976, *Final Report on Study of the Effects of Building Materials on Population Dose Equivalent*, School of Public Health, Harvard University, Boston, MA.

Nyberg, P.C. and Bernhardt, D.E., 1983, *Measurement of Time-Integrated Radon Concentrations in Residences*, Health Physics, Vol. 45, pp. 539-543.

Pasternack, B.S. and Harley, N.H., 1971, *Detection Limits for Radionuclides in the Analysis of Multi-Component Gamma Ray Spectrometer Data*, Nuclear Instr. and Methods, Vol. 91, pp. 533-540.

Perritt, R.L., Hartwell, T.D., Sheldon, L.S., Cox, B.G., Clayton, C.A., Jones, S.M., and Smith, M.L., 1990, *Radon-222 Levels in New York State Homes*, Health Physics, Vol. 58, No. 2, pp. 147-155.

Put, L.W. and de Meijer, R.J., 1988, *Variation of Time-Averaged Indoor and Outdoor Radon Concentrations with Time, Location and Sampling Height*, Radiat. Prot. Dosim., Vol. 24, No. 1/4, pp. 317-320.

Ronca-Battista, M. and Magno, P., 1988, *A Comparison of the Variability of Different Techniques and Sampling Periods for Measuring Rn-222 and its Decay Products*, Health Physics, Vol. 55, No. 5, pp. 801-807.

Steck, D.J., 1992, *Spatial and Temporal Indoor Radon Concentrations*, Health Physics, Vol. 62, No. 4, pp. 351-355.

Stranden, E., Berteig, L., and Ugletveit, F., 1979, *A Study on Radon in Dwellings*, Health Physics, Vol. 36, pp. 413-421.

Szalai, A., 1972, *The Use of Time: Daily Activities of Urban and Suburban Populations in Twelve Countries*, Mouton, The Hague, Paris.

U.S. Department of Energy, 1990, *Procedures Manual*, U.S. DOE Environmental Measurements Laboratory, 376 Hudson Street, N.Y., N.Y. 10014-3621 (HASL-300).

U.S. Environmental Protection Agency, 1980, *Interim Guidelines and Specifications for Preparing Quality Assurance Project Plans*, QAMS-005/80, Office of Monitoring Systems and Quality Assurance, Office of Research and Development, Washington, D.C.

U.S. Environmental Protection Agency, December 1984, *Quality Assurance Handbook for Air Pollution Measurement Systems: Volume 1*, EPA 600/9-76-005, Washington, D.C.

U.S. Environmental Protection Agency, 1987, *Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Measurements*, EPA 520/1-86-014-1, Office of Radiation Programs, Washington, D.C.

U.S. Environmental Protection Agency, 1991, *Radon Measurement Proficiency (RMP) Program Handbook*, EPA 520/1-91-006, Office of Radiation Programs, Washington, D.C.

U.S. Environmental Protection Agency, Office of Radiation Programs; U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, 1992a, *A Citizen's Guide to Radon*, EPA 402-K-92-001, Washington, D.C.

U.S. Environmental Protection Agency, 1992b, *Consumer's Guide to Radon Reduction*, EPA 402-K-92-003, Office of Air and Radiation, Washington, D.C.

U.S. Environmental Protection Agency, 1992c, *Indoor Radon and Radon Decay Product Measurement Device Protocols*, EPA 520-402-R-92-004, Office of Radiation Programs, Washington, D.C.

U.S. Environmental Protection Agency, 1992d, *Interim Radon Mitigation Standards*, Office of Radiation Programs, Washington, D.C.

U.S. Environmental Protection Agency, 1992e, *National Radon Measurement Proficiency Program, National Proficiency Report*, EPA 520/1-91-014-3N, Office of Air and Radiation, Washington, D.C.

U.S. Environmental Protection Agency, 1992f, *Radon Contractor Proficiency (RCP) Program Application Information Packet*, EPA 402-K-92-001, Washington, D.C.

U.S. Environmental Protection Agency, 1992g, *Technical Support Document for the 1992 Citizen's Guide to Radon*, EPA 400-R-92-011, Office of Air and Radiation, Washington, D.C.

U.S. Environmental Protection Agency, 1993, *Home Buyer's and Seller's Guide to Radon*, EPA 402-R-93-003, Office of Radiation Programs, Washington, D.C.

Wilkening, M. and Wicke, A., 1986, *Seasonal Variations of Indoor Rn at a Location in the Southwestern United States*, Health Physics, Vol. 51, pp. 427-436.

Wilson, D.L., Gammage, R.B., Dudney, C.S., and Saultz, R.J., 1991, *Summertime Elevation of Rn-222 Levels in Huntsville, Alabama*, Health Physics, Vol. 60, No. 3, pp. 393-398.